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Analysis of the level of sound noises imitted into the passenger compartment by road vehicles

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Abstract. This scientific paper presents an analysis carried out by the authors in order to implement some concepts, in which technical aspects (theoretical and practical) are presented concerning sound noises, imitated in the passenger compartment by road vehicles, determined on the basis of the second order active type experiment, under the conditions of their running in urban and extraurban environment at different speed regimes (30, 50 and 130 km/h). For the research, a sample of passenger cars from the national fleet of road vehicles, with spark ignition engines, with European pollution standard in the range [Euro 3 - Euro 6], cylinder capacities (cylinders displacement) in the range [1,400 – 1,600] cm^3 and manual and continuously variable transmissions (CVT), which includes all vehicles belonging to owners (natural persons) and legal persons (road transport organisations) at national level. Finally, the conclusions in the field are presented.

Keywords: *road vehicles, noise, immission, pollution, urban and extra-urban road traffic, traffic speed.*

Introduction

In everyday life, the effects of road transport noise are felt by people and sometimes become unbearable in large urban agglomerations where road traffic is heavy. Modern cars are getting quieter. However, when traffic is heavy, the noise is multiplied and amplified by the vertical walls of nearby buildings. Literature research shows that 20% of the European population is currently affected by road traffic noise, which means that noise pollution targets in Europe have not been met. High levels of noise and vibration have various effects on human health, creating discomfort (22 million cases per year), sleep disturbance (6.5 million cases per year), adversely affecting the cardiovascular system (48,000 cases of ischaemic heart disease per year), the metabolic system (12,000 premature deaths per year) and cognitive impairment in children (more than 12,000 children have difficulty reading) [1, p. 133]. Noises are sensations due to stimulation of the auditory nerves and auditory centres of the brain, usually by vibrations transmitted in a material medium (e.g. air), which affect the human auditory

organ (the ear). The vibrational energy that causes such a sensation is defined by sounds. They propagate through progressive longitudinal vibratory disturbances (sound waves) [2, pp. 950-951].

The comfort offered by a vehicle is defined as a state of well-being that positively influences the physical and mental state of the user, causing satisfaction. Acoustic comfort consists of passive sensory concepts rooted in the spectrum of civilisation, cleanliness, comfort, peace of mind, and warmth, making driving and travelling easy and convenient. The comfort of a car is not just about being comfortable in the seats or seats on which we sit and travel. Automobile comfort is also defined by the vibrations and noises transmitted by the engine, transmissions, axles and wheels of a car, but also by those systems, installations, mechanisms and functional elements of the car that support the driver and ease his load (e.g. power steering, power brakes, adjustable and heated or cooled seats, electronic assistance and safety systems for the driver or passengers, electronically controlled climate control systems in different zones, sound and entertainment systems in the passenger compartment, rain and parking assistance sensor systems, close-up camera systems, pleasant vibrations and noises produced by the engine or operating parts, the power provided by the engine(s) that we feel in the seats when accelerating, reduced fuel or energy consumption, etc.).

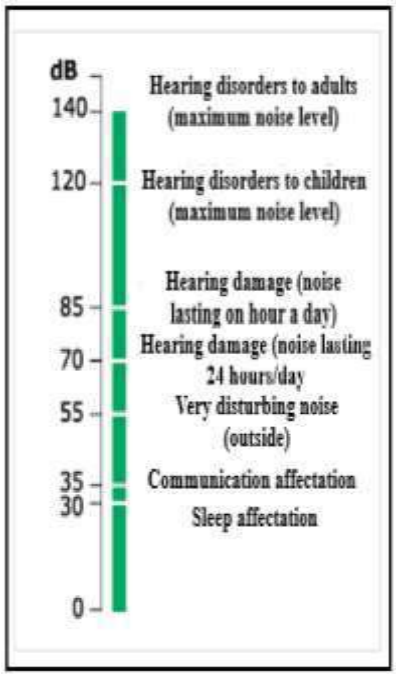

Figure 1. The negative effects of noise on human health [1, p. 78], [7].

The physical perception of sound by humans through their hearing organs (ears) is limited to a certain frequency range. Humans perceive sound waves at frequencies in the range [20-20,000 Hz], the upper limit decreasing with age [3, p. 249]. Most of the time sound refers only to those vibrations with frequencies that are included in the audible range of humans [4]. Figure 1 shows the negative effects of noise on human health. Acoustic comfort [5] is defined by engine noises, rotating or translational moving organs, frictional forces, tire contact with the ground, or the air frictional forces of the vehicle in motion [6, p. 106]. The noises produced by the motor vehicle are perceived by the human ear at a certain sound level, and if they exceed the value of 80 dB, they become dangerous to human health [7, p. 7]. The literature shows that, at European level, more than 20% of the inhabitants of EU countries are affected by road traffic noise [8, p. 117]. It is also estimated, according to the World Health Organization, that more than 40% of Europe's population is affected by road vehicle noise exceeding 55 dB [9].

Regarding EU policies on noise pollution, the Green Book refers to future noise policies. In relation to these policies, the EC has identified environmental noise as the main environmental problem on the European continent.

In view of the research objective, the following two components are of interest:

- acoustic comfort, defined by the level of noise produced by engines, rotating or translating parts, tyre contact with the ground or friction of the moving car with the air.
- vibrational comfort, defined as the resonance of mechanical waves in the structure of the car, perceived at body level by passengers, are caused by rotating or translating elements of the car's organs or by irregularities in the surfaces on which the car runs.

To date, the question of demonstrating these two components of car comfort (acoustics and vibration) has been more or less debated. In view of the above, I have set out to verify in practice, by means of a second-order active type experiment, at different engine speeds and revs in urban and extraurban environments, on conventional (internal combustion) and hybrid vehicles equipped with manual and continuously variable transmissions (CVT), the level of noise pollution in the passenger compartment. The vehicles used in the research have different comfort classes.

1. Literature review, legislative regulation and specific conditions for conducting experimental research

1.1 Reference data on noise emissions from road motor vehicles with spark ignition and compression ignition engines

Noise pollution is the noise produced by cars during operation and is created by frictional forces between moving parts or components. Noise pollution is also produced by cars in dynamic motion when tyres are in contact with the road surface and when air is rubbing against the outer bodywork.
The physical characteristics of noise are [1, pp. 117-118]:

- *intensity (or strength)* - depends on the properties of the generating source, space and the probability of transmission or multiplication. Its unit of measurement is the phonon or decibel (human ear perception), which is a logarithmic unit measured from the lower threshold of audibility (1,000 Hz = 0 dB);
- *duration* - the time the sound waves act on the analysis device (human ear or sound level meter);
- *frequency (sound pitch)* - number of vibrations/second. Its unit of measurement is the hertz (Hz).

The A-weighted decibel, or dB(A), is the unit of measurement used to evaluate the loudness as perceived by the human ear, since the sensitivity of hearing is not the same over the entire frequency range. A mechanical instrument, e.g. a microphone, will perceive all frequencies equally in decibels, whereas the human ear, while perceiving sounds between 20 Hz and 20 kHz, is much more sensitive to sounds with frequencies between 250 and 5,000 Hz. The A-weighting of sound level meter measurements gives a higher value to sounds in the frequency range where the ear is sensitive and a lower value to sounds outside this range. In terms of audibility, the perceived loudness of sounds ranges from 0 to 120 dB(A). Normal conversational noise is in the range 30-60 dB(A). The lower limit at which hearing is considered to suffer over time with prolonged exposure is 85 dB(A). Intensities of 140 dB(A) and above create a painful sensation and possible serious hearing damage.

The European Union has regularly amended its legislation on maximum noise levels emitted by road vehicles in an attempt to reduce noise pollution. The first piece of legislation regulating pollution standards for motor vehicles was Directive 70/157/EEC/06.02.1970, which regulated for the first time noise emission limits from motor vehicles and set out technical specifications for measurable levels of noise emitted outdoors by road vehicles during operation. The Directive was amended by UNECE Regulation No 51. Finally, on 09.12.2011, the European Commission proposes to the European Parliament and the Council a Regulation setting the noise threshold of road vehicles, repealing Directive 70/157/EEC/06.02.1970 [10] . Table 1 shows the legal sound level limit values as specified in Appendix III of the Regulation on the sound level of motor vehicles, issued by the European Commission on 16.04.2014.

Table 1. Legal limit values of the measured noise level as specified in Appendix III of the Regulation on the sound level of motor vehicles [10].

Vehicle category	**Description of vehicle category**	**Limit values expressed in dB(A) [decibels (A)]**		
		Stage 1, applicable to new types of vehicles from July 01. 2016	**Stage 2, applicable to new vehicle types from 1 July 2020 and for first registration from July 01. 2022**	**Stage 3, applicable to new vehicle types from 01 July 2024 and for first registration from July 01. 2026**
Vehicule pentru transportul de persoane din categoria M				
M_1	Power to mass ratio ≤ 120 kW/ 1,000 kg	72(*)	70(*)	68(*)

(*) M1 category vehicles derived from N1 category: vehicles with a mass of 2,500 kg must comply with the limit values for N1 category (2,500 kg < M1 category mass with R point > 850 mm above the ground and a total permissible mass ≤ 3,500 kg) [10].

For M1 vehicles, the higher limit values for off-road vehicles apply only if the maximum authorised mass is > 2 tonnes [10].
The yellow coloured column in Table 1 is the subject of the research. The noise produced by the cars used in the experimental research falls within the sound value of 72 dBA.

1.2 Power to mass ratio

In order to fit each car on which we conducted experimental research into the legal noise standard according to Annex III of the Motor Vehicle Noise Regulation issued by the European Commission on April 16. 2014 (Table 2), it was necessary to calculate the Power to Mass Ratio (PMR).

The Power to Mass Ratio (PRM) is determined with the mathematical relation [10, p. 131]:

$$PRM = (P_n/m_t) \times 1.000 \quad [kW/kg] \qquad (1)$$

where,

P_n is the rated power and is measured in kilowatts (kW);

m_t - the total mass of the vehicle and shall be measured in kilograms (kg),

but,

$$m_t = m_{ro} \quad [kg] \qquad (2)$$

were,

m_{ro} means the mass of the vehicle in running order [11, p. 70].

Vehicle mass in running orde (m_{ro}) is defined as the weight of an unladen vehicle, with the box, freight container or passenger compartment/passenger compartment, with coupling or towing hitch in the case of a towing vehicle, with the weight of the rigid strength frame (chassis) and the driver's compartment (cab), if the vehicle is delivered without the box or bodywork and/or the manufacturer's towing device, including the full load of the cooling system, engine and transmission lubrication system, with the full load of the fuel tank (90%) and other special fluids (100%). Exceptions are waste water, dashboard and other instruments, spare wheel, driver with a maximum weight of 75 kg, and for public transport (minibuses, trolleybuses, buses, coaches) the weight of the accompanying person is taken into account, which must be a maximum of 75 kg (if the vehicle is equipped with a seat for an accompanying person) [11, p. 70]. The Power to Mass Ratio (PMR) is dimensionless.

Table 2 shows the power-to-mass ratio (PMR), calculated from the mathematical relation (1), for cars for which noise noises have been determined.

Table 2. Power to Mass Ratio (PMR) calculated for the vehicles for which noise was determined.

Type	**Make of vehicle, engine capacity and European pollution standard**	**Year of manufac-ture**	**Engine/ engines power** [kW]	**Own mass of the vehicle** [kg]	**PMR** [kw/1.000 kg]
A. Hybrid vehicles with spark ignition engines					
Car	Toyota RAV 4 - 2.5 L, Euro 6	2019	131	1,730	**75**
B. Motor vehicles with spark ignition engines					
Car	Volkswagen Jetta TSI 1.4 L, Euro 6	2015	92	1,341	**69**
Car	Volkswagen Jetta TSI 1.4 L, Euro 5	2009	125	1,440	**87**
Car	Dacia Logan 1.4 MPI, Euro 4	2009	55	1,105	**50**
Car	Volkswagen Golf 1.6 L, Euro 4	2006	75	1,283	**58**
Car	Ford Focus ZX 4, SUA 2.0 L, Euro 3	2007	165	1,685	**98**
Car	Dacia Solenza 1.4 MPI, Euro 3	2004	55	980	**56**

Immediate conclusion: The analysis of the data presented in Table 2 shows that all the passenger cars investigated for noise emissions fall into the category M1 passenger cars with a power to mass ratio ≤ 120 kW/1000 kg (Table 1). They fall under stage we which is applicable to new vehicles manufactured from July 01, 2016 at the noise, i.e. at the sound value to which the research relates – **72 dBA**.

1.3 Specific conditions for conducting experimental research

As regards the research on noise pollution measured inside the passenger compartment of motor vehicles, it was carried out in order to define the acoustic comfort provided to the driver and passengers while driving the vehicle. They were carried out by measuring and recording the sound waves and vibrations produced by the vehicle when driving in urban areas at different speeds (30 km/h and 50 km/h) and on motorways at the maximum legal speed limit (130 km/h) using a professional TROTEC SL 400 sound level meter (Fig. 2). All data were recorded in the internal memory of the sound level meter. The TROTEC SL 400 professional sound level meter is a device that meets the requirements for noise measuring instruments, accuracy class 2 according to IEC 61672-1 as well as ANSI S1.4, and is recommended for documenting road traffic noise, workplace measurements or environmental auditing [12]. The four-position display has bar graph representation, which can be easily read in all conditions, even in the dark, thanks to the backlit LCD display. The SL 400 professional sound level meter is a perfect solution for professional noise measurements. The practical size, low weight and one-hand operation due to the optimised layout of the keys makes this device the perfect equipment for sound level measurement in workshops and industrial halls, labour and environmental protection. The SL 400 professional sound level meter has an additional live logging function and a data memory for up to 32,700 values. The data obtained from the experimental investigations are related to the legislative provisions shown in Table 2 and were transferred to a computer system, through which the experimental data were processed [13], using Excel software. The processing of noise data was also done using the SL-400 sound level meter's own software. Following the processing of the noise data, the results were analysed and interpreted and conclusions and further research directions were drawn.

Figure 2. Professional Sound Level Meter SL 400 and aspects during the research.

The following conditions were respected during the experimental research:

- the test was carried out on routes consisting of streets of all categories within Sibiu and on the A1 motorway, over distances of 5-30 km;
- accelerations and decelerations were not programmed, but were those required by compliance with road traffic rules, the principles of preventive traffic and eco-driving;
- speed on urban streets: 30 km/h and 50 km/h respectively, and 130 km/h on motorways (in compliance with road traffic rules);
- the vehicle was equipped with a portable noise emission measurement system (SL 400 sound level meter), mounted inside the passenger compartment;
- test time was within the range 15-45 minutes;
- outside ambient temperature was between +20 and +25 °C;
- the experimental route, both urban and extraurban, was the same for all vehicles

2. Centralisation of experimental results

The experimental research was carried out on vehicles of different makes. Experimental investigations were carried out on motor vehicles with petrol engines, with cylinder capacities in the range [1,400-2,500] cm^3, with European pollution standards in the range [Euro 3-Euro 6].

The experimental investigations were carried out for each type of vehicle by driving on predetermined routes in urban areas at a relatively constant speed of 30 km/h and 50 km/h respectively, and on motorways at a constant speed of 130 km/h. They were carried out at different times of the day, under the same outdoor temperature and traffic conditions. To see if there was a difference in chemical and noise noxious emissions, a hybrid car with a cylinder capacity of 2,500 cm^3 and a European Euro 6 pollution standard was also tested.

The physical wear of each vehicle used for the experiments is defined by the number of kilometres driven, and the moral wear is defined by the age in years. The exception was the Ford Focus ZX 4 USA car, which has 81,525 km of mileage, although it has a considerable amount of moral wear. For this car, the average actual kilometres driven per year of age is 5,435 km/year.

The average actual kilometres travelled per year of age for the other cars with spark ignition engines used in the experiments is as follows: Toyota RAV 4 hybrid car, Euro 6 - 8,566 km; Volkswagen Jetta 1.4 liters, Euro 4 car - 9,327 km; Dacia Solenza 1.4 MPI, Euro 3 car - 9,509 km; Dacia Logan 1.4 litres, Euro 4 car - 10,264 km; Volkswagen Jetta 1.4 liters TSI, Euro 6 car - 11,317 km; Volkswagen Golf 1.6 liters, Euro 4 car - 14,909 km.

I specify these aspects because the physical wear and tear of a vehicle can lead to a different level of noise pollution (a vehicle whose engine mechanism is in an advanced state of physical wear and tear, whose parts or components are worn out, produces much greater vibrations and noise than a new one).

The sound level data measured with the SL 400 sound level meter in the passenger compartment cars are presented as follows:

- in Table 3 for passenger cars with hybrid and spark ignition engines at 30 km/h in urban areas;
- in Table 4 for passenger cars with hybrid and spark ignition engines at 50 km/h in urban areas;
- in Table 5 for passenger cars with hybrid and spark ignition engines at 130 km/h on motorways in extraurban areas.

Table 3. Centralizer with minimum, average and maximum noise values measured in the passenger compartment of cars with hybrid and spark ignition engines when driving in urban areas at 30 km/h.

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	Kilometre at board (actual km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minimum	Average	Maximum
A. Hybrid cars with spark ignition engines							
TOYOTA RAV 4 hibrid car	Euro 6	2,500	25,696	3	51.7	57.2	66.6
B. Cars with spark ignition engines							
VOLKSWAGEN JETTA TSI car	Euro 6	1,400	79,217	7	56.1	61.5	77.7
VOLKSWAGEN JETTA TSI car	Euro 5	1,400	121,244	13	53.0	65.0	79.6
DACIA LOGAN car	Euro 4	1,400	133,426	13	45.8	57.7	72.7
VOLKSWAGEN GOLF car	Euro 4	1,600	238,897	16	58.9	68.7	86.1
FORD FOCUS ZX 4 SUA car	Euro 3	2,000	81,525	15	56.9	64.9	76.4
DACIA SOLENZA car	Euro 3	1,400	171,161	18	59.2	68.1	83.3

Table 4. Centralizer with minimum, average and maximum noise values measured in the passenger compartment of cars with hybrid and spark ignition engines when driving in urban areas at 50 km/h.

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	Kilometre at board (actual km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minimum	Average	Maximum
A. Hybrid cars with spark ignition engines							
TOYOTA RAV 4 hibrid car	Euro 6	2,500	25,696	3	47.8	59.1	72.8
B. Cars with spark ignition engines							
VOLKSWAGEN JETTA TSI car	Euro 6	1,400	79,217	7	55.2	63.0	75.3
VOLKSWAGEN JETTA TSI car	Euro 5	1,400	121,244	13	56.2	61.9	72.2
DACIA LOGAN car	Euro 4	1,400	133,426	13	44.3	58.1	76.9
VOLKSWAGEN GOLF car	Euro 4	1,600	238,897	16	58.1	69.2	86.8
FORD FOCUS ZX 4 SUA car	Euro 3	2,000	81,525	15	52.6	66.9	84.3
DACIA SOLENZA car	Euro 3	1,400	171,161	18	55.8	70.6	85.6

Table 5. Centralizer with minimum, average and maximum noise noises measured in the passenger compartment of cars with hybrid and spark ignition engines when driving on the extraurban motorway at 130 km/h.

Type and make of vehicle	European pollution standard	Cylinder capacity (cm^3)	Kilometre at board (actual km)	Age (years)	Sound values measured inside the passenger compartment dB(A)		
					Minimum	Average	Maximum
A. Hybrid cars with spark ignition engines							
TOYOTA RAV 4 hibrid car	Euro 6	2,500	25,696	3	67.1	73.1	77.6
B. Cars with spark ignition engines							
VOLKSWAGEN JETTA TSI car	Euro 6	1,400	79,217	7	67.1	73.2	89.3
VOLKSWAGEN JETTA TSI car	Euro 5	1,400	121,244	13	64.8	71.0	87.0
DACIA LOGAN car	Euro 4	1,400	133,426	13	52.1	72.0	82.1
VOLKSWAGEN GOLF car	Euro 4	1,600	238,897	16	64.6	76.1	89.0
FORD FOCUS ZX 4 SUA car	Euro 3	2,000	81,525	15	64.1	73.7	83.1
DACIA SOLENZA car	Euro 3	1,400	171,161	18	76.3	81.1	85.5

The legend

Legal rule in Appendix III of the ***Regulation on the sound level of motor vehicles***, issued by the European Commission on April 16. 2014	**EUROPEAN VEHICLE POLLUTION STANDARD**	**Maximum permissible sound limit dB(A)**	Normal values, not exceeding legal limit
	Vehicles for the carriage of passengers of category M1 having a Power to Mass Ratio (PMR) ≤ 120 kW/1,000 kg	72	Values above the legal limit

3. Research hypotheses

Research hypothesis no. 1: *Hybrid cars, although part of the environmentally friendly road transport category, generate noise emissions due to the thermal engine fitted to them, which produces noise and vibration during operation/dynamics;*

***Research hypothesis no.* 2:** *At low speeds (30 km/h and 50 km/h), car engines run at higher revs and noise pollution increases;*

***Research hypothesis no.* 3:** *When vehicles are driven on a motorway route, the thermal engine running at higher engine speeds, tyre-road contact and friction of the car with the air increase noise levels;*

4. Results and discussions

4.1 Noise in the passenger compartment of the Toyota RAV 4 hybrid, Euro 6 car

Figure 3 shows the graph of the evolution of the noise perceived in the passenger compartment of the Toyota RAV 4 hybrid car 2.5 liters, Euro 6 car, during urban and highway driving.

An analysis of the development of noise in the passenger compartment of the Toyota RAV 4 hybrid 2.5 liters, Euro 6 car emission standard shows the following data:

- when driving the urban route at 30 km/h, minimum noise value = 51.70 dBA, average value = 57.20 dBA, maximum value = 66.60 dBA;
- when driving the urban route at 50 km/h, minimum noise value = 47.80 dBA, average value = 59.10 dBA, maximum value = 72.80 dBA;
- when driving on the A1 - Sibiu motorway, minimum noise value = 67.10 dBA, average value = 73.10 dBA, maximum value = 77.60 dBA.

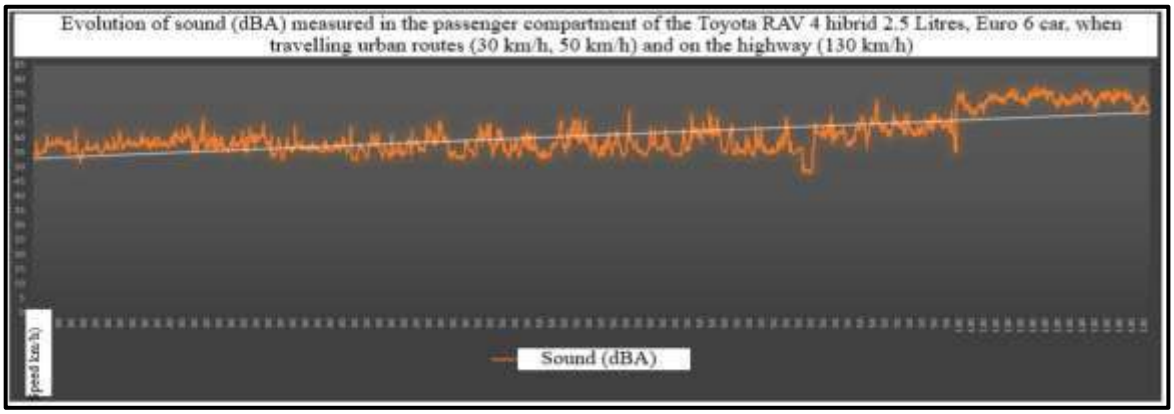

Figure 3. The evolution of sound (dBA) measured in the passenger compartment of the Toyota RAV 4 hibrid 2.5 liters, Euro 6 car, when travelling urban routes (30 km/h, 50 km/h) and on the highway (130 km/h).

4.2 Noise in the passenger compartment of the Volkswagen Jetta, 1,4 l, TSI, Euro 6 car

Figure 4 shows the graph of the evolution of the noise perceived in the passenger compartment of the Volkswagen Jetta 1.4 liters TSI, Euro 6 car, when driving in urban areas and on motorways.

An analysis of the development of noise in the passenger compartment of the Volkswagen Jetta, 1.4 liters TSI, Euro 6 car, the following data are available:

- when driving the urban route at 30 km/h, minimum noise value = 56.10 dBA, average value = 61.50 dBA, maximum value = 77.70 dBA;
- when driving the urban route at 50 km/h, minimum noise value = 55.20 dBA, average value = 63.00 dBA, maximum value = 75.30 dBA;
- when driving on the A1 - Sibiu motorway, minimum noise value = 67.10 dBA, average value = 73.20 dBA, maximum value = 89.30 dBA.

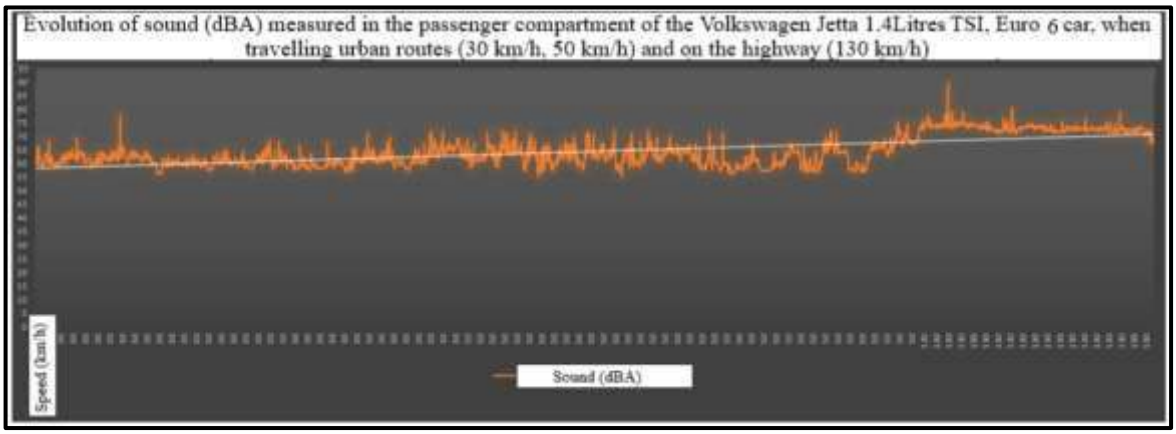

Figure 4. The evolution of sound (dBA) measured in the passenger compartment of the Volkswagen Jetta 1.4 liters TSI, Euro 6 car, when travelling urban routes (30 km/h, 50 km/h) and on the highway (130 km/h).

4.3 Noise in the passenger compartment of the Volkswagen Jetta, 1,4 liters, Euro 5 car

Figure 5 shows the graph of the evolution of the sound received in the passenger compartment of the Volkswagen Jetta, 1.4 liters, Euro 5 car, during urban and motorway driving.

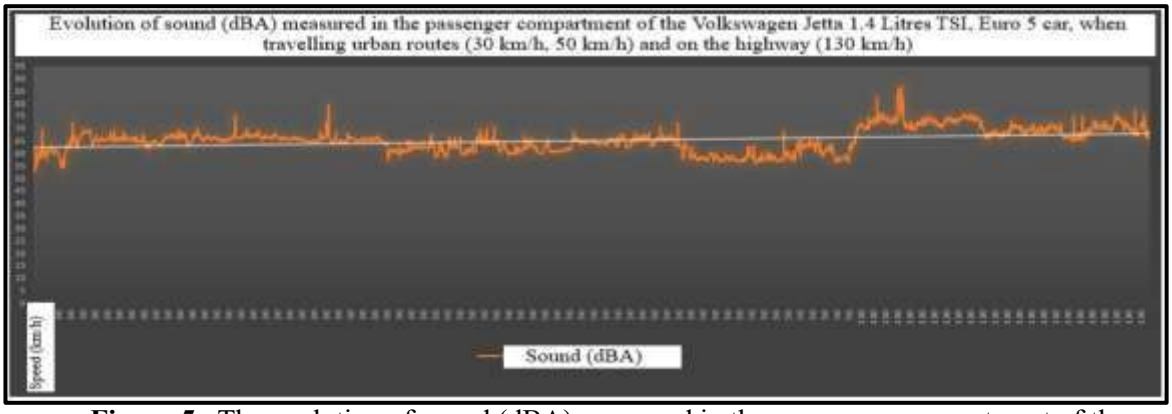

Figure 5. The evolution of sound (dBA) measured in the passenger compartment of the Volkswagen Jetta 1.4 liters TSI, Euro 5 car, when travelling urban routes (30 km/h, 50 km/h) and on the highway (130 km/h).

An analysis of the evolution of the sound in the passenger compartment of the Volkswagen Jetta 1.4 liters TSI, Euro 5 car, shows the following data:

- when driving the urban route at 30 km/h minimum sound value = 53.00 dBA, average sound value = 65.00 dBA, maximum sound value = 79.60 dBA;
- when driving on the urban route at a speed of 50 km/h minimum sound value = 56.20 dBA, average sound value = 61.90 dBA, maximum sound value = 72.20 dBA;
- when driving on the A1 - Sibiu motorway at a speed of 130 km/h minimum sound value = 64.80 dBA, average sound value = 71.00 dBA, maximum sound value = 87.00 dBA.

4.4 Noise in the passenger compartment of the Dacia Logan, 1,4 liters MPI, Euro 4 car

Figure 6 shows the graph of the evolution of the sound received in the passenger compartment of the Dacia Logan 1.4 liters, Euro 4 car, while driving in urban areas and on motorways.

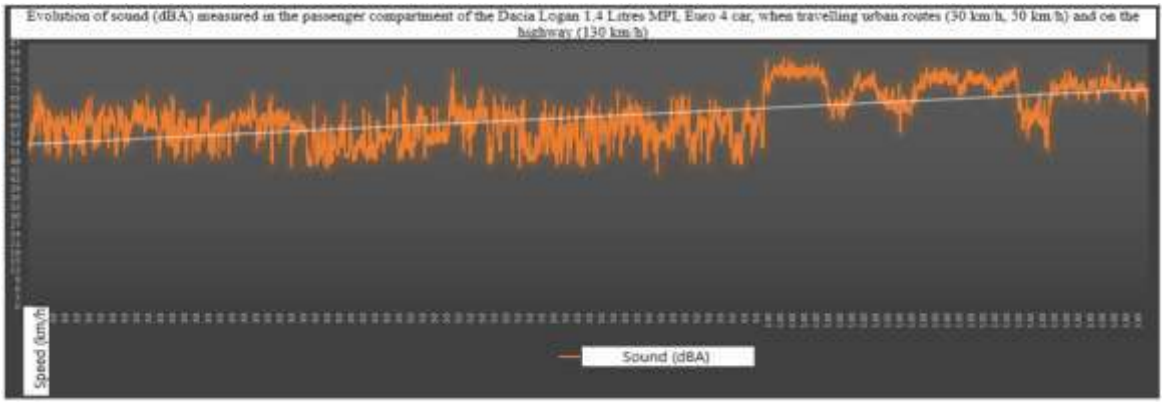

Figure 6. The evolution of sound (dBA) measured in the passenger compartment of the Dacia Logan 1.4 liters MPI, Euro 4 car, when travelling urban routes (30 km/h, 50 km/h) and on the highway (130 km/h).

An analysis of the evolution of the sound in the passenger compartment of the Dacia Logan 1.4 liters, Euro 4 car shows the following data:

- when driving the urban route at 30 km/h minimum sound value = 45.80 dBA, average sound value = 57.70 dBA, maximum sound value = 72.70 dBA;
- when driving on the urban route at a speed of 50 km/h minimum sound value = 44.0 dBA, average sound value = 58.10 dBA, maximum sound value = 76.90 dBA;
- when driving on the A1 - Sibiu motorway at a speed of 130 km/h minimum sound value = 52.10 dBA, average sound value = 7.00 dBA, maximum sound value = 82.10 dBA.

4.5 Noise in the passenger compartment of the Volkswagen Golf 1,6 liters, Euro 4 car

Figure 7 shows the graph of the evolution of the sound received in the passenger compartment of the Volkswagen Golf 1.6 liters, Euro 4 car, during urban and motorway driving.

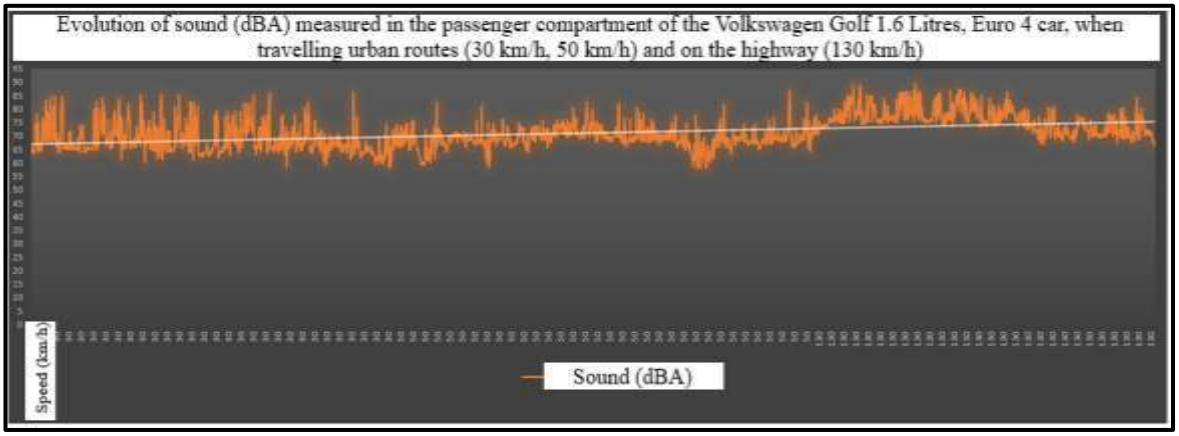

Figure 7. The evolution of sound (dBA) measured in the passenger compartment of the Volkswagen Golf 1.6 liters, Euro 4 car, when travelling urban routes (30 km/h, 50 km/h) and on the highway (130 km/h).

An analysis of the evolution of the sound in the passenger compartment of the Volkswagen Golf 1.6 liters, Euro 4 car, shows the following data:

- when driving through the urban route at a speed of 30 km/h minimum sound value = 58.90 dBA, average sound value = 68.70 dBA, maximum sound value = 86.10 dBA;

- when driving on the urban route at a speed of 50 km/h minimum sound value = 58.10 dBA, average sound value = 69.20 dBA, maximum sound value = 86.80 dBA;
- when driving on the A1 - Sibiu motorway at a speed of 130 km/h minimum sound value = 64.60 dBA, average sound value = 76.10 dBA, maximum sound value = 89.60 dBA.

4.6 Noise in the passenger compartment of the Ford Focus ZX4 SUA 2,0 liters, Euro 3 car

Figure 8 shows the graph of the evolution of the sound received in the cabin of the Ford Focus ZX4 USA 2.0 liters, Euro 3 car, when driving in urban areas and on motorways.

An analysis of the evolution of sound in the passenger compartment of the Ford Focus ZX 4 USA, 2.0 liters, Euro 3 car, shows the following data:

- when driving through the city at a speed of 30 km/h minimum sound value = 56.90 dBA, average sound value = 64.90 dBA, maximum sound value = 76.40 dBA;
- when driving on the urban route at a speed of 50 km/h minimum sound value = 52.60 dBA, average sound value = 66.90 dBA, maximum sound value = 84.30 dBA;
- when driving on the A1 - Sibiu motorway at a speed of 130 km/h minimum sound value = 64.10 dBA, average sound value = 73.70 dBA, maximum sound value = 83.10 dBA.

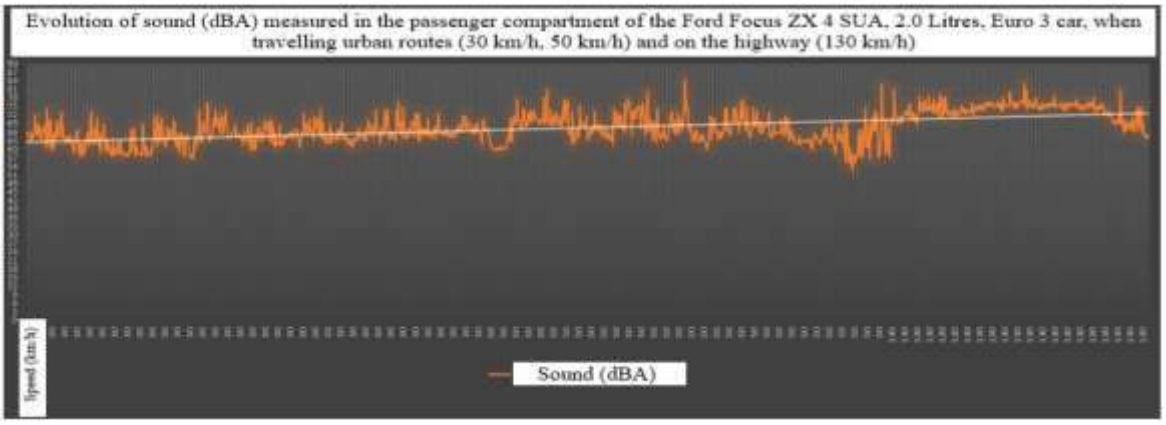

Figure 8. The evolution of sound (dBA) measured in the passenger compartment of the Ford Focus ZX 4 SUA, 2.0 liters, Euro 3 car, when travelling urban routes (30 km/h, 50 km/h) and on the highway (130 km/h).

4.7 Noise in the passenger compartment of the Dacia Solenza 1,4 MPI, Euro 3 car

Figure 9 shows the graph of the evolution of the sound received in the passenger compartment of the Dacia Solenza 1,4 MPI, Euro 3 car.

An analysis of the evolution of the sound in the passenger compartment of the Dacia Solenza 1.4 liters MPI, Euro 3 car, shows the following data:

- when driving through the city at a speed of 30 km/h the minimum sound value = 59.20 dBA, the average sound value = 68.10 dBA, the maximum sound value = 83.30 dBA;
- when driving on the urban route at a speed of 50 km/h minimum sound value = 55.80 dBA, average sound value = 70.60 dBA, maximum sound value = 85.60 dBA;
- when driving on the A1 - Sibiu motorway at a speed of 130 km/h minimum sound value = 76.30 dBA, average sound value = 81.10 dBA, maximum sound value = 85.50 dBA.

za 1.4 MPI, Euro 3 car, while driving in urban areas and on motorways.

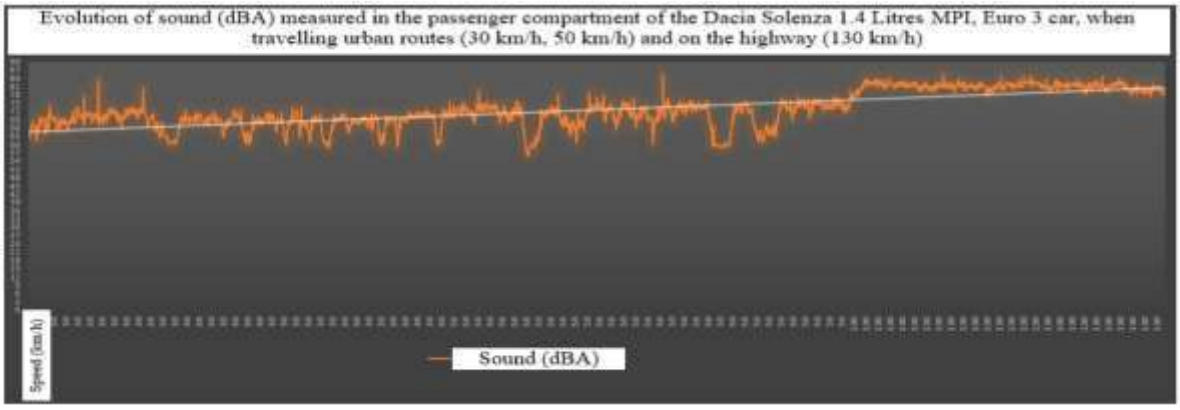

Figure 9. The evolution of sound (dBA) measured in the passenger compartment of the Dacia Solenza 1.4 liters MPI, Euro 3 car, when travelling urban routes (30 km/h, 50 km/h) and on the highway (130 km/h).

5. Conclusions

1. The trend in cabin noise in the **Toyota RAV 4 hybrid 2.5 liters, Euro 6 car**, on both urban and motorway routes is increasing. The level of cabin noise increases with increasing speed. When driving the urban route at a speed of 30 km/h, the noise levels do not exceed the legal standard (72 dBA), which does **not confirm** research hypothesis No 1. When driving the urban route at 50 km/h, the minimum and average values of imis noise do not exceed the legal norm, which does **not confirm** research hypothesis No. 1. The maximum values exceed the legal norm, which **confirms** research hypothesis 1. When driving on the A1 - Sibiu motorway, the minimum noise values do not exceed the legal standard, but the average and maximum values exceed it, which **confirms** research hypothesis No 1. The noise imitted by the car increases with the increase in urban traffic speed from 30 km/h to 50 km/h and thus to 130 km/h. The linear evolution of the noise emitted on the three routes shows a rapid increase in values.

2. The trend in cabin noise in the **Volkswagen Jetta 1.4 liters TSI, Euro 6 car**, on both urban and motorway routes is increasing. The level of cabin noise increases with increasing speed. When driving the urban route at a speed of 30 km/h, the minimum and average values of the noise level do not exceed the legal standard of 72 dBA. The maximum values exceed the legal standard, which **confirms** research hypothesis No 2. When driving on the urban route at 50 km/h, the minimum and average values of imis noise do not exceed the legal standard. The maximum values exceed the legal standard. When driving on the A1 - Sibiu motorway, the minimum imis noise values do not exceed the legal standard. The maximum and average values exceed the legal standard, which **confirms** research hypothesis No 3. The noise imitted by the car decreases with the decrease of the urban traffic speed from 50 km/h to 30 km/h. The linear evolution of noise on the three routes shows a rapid increase in values.

3. The trend in the sound level in the passenger compartment of the **Volkswagen Jetta 1.4 liters, Euro 5 car** on both urban and motorway routes is slightly increasing. The level of noise in the passenger compartment increases with increasing speed. When driving the urban route at a speed of 30 km/h the minimum and average values of the noise level do not exceed the legal standard of 72 dBA. The maximum imis sound values exceed the legal norm, which **confirms** research hypothesis No 2. When driving the urban route at a speed of 50 km/h the minimum and average values of immis sound do not exceed the legal standard. The maximum values of imis exceed the legal standard. When driving on the A1 - Sibiu motorway at a speed of 130 km/h the minimum and average values of the immis sound do not exceed the legal norm. The maximum imis sound values exceed the legal norm, which **confirms** research hypothesis No 3. The noise imitted by the car in the passenger compartment

decreases slightly with the decrease of the driving speed in the urban environment from 30 km/h to 50 km/h. The linear evolution of the noise on the three routes shows a slow increase in values.

4. The trend of the sound in the passenger compartment of the **Dacia Logan 1.4 liters, Euro 4 car**, on both urban and motorway routes is increasing. The level of cabin noise increases with increasing speed. When driving the urban route at a speed of 30 km/h the minimum and the average value of the noise immission does not exceed the legal standard of 72 dBA. The maximum imis values exceed the legal standard, which **confirms** research hypothesis No 2. When driving the urban route at a speed of 50 km/h the minimum and average values of immis sound do not exceed the legal standard. The maximum values of imis exceed the legal norm. When driving on the A1 - Sibiu motorway at a speed of 130 km/h the minimum and average values of the immis sound do not exceed the legal norm. The maximum imis sound values exceed the legal norm, which **confirms** research hypothesis No 3. The noise imitted by the car in the passenger compartment decreases with the decrease of the driving speed in urban areas from 30 km/h to 50 km/h. The linear evolution of the noise on the three routes shows a rapid increase in values.

5. The trend in the sound level in the passenger compartment of the **Volkswagen Golf 1.6 liters, Euro 4 car**, on both urban and motorway routes is increasing. The level of noise in the passenger compartment increases with increasing speed. When driving the urban route at a speed of 30 km/h, the minimum noise level and the average noise level do not exceed the legal standard. The maximum imis sound values exceed the legal standard, which is 72 dBA, wich **confirms** research hypothesis No 2. When driving the urban route at a speed of 50 km/h, the minimum sound values and the average immission value do not exceed the legal standard. When driving on the A1 - Sibiu motorway at a speed of 130 km/h, the minimum sound values do not exceed the legal standard. The maximum and average values of imis sound exceed the legal norm, which **confirms** research hypothesis No 3. The noise imitted by the car in the passenger compartment decreases with the decrease of the driving speed in the urban environment from 30 km/h to 50 km/h. The linear evolution of the noise on the three routes shows a slow increase in values.

6. The trend in the sound development in the cabin of the **Ford Focus ZX 4 SUA 2.0 liters, Euro 3 car**, on both urban and motorway routes is increasing. The level of cabin noise increases with increasing speed. When driving the urban route at a speed of 30 km/h the minimum values and the average value of the noise immission do not exceed the legal norm. The maximum values of imis exceed the legal standard of 72 dBA, which **confirms** research hypothesis No 2. When driving the urban route at a speed of 50 km/h the minimum and average values of immis sound do not exceed the legal standard. The maximum values of imis exceed the legal standard. When driving on the A1 - Sibiu motorway at a speed of 130 km/h the minimum values of immis sound do not exceed the legal standard. The maximum and average values of imis exceed the legal norm, which **confirms** research hypothesis No 3. The noise imitted by the car in the passenger compartment decreases with the decrease of the driving speed in the urban environment from 30 km/h to 50 km/h. The linear evolution of the noise on the three routes shows a rapid increase in values.

7. The trend of the sound in the passenger compartment of the **Dacia Solenza 1.4 liters MPI, Euro 3 car**, on both urban and motorway routes is increasing. The level of cabin noise increases with increasing speed. When driving the urban route at a speed of 30 km/h the minimum values and the average value of the noise immission do not exceed the legal norm. The maximum values of imis exceed the legal standard of 72 dBA, which **confirms** research hypothesis No 2. When driving the urban route at a speed of 50 km/h the minimum and average values of immis sound do not exceed the legal standard. The maximum values of imis exceed the legal standard. When driving on the A1 - Sibiu motorway at a speed of 130 km/h, all the imis sound values exceed the legal norm, which **confirms** research hypothesis No 3. The noise imitted by the car in the passenger compartment decreases with the decrease of the driving speed in urban areas from 30 km/h to 50 km/h. The linear evolution of the noise on the three routes shows a rapid increase in values.

Analysed in terms of average values, for noise noises that are regulated by legislation, for **hybrid** and **spark ignition cars**, the situation is as follows:

- cars that exceeded the legal standard of 72 dBA in the extraurban environment on the motorway: Toyota Rav 4 hybrid Euro 6 car (73.10 dBA); Volkswagen Jetta 1.4 TSI, Euro 6 car (73.20 dBA); Volkswagen Golf 1.6 l, Euro 4 car (76.10 dBA); Ford Focus ZX4 USA, Euro 3 car (73.10 dBA) and Dacia Solenza 1.4 MPI, Euro 3 car (81.10 dBA);
- Dacia Solenza 1.4 MPI, Euro 3 car is the most polluting car in terms of noise in the passenger compartment. When driving on the motorway, the minimum, average and maximum values were exceeded (minimum value = 76.3 dBA; average value = 81.10 dBA; maximum value = 85.5 dBA);
- peak noise levels in the passenger compartment in the urban environment, when driving at 30 km/h, were reached by: Volkswagen Jetta 1.4 TSI, Euro 6 car = 77.7 dBA; Volkswagen Jetta 1.4 TSI, Euro 5 car = 79.6 dBA; Dacia Logan 1.4 MPI, Euro 4 car = 72.7 dBA; Volkswagen Golf 1.6 l, Euro 4 car = 86.10 dBA; Ford Focus ZX4 USA, 2.0 liters, Euro 3 car = 76.4 dBA; Dacia Solenza 1.4 MPI, Euro 3 car = 83.3 dBA;
- peak noise levels in the passenger compartment in the urban environment, when driving at 50 km/h, were reached by: Toyota RAV 4 hybrid 2.5 liters, Euro 6 car = 72.8 dBA; Volkswagen Jetta 1.4 TSI, Euro 6 car = 75.3 dBA; Volkswagen Jetta 1.4 TSI, Euro 5 car = 72.2 dBA; Dacia Logan 1.4 MPI, Euro 4 car = 76.9 dBA; Volkswagen Golf 1.6 liters, Euro 4 car = 86.8 dBA; Ford Focus ZX4 USA, 2.0 l, Euro 3 car = 84.3 dBA; Dacia Solenza 1.4 MPI, Euro 3 car = 85.6 dBA;
- peak noise levels in the passenger compartment in the extra-urban environment, when driving on the motorway at 130 km/h, were reached by: Toyota RAV 4 hybrid 2.5 liters, Euro 6 car = 77.6 dBA; Volkswagen Jetta 1.4 TSI, Euro 6 car = 89.3 dBA; Volkswagen Jetta 1.4 TSI, Euro 5 car = 87.00 dBA; Dacia Logan 1.4 MPI, Euro 4 car = 82.1 dBA; Volkswagen Golf 1.6 l, Euro 4 car = 89.6 dBA; Ford Focus ZX4 USA, 2.0 liters, Euro 3 car = 83.1 dBA; Dacia Solenza 1.4 MPI, Euro 3 car = 85.5 dBA;

In the case of the cars used in this research, from the analysis of the data presented, the level of noise pollution imitted in the passenger compartment is determined by the level of engine speed, the type and profile of the tyres, the condition and degree of deterioration of the road surface, the state of maintenance, the level of noise produced by the transmission components and organs, the soundproofing level of the bodywork, the age in years (moral wear) and physical wear.

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Occupational Health and Safety training using online platforms in road transport - a case study

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Abstract. Road transport is characterized by high occupational health and safety (OSH) risks and considerable operational variability, which makes the effective management of worker safety a major challenge for transport companies. In recent years, digital training platforms have been increasingly adopted in this sector as a means of improving safety management and regulatory compliance. However, the evaluation of their effectiveness continues to rely mainly on linear and simplified assessment models, which often fail to reflect the complex interactions between training, operational behavior, and overall system performance. This study examines the impact of digital OSH training in three road transport companies by applying a mixed-method research design that combines the Kirkpatrick evaluation model, functional variability analysis, and comparative pre- and post-intervention assessment. The empirical investigation involved a sample of 47 professional drivers who participated in a structured online training program focusing on occupational risks, fatigue management, compliance with driving regulations, and simulations of critical work situations.Training effectiveness was evaluated using learning outcomes at Kirkpatrick Level 2, behavioral indicators derived from telematics systems at Level 3, and organizational safety outcomes at Level 4. On this basis, a composite training efficiency indicator was developed and correlated with changes in functional system performance. The results indicate significant improvements in knowledge acquisition and safety-related behavior, accompanied by an average reduction of approximately 44% in functional variability within critical operational functions. Furthermore, strong correlations were identified between training efficiency and functional stabilization, as well as moderate but consistent correlations with organizational safety indicators.These findings suggest that digital OSH training contributes to safety not only by enhancing individual competencies, but also by regulating functional interactions and reducing unwanted variability in complex socio-technical systems.

Keywords: *occupational health and safety, digital platforms, road transport, socio-technical systems.*

Introduction

Road transport is a key component of the modern economy and of social mobility. However, it remains one of the sectors with the highest occupational health and safety risks. Drivers and auxiliary personnel are exposed daily to multiple hazards. These include traffic accidents, physical and mental fatigue, psychosocial stress, manual handling of loads, unfavorable weather, and time pressure related to delivery schedules.These risks are intensified by the specific structure of the sector. Activities are performed over large distances. The workforce is mobile. Direct supervision and traditional training are difficult to apply. For many years, OHS management in road transport has relied mainly on face-to-face training sessions, paper documents, and periodic inspections. Although these methods meet legal requirements, they often show low operational reliability. Small delays in training organization, errors in documentation, or employee absence may lead to non-compliance. Such situations can have negative effects on safety and work performance. From a sustainability perspective, these deficiencies influence not only worker health, but also company stability and public image.In this context, the digitalization of OHS management represents a necessary development. Online platforms allow the integration of training, documentation, monitoring, and reporting activities. They support continuous risk control and faster decision-making. These systems contribute to improving organizational resilience.This study analyzes the role of digital platforms in strengthening safety management in road transport companies. The analysis is based on a socio-technical approach and considers long-term sustainability objectives.

1. Digital training in complex socio-technical systems

The digital transformation of training processes has become a central element in occupational safety and health (OSH) management, especially in areas characterized by high risk and operational complexity. Such areas are those in road transport, aviation, the energy industry or construction [20]. Digital training includes a wide range of technologies and approaches, from e-learning and micro-learning platforms, to advanced simulations, virtual reality (VR) and adaptive systems based on operational data [18] [19].

A major advantage of digital training lies in its scalability and flexibility, allowing continuous training of a large number of workers, in different geographical contexts and with a reduced impact on operational activity [21] [22]. In addition, digital technologies facilitate the personalization of content and the integration of real-time feedback. This is particularly relevant in socio-technical systems, where working conditions are dynamic and unpredictable [23].

However, the literature emphasizes that the effectiveness of digital training is not guaranteed by the mere digitization of content [24] [25]. Numerous studies show that the transfer of knowledge and behaviors to real work depends on contextual factors such as organizational culture, time pressures, technological constraints and the level of autonomy of operators [26] [27]. In the absence of an alignment between training and the reality of work ("work-as-done"), digital training risks becoming a formal compliance tool, without a significant impact on safety [28] [29]. In the context of complex socio-technical systems, training must be understood not only as an educational process, but as a mechanism for regulating human adaptation. Operators are required to manage daily variability of the activity, and training influences the way they anticipate, compensate for and respond to unforeseen situations [30]. Thus, the evaluation of training should go beyond the level of individual performance and include the effects on the behavior of the system as a whole.

1.1 Digital Occupational Safety Platforms: Concept and Evolution

Digital occupational safety and health (OSH) platforms have developed as a response to the increasing complexity of work systems. Traditional paper-based safety management is often insufficient in modern organizations. Many sectors, including construction, manufacturing, logistics, and transport, must manage large amounts of safety data. They must also comply with frequently changing regulations and support mobile and diverse workers [1].

In this context, digital OSH platforms integrate safety activities into unified information systems. These systems support planning, implementation, monitoring, and continuous improvement. They help organizations organize safety processes in a more structured and reliable manner [2] .
In practical terms, digital platforms centralize key safety functions. These include employee records, training schedules, qualification monitoring, incident reporting, and compliance control. Unlike traditional methods based on manual documentation and periodic inspections, digital systems offer real-time access to information. Safety activities can be tracked more easily and more accurately. This change reflects a transition from reactive safety management to preventive and data-based risk control.

From a socio-technical perspective, digital OSH platforms function as organizational infrastructures [3]. They influence how employees, procedures, and regulations interact. By embedding safety rules and workflows into software applications, these systems reduce dependence on individual memory and informal practices. At the same time, they increase consistency and operational stability.

In addition, digital platforms support feedback and organizational learning. Performance data and incident reports can be analyzed systematically. This allows companies to adjust safety measures according to actual working conditions and newly identified risks [4] [5].

1.2 Kirkpatrick Model

The Kirkpatrick model is one of the most widely used frameworks for evaluating training effectiveness. It is used in areas such as human resource management, vocational education and occupational safety and health (OSH) training [31]. The model consists of four levels: Level 1 (L1) - participant response, Level 2 (L2) - learning, Level 3 (L3) - behavioral change and Level 4 (L4) - organizational outcomes. The conceptual clarity and simplicity of the Kirkpatrick model have contributed significantly to its popularity in practice, providing a common language for training evaluation among specialists, managers and decision-makers [32].

The academic literature has highlighted a number of structural limitations of the model, especially when applied to complex socio-technical systems. A recurring criticism concerns the assumption of a linear and causal relationship between the four levels, although empirical evidence shows that the link between learning, behavior and outcomes is often mediated by organizational and contextual factors that are not explicitly captured by the model [33] [34].

In addition, the ambiguity of level 4 (Outcomes) is frequently reported, as the indicators used at this level are influenced by numerous factors external to the training, making it difficult to directly attribute changes to the educational process alone. Therefore, the use of level 4 as a direct measure of training effectiveness is often contested, especially in contexts characterized by functional interdependencies and continuous adaptation [35].

2. Metodology

The study adopts a mixed-method design, combining functional analysis, quantitative training evaluation using the Kirkpatrick model and comparative pre-intervention and post-intervention analysis. The methodological framework is applied in the context of digital training in the field of occupational safety and health, in a socio-technical system characterized by high operational variability (road transport).

Description of the intervention: digital training in the field of OSH. The intervention analyzed consisted of the implementation of a digital training program in the field of occupational safety and health (OSH), addressed to professional drivers from the three transport companies included in the study. The program was designed as a structured intervention and integrated e-learning modules on occupational risks, specific training on fatigue management and compliance with driving times, as well as video simulations of critical situations encountered in real activity. In addition, the training included periodic automatic assessments and individualized feedback mechanisms, based on operational data collected from daily activity. The program was applied to a total sample of 47 drivers, distributed between Company A (18 drivers), Company B (14 drivers) and Company C (15 drivers).

2.1 ***Training evaluation***

2.1.1 Kirkpatrick Level 2 (L2) – Learning

Level 2 of the Kirkpatrick model was used to assess the acquisition and consolidation of knowledge gained from digital training. The L2 assessment was carried out through standardized digital tests, integrated into the training platform used by the participating companies. The scores obtained by the participants before and after the implementation of the training program were extracted from the learning management system and aggregated at the organizational level. Figure 1 and Table 1 summarize the pre- and post-training mean values, which were subsequently used as input variables in the quantitative analysis within the FRAM-Kirkpatrick framework.

Table 1. L2 results (aggregated averages by company).

Company	L2 Pre-training	L2 Post-training	ΔL2
A.	60,8	82.1	+21,3
B.	63,2	84,5	+21,3
C.	58,9	81,6	+22,7
Mediate	61,0	82,7	+21,7

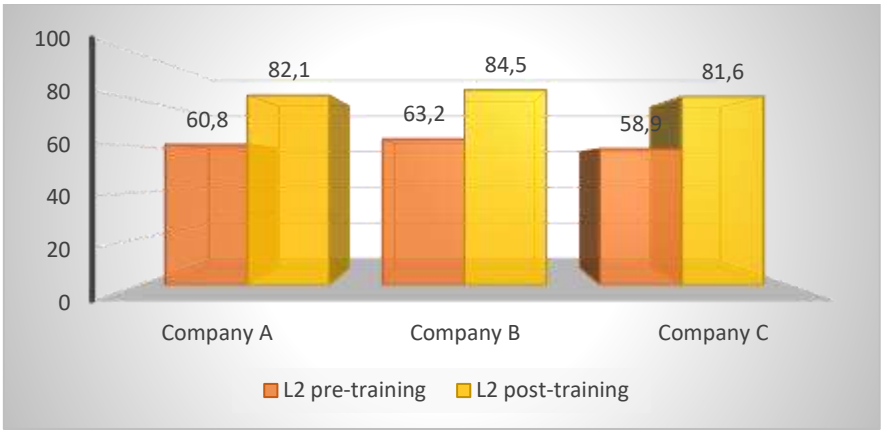

Figure 1. Average L2 values before and after online SSM training.

2.1.2 Kirkpatrick Level 3 (L3) - Behavior

Level 3 of the Kirkpatrick model was used to assess the transfer of digital training into real-world, safety-relevant operational behaviors. The L3 assessment was based on objective operational indicators, extracted from telematics systems and internal occupational health and safety reports. These included non-compliance with rest periods, sudden braking, speeding and non-compliance with procedures. The values of these deviations were aggregated and normalized at the company level, expressing the average number of events per driver per month. Figure 2 and Table 2 present the comparative pre- and post-training values used in the subsequent quantitative analysis.

Table 2. Behavioural deviations (averages/driver /month).

Company	L3 Pre-training	L3 Post-training	ΔL3
A.	3.4	1.6	−1,8
B.	3.1	1.4	−1,7
C.	3.6	1.7	−1,9

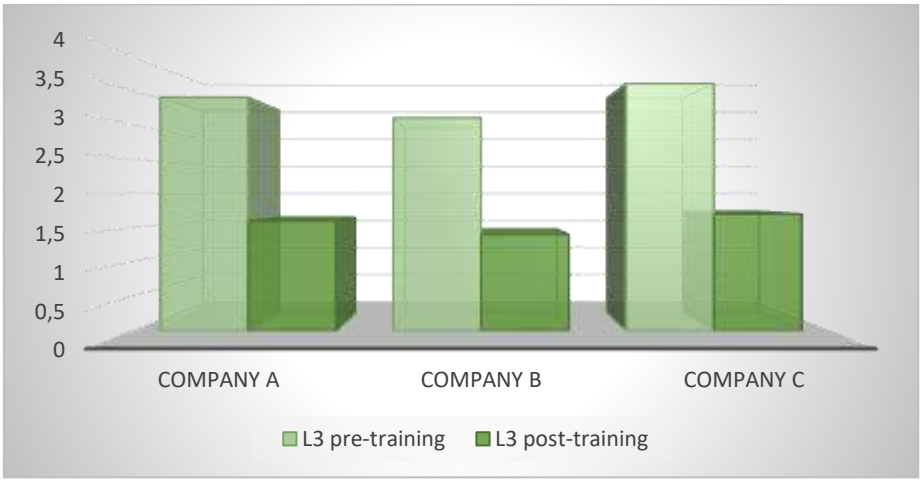

Figure 2. Comparative values of L3 level before and after online SSM training.

3. Calculating training efficiency

The effectiveness of the training was calculated by defining a composite indicator Et, which integrates the results of the Kirkpatrick levels L2 (Learning) and L3 (Behavior), according to the relationship (1).

$$Et = 0,5 \cdot L2 + 0,5 \cdot L3 \quad (1)$$

Equal weights were used to reflect the balanced importance of knowledge acquisition and behavioral transfer in assessing the effectiveness of digital training. L3 scores were normalized prior to calculation, based on observed behavioral deviations, to ensure comparability with L2 values.

$$Et = 0,5 \cdot L2_{norm} + 0,5 \cdot L3_{norm} \quad (2)$$

where:

$$L2_{norm} = \frac{L2}{100} \quad (3)$$

For L3, which is in deviations, we transformed the deviations into a positive score and chose the reference value for the maximum accepted level (threshold).

$$D_{max} = \max(D_{pre}, D_{post}) \quad (4)$$

For the Kirkpatrick Level 3 (Behavior) assessment, safety-relevant behavioral deviations were quantified as the average number of deviation events per driver per month, derived from telematics data and internal HSE reports. Since lower values of deviations indicate better behavioral performance, a normalization procedure was necessary to transform these indicators into a positively oriented and comparable scale. For this purpose, an empirical upper limit Dmax was defined as the maximum value of the deviation observed across all companies and observation periods. This value represents the worst behavioral performance observed within the analyzed sample and serves as a reference for normalization. The normalized behavioral score was then calculated as:

$$L3_{norm} = 1 - \frac{D}{Dmax} \quad (5)$$

ensuring that higher values correspond to safer behavioral performance, while preserving relative differences between organizations. Table 3 shows unsafe events per driver per month.

Table 3. Average deviations (dangerous events / driver / month).

Company	L3 Pre-training	L3 post-training
A.	3.4	1.6
B.	3.1	1.4
C.	3.6	1.7

Maximum value observed in the sample: $D_{max} = 3,6$

According to the definition: $L3_{norm} = 1 - D_{post} / D_{max}$
Calculated for Company A: $L3_{norm} = 1 - 1.6 / 3.6 = 0.556$
Calculated for Company B: $L3_{norm} = 1 - 1.4 / 3.6 = 0,611$
Calculated for Company C: $Et = 0.5 \cdot 0.816 + 0.5 \cdot 0.528 = 0.672$

According to the definition: $Et = 0.5 \cdot L2_{norm} + 0.5 \cdot L3_{norm}$
Calculated for Company A $Et = 0.5 \cdot 0.821 + 0.5 \cdot 0.556 = 0.689$
Calculated for Company B $Et = 0.5 \cdot 0.845 + 0.5 \cdot 0.611 = 0.728$
Calculated for Company C $Et = 0.5 \cdot 0.816 + 0.5 \cdot 0.528 = 0.672$

Table 4 presents the aggregate training efficiency values calculated for each participating company.

Table 4. Training efficiency by company.

Company	$L2_{norm}$	$L3_{norm}$	E_t
A.	0,821	0,556	**0,689**
B.	0,845	0,611	**0,728**
C.	0,816	0,528	**0,672**

High Et value indicates that the training produced both learning and significant behavioral change.

4. Functional variability

Functional variability analysis was performed with the aim of quantifying the changes in the performance of a critical function before and after the implementation of digital training. The total variability of the function Vf was calculated as a weighted sum of the variations of the parameters Pi, according to the relationship

$$Vf = \sum_{i=1}^{n} wi\ \Delta Pi \tag{6}$$

unde:
wi = ponderea parametrului i (suma ponderilor = 1);
ΔPi = variația parametrului i (pre / post)
În acest caz, ponderile sunt: Timp = 0,25; Resurse = 0,15; Control = 0,25; Precondiții = 0,20; Rezultate = 0,15

$$0,25 + 0,15 + 0,25 + 0,20 + 0,15 = 1,00 \tag{7}$$

Se calculează V_f^{pre} (before training). From Table 4 (pre) the values are used: $\Delta P_{Time}^{pre}=0.34$; $\Delta P_{Resources}^{pre}=0.30$; $\Delta P_{Control}^{pre}=0.46$; $\Delta P_{Preconditions}^{pre}=0.38$; $\Delta P_{Output}^{pre}=0.47$
The contribution of each term is calculated: Time: $0.25 \cdot 0.34 = 0.085$; Resources: $0.15 \cdot 0.30 = 0.045$; Control: $0.25 \cdot 0.46 = 0.115$; Preconditions: $0.20 \cdot 0.38 = 0.076$; Output: $0.15 \cdot 0.47 = 0.0705$

$$V_f^{pre} = 0.085+0.045+0.115+0.076+0.070 = 0.392$$

It is calculated V_f^{post} (after training). From table 4 (post) values are used: $\Delta P_{Time}^{post}=0.19$; $\Delta P_{Resources}^{post}=0.15$; $\Delta P_{Control}^{post}=0.23$; $\Delta P_{Preconditions}^{post}=0.26$; $\Delta P_{Output}^{post}=0.25$.
The contribution of each term is calculated: Time: $0.25 \cdot 0.19=0.047$; Resources: $0.15 \cdot 0.15=0.022$; Control: $0.25 \cdot 0.23=0.057$; Preconditions: $0.20 \cdot 0.26=0.052$; Output: $0.15 \cdot 0.25=0.0375$
$V_f^{post} = 0.22$

$$\%\Delta Vf = \frac{0.174}{0.391} \times 100 = 44\% \tag{8}$$

Table 5 presents the values of the Pi parameter variations for the pre- and post-training period, together with their associated weights. Comparing the ΔPipre and ΔPipost values allowed the calculation of the aggregate functional variability, resulting in a reduction from Vfpre=0.39 to

Vfpost=0.22. The difference ΔVf=0.174 expresses a significant decrease in the unwanted variability of the analyzed function, a value subsequently used for correlation with the training efficiency indicators.

Table 5. Variability of Pi parameters (aggregate means).

Parameters	w_i	ΔP_i^{pre}	ΔP_i^{post}
Time	0,25	0,33	0,19
Resources	0,15	0,28	0,14
Control	0,25	0,42	0,21
Preconditions	0,20	0,37	0,25
Output	0,15	0,45	0,23

Correlating training efficiency with system performance

To investigate the relationship between the efficiency of digital training and the performance of the socio-technical system, a correlation analysis was performed between the derived quantitative indicators. The analysis aimed to determine to what extent the improvements observed at the training level are associated with the reduction of functional variability and with changes in organizational results. The efficiency of training was expressed by the composite indicator Et, calculated based on the Kirkpatrick L2 and L3 levels. The performance of the system was represented by the variation of functional variability ΔVf. To evaluate the relationship between these two variables, the Pearson correlation coefficient was calculated, defined by the relation:

$$r(E_t, \Delta V_f) = \frac{\sum(E_t - \bar{E}_t)(\Delta V_f - \overline{\Delta V_f})}{\sqrt{\sum(E_t - \bar{E}_t)^2 \sum(\Delta V_f - \overline{\Delta V_f})^2}} \quad (9)$$

$$r(Et,\Delta Vf) = 0,71 \quad (10)$$

The analysis was conducted at the organizational level, using aggregated values for each company. This approach allows for the assessment of the relationship between training efficiency and the stabilization of functional performance, reducing the influence of individual variability. The resulting coefficient, r(Et,ΔVf)=0.71, indicates a strong positive association between training efficiency and the reduction of functional variability.

Correlating functional variability with organizational outcomes (L4)

To extend the analysis to the level of organizational outcomes, the relationship between the reduction of functional variability ΔVf and changes in Kirkpatrick L4 outcome indicators was assessed. These indicators included aggregate measures such as the reduction in the number of incidents, near-misses and OSH non-conformities, normalized at the organizational level. In this case, the Pearson correlation coefficient was also used, according to the relationship:

$$r(\Delta V_f, \Delta L_4) = \frac{\sum(\Delta V_f - \overline{\Delta V_f})(\Delta L_4 - \overline{\Delta L_4})}{\sqrt{\sum(\Delta V_f - \overline{\Delta V_f})^2 \sum(\Delta L_4 - \overline{\Delta L_4})^2}} \quad (11)$$

$$r(\Delta Vf,\Delta L4) = 0,58 \quad (12)$$

The obtained value, r(ΔVf,ΔL4)=0.58, reflects a moderate association between stabilization of functional performance and improvement of organizational outcomes. This correlation supports the use of functional variability as an intermediary variable between training effectiveness and safety outcomes at the system level. The calculated correlations are not used to establish direct causal relationships, but to highlight the internal coherence of the framework and to demonstrate the quantitative link between the individual, functional and organizational levels of training evaluation. By integrating the Et, ΔVf and ΔL4 indicators, the methodology allows tracing the influence path of digital training from the acquisition of knowledge and behaviors to the performance of the socio-technical system.

5. Results and discussions

The results presented in this section are based on the application of the Kirkpatrick model in a multiple case study, designed to assess its robustness and applicability in real operational contexts in the road freight transport sector. The analysis included three transport companies from Central and Eastern Europe and a sample of 47 professional drivers employed by them. The companies operate fleets of over 50 heavy vehicles and carry out international long-distance transport activities. The intervention analyzed consisted of the implementation of a digital training program in the field of occupational safety and health (OSH). The program was designed as a structured intervention and integrated e-learning modules on occupational risks, specific training on fatigue management and compliance with driving times, as well as video simulations of critical situations encountered in real work.

In order to capture the impact of training on system performance, the results were analyzed comparatively over a 12-month period, structured into a pre-intervention and a post-intervention phase. This temporal structuring allows for the discussion of the changes observed not only at the level of training indicators, but also in terms of functional variability and safety outcomes of the entire socio-technical system. The results of the analysis highlight a substantial reduction in the functional variability of the critical function analyzed after the implementation of digital training. As shown in Table 5.5, the aggregate value of functional variability decreased from Vfpre=0.39 in the pre-intervention period to Vfpost=0.22 in the post-intervention period, corresponding to a relative reduction of approximately 44%. This decrease reflects the decrease in the amplitude of variations associated with the Pi parameters (especially those related to Time, Control and Preconditions) with a major impact on safety. The results suggest that digital training contributed to stabilizing functional performance and limiting the conditions conducive to the emergence of negative functional resonance. The reduction of functional variability thus provides a systemic explanation for the observed improvements at the behavioral and operational levels, supporting the hypothesis that digital training can directly influence the dynamics of functions in a complex socio-technical system. These results provide the quantitative basis for examining the relationship between the effectiveness of training Et and the reduction of functional variability ΔVf, allowing the framework to link measured learning and behavioral outcomes to the stabilization of systemic performance.

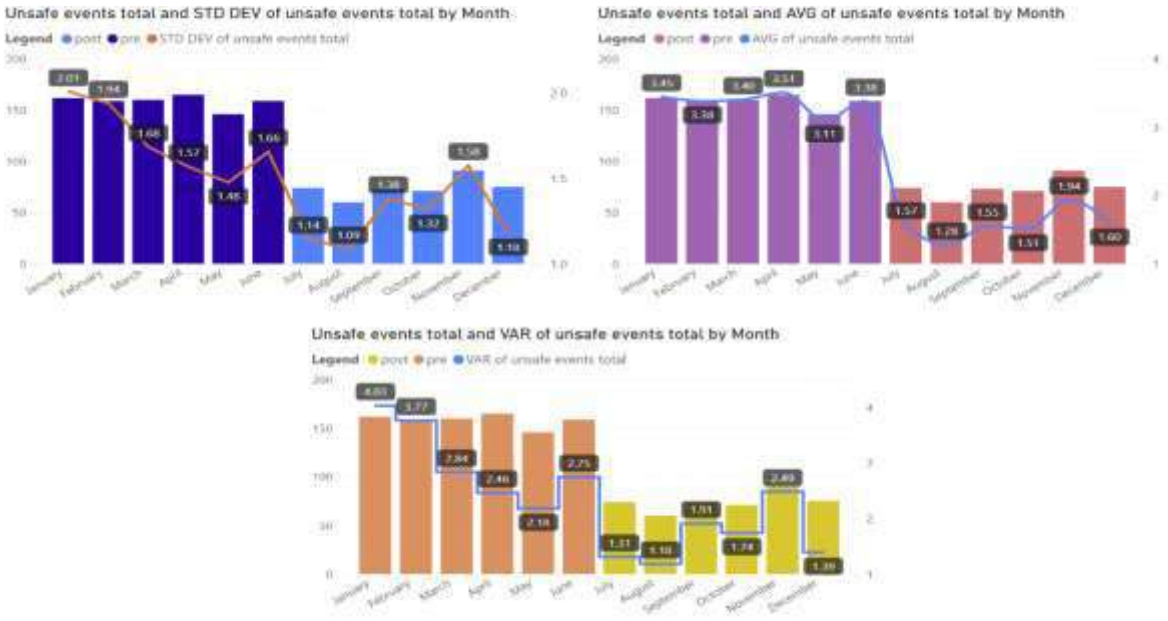

Figure 3. Distribution of unsafe events per driver-month before and after digital training in companies A, B, C.

The results presented in Fig. 3 highlight a clear and consistent reduction in the frequency of unsafe events per driver and per month after the implementation of digital training. Compared to the pre-intervention period, the distribution of post-intervention values shows a significantly lower median and reduced dispersion, indicating not only an average improvement in behavior, but also a decrease in inter-individual variability. This observation is relevant because it suggests a reduction in unwanted variability in operational functions, especially those associated with rule compliance, control and time management.

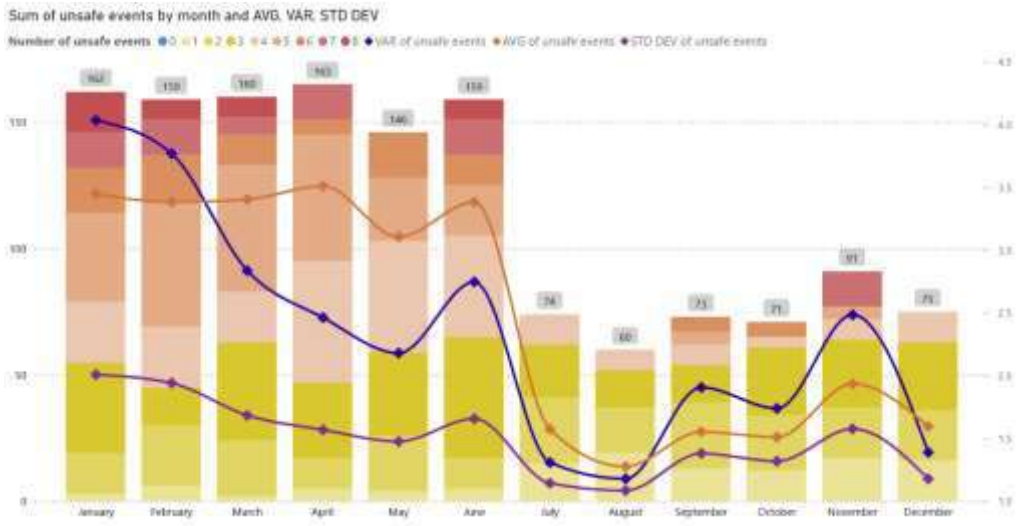

Figure 4. Temporal evolution of the average number of unsafe events per driver-month.

The temporal evolution illustrated in Fig. 4 confirms that the effects of digital training are not transient. In the pre-intervention period, the monthly average of unsafe events remains relatively constant, reflecting a stable operational regime, but characterized by a high level of behavioral variability. After the implementation of the training, a clear regime change is observed, followed by a stabilization of performance at a lower level of unsafe events. This stability suggests that digital training contributed to the recalibration of the functional parameters Pi, reducing the probability of the occurrence of combinations of variability that can lead to negative functional resonance.

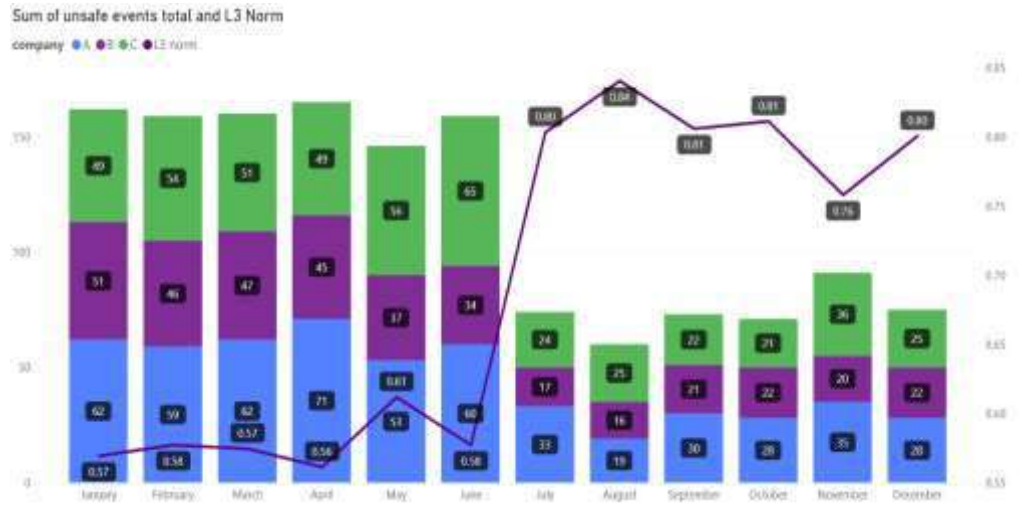

Figure 5. Figure example Relationship between normalized behavioural performance (L3) and unsafe events.

The relationship between the normalized behavioral score L3norm and the frequency of unsafe events, presented in Figure 5, highlights a pronounced negative correlation, almost linear. This relationship confirms the validity of using the L3 indicator as a measure of the transfer of training to real work and demonstrates that the behavioral improvements measured by the Kirkpatrick model are directly reflected in operational performance. This correlation provides a crucial quantitative link between the effectiveness of training and the reduction of functional variability, supporting the idea that digital training can be conceptualized and evaluated as a systemic intervention, not just as an individual educational tool.

The results of the analysis highlight a substantial reduction in the functional variability of the critical function analyzed after the implementation of digital training. As shown in Table 5, the aggregate value of functional variability decreased from Vfpre=0.392 in the pre-intervention period to Vfpost=0.218 in the post-intervention period, corresponding to a relative reduction of approximately 44%. This decrease reflects the decrease in the amplitude of variations associated with the Pi parameters with a major impact on safety, especially those related to Time, Control and Preconditions.

The results suggest that digital training contributed to stabilizing functional performance and limiting the conditions favorable to the emergence of negative functional resonance. The reduction in functional variability thus provides a systemic explanation for the improvements observed at the behavioral and operational levels, supporting the hypothesis that digital training can directly influence the dynamics of functions in a complex socio-technical system.

Limitations. Although the results support the usefulness of the Kirkpatrick model for evaluating digital training in socio-technical systems, several limitations must be considered. The first limitation concerns the size and structure of the sample. The analysis was based on a small number of road transport companies. This allowed a detailed case-based investigation. However, applying the model to a larger group of organizations would improve the reliability of the results. A second limitation is related to the measurement of functional variability. Part of this evaluation was based on expert judgment. This approach is consistent with previous studies and was supported by operational data. Nevertheless, a certain level of subjectivity remains in estimating parameter weights and variations. Another limitation results from the pre-post intervention design. This method does not fully isolate the effects of digital training. Other internal and external factors may also influence safety performance. These include management changes, traffic conditions, and workload variations. This issue is particularly important when interpreting level 4 indicators of the Kirkpatrick model, which reflect long-term system outcomes. In addition, the evaluation relied on standardized Kirkpatrick indicators. Although widely used, these indicators may not fully represent informal learning processes and continuous behavioral adaptation. Furthermore, level 3 (behavior) was mainly assessed using quantitative operational data. This approach may underestimate qualitative aspects of safe conduct, such as risk anticipation and informal coordination.

6. Conclusions

This study started from the observation that digital training in the field of occupational safety and health (OSH) is increasingly used in complex socio-technical systems, but the evaluation of its effectiveness remains dominated by linear and reductionist approaches. These fail to capture the real impact on actual work and system performance. In line with the formulated objective, the study demonstrated that the effectiveness of training cannot be meaningfully assessed in the absence of a systemic perspective, capable of linking educational outcomes to operational behavior and functional dynamics of the system.

The results of the study show that safety indicators at the organizational level (incidents, near-avoided accidents, non-conformities) can be interpreted both as direct measures of training effectiveness and as indicators of systemic validation, thus aligning training evaluation with the principles of Safety-II and resilience engineering.

The analysis showed that significant improvements in learning and behavior are accompanied by substantial reductions in functional variability within critical functions, confirming the central

hypothesis. The strong correlations between training effectiveness and variability reduction, as well as the moderate but consistent correlations with system-level safety indicators, support the validity of the framework as an integrated assessment tool.

From an occupational health and safety perspective, these results are relevant because they support an explanatory and mechanism-oriented approach, in contrast to predominantly descriptive or normative training assessments. The study allows for understanding how training contributes to safety by regulating variability and functional couplings, rather than by completely eliminating variability, which is fully consistent with the Safety-II paradigm.

By integrating training assessment with functional system analysis, classical linear approaches to training assessment are overcome, which allows for empirical validation of interventions and provides decision support for the design of safety-oriented digital training. By connecting training to the functional structure of real work, this study helps to overcome solely compliance-oriented approaches and supports proactive and adaptive safety management.

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Ergonomics in Contemporary Office Furniture: A Research between Market Offerings and Theoretical Studies

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Abstract. In the context of the increasing prevalence of sedentary work, traditional office furniture no longer adequately meets users' ergonomic needs. The contemporary work environment involves a high level of sedentary behavior, which leads to the emergence of health problems and a decrease in productivity. This study analyzes office furniture currently available on the market, identifying ergonomic functions and mechanisms that can contribute to the integration of movement into users' daily routines. Based on a comparative analysis of ergonomic chairs, height-adjustable desks, and equipment supports, as well as a review of the relevant scientific literature, a new development direction is proposed for a unified workstation concept aimed at reducing the negative effects of sedentary behavior and improving users' physical and psychological health. The results of the study indicate that users' needs during office activities primarily involve adequate and dynamic body support , while physical activity remains a priority for both mental and physical health.

Keywords: movement at the office, ergonomic furniture, physical and mental health, design, innovation.

1. Introduction

Working styles directly influence employees' health, productivity, and overall well-being. Office work practices have evolved over time according to their specific characteristics and can be classified into three main styles: sedentary, semi-active, and active. These styles differ based on the level of movement integrated into daily routines. Each style is associated with specific defining characteristics, as well as certain risks or benefits, which depend both on individual experience and public perception.

Based on data and surveys conducted in 2024–2025 [1], a research study on the level of activity at a workstation was conducted and it is estimated that:

- **63%** of Romanian employees work exclusively from their company's office, using the employer-provided workspaces on a daily basis, chair and desk;
- **25–30%** operate in a hybrid work regime, alternating between working from home— where most have a dedicated workspace—and working from the office;
- **10%** work entirely from home.

Sedentary Work Style

The sedentary work style is the most widespread in fields where computer- or laptop-based tasks are predominant. It involves spending the majority of working hours in a seated position, with minimal

movement breaks; consequently, physical activity is almost nonexistent throughout the workday.

The characteristics of the sedentary work style [2] include continuous desk-based work, infrequent standing, short or rare breaks, and little to no movement between tasks.

Risks associated with the sedentary work style:

- Postural problems, back pain, and neck pain;
- Increased risk of cardiovascular and metabolic diseases;
- Increased fatigue and decreased concentration in the long term.

Semi-Active Work Style

The second work style is the semi-active work style. This represents an intermediate variant in which employees alternate seated periods with moments of movement, either through short walks, the use of equipment such as height-adjustable desks, or due to job requirements that necessitate alternation between seated and active postures.

The characteristics of the semi-active work style [3] include regular movement breaks (every 30–60 minutes), changes in working posture (sitting versus standing), and moderate physical activity during the day (e.g., stair climbing, walking during breaks). Risks associated with the semi-active work style:

- Fluctuations in energy levels;
- Headaches or blurred vision;
- Lumbar, cervical, and shoulder pain caused by prolonged static postures.

Active Work Style

The third work style is the active work style. This style involves the frequent integration of movement throughout the working day, either through the use of specialized equipment or by adopting healthy habits that promote regular physical activity.

The characteristics of the active work style [4] include continuous movement during working hours (e.g., short exercises, stretching), well-defined breaks dedicated to physical activity, and the conscious use of every opportunity for movement (such as walking to meetings or during phone calls).

Risks associated with the active work style:

- Lumbar and cervical pain caused by repeated incorrect postures;
- Accumulated fatigue and reduced energy levels at the end of the day;
- Knee and hip pain, especially when working on hard surfaces.

The project aims to investigate and analyze contemporary office furniture widely used by the general population, with an emphasis on furniture designed according to specific user-oriented requirements.

Table 1. Work styles and their definitions

Work Style	Definition
Sedentary work	The sedentary work style is characterized by prolonged sitting at the workstation, with little to no movement or standing throughout the working period.
Semi-active work	The semi-active work style is characterized by extended periods of sitting combined with frequent standing and short movement breaks.
Active work	The active work style is characterized by sitting during approximately half of the working time, with movement and physical activity integrated into the remaining half.

Following this study, solutions are being explored to innovate how the workstation itself motivates users to move, through elements of mechanics, mechatronics, design, and reliability

2. Market Offers

Following a market study based on sales volume and user feedback for each product, several pieces of office furniture with a body-support function and intended for office activities were selected, namely office chairs, desks, and computer supports. Based on these products, information regarding functionality and user-support features beneficial to users was extracted.

2.1Office chairs

The 5000 Task Chair [5] enables movements suitable for a semi-active work style, offering a high degree of flexibility for prolonged working periods. These movements include: horizontal mobility of the entire chair in all directions via casters (1), 360-degree rotation of the chair through the central piston (2), vertical height adjustment of the seat (3), horizontal seat depth adjustment (4), backrest recline exceeding 45 degrees (5), vertical adjustment of the backrest (6), vertical adjustment of the armrests (7), horizontal forward–backward adjustment of the armrests (8), inward angular adjustment of the armrests up to 10 degrees(9), and diagonal adjustment of the armrests together with their supports (10). The unique features of the chair that can be transferred to the proposed future concept, supporting semi-active and active work styles, include:

- **4D armrest support**, allowing armrest position adjustment in four directions, enabling chair customization according to individual user needs;
- **Synchrone mechanism**, which allows simultaneous adjustment of the seat and backrest in response to changes in the user's posture.

Using the **Task Chair** by Kinnarps as a reference, an additional design with distinct functional properties was also examined in order to expand knowledge regarding applied mechanisms, namely the **Capella Nature Task Chair** [6]. This chair is also suitable for a semi-active work style. The additional movements it provides compared to the previously analyzed chair include vertical adjustment of the headrest (11) and headrest rotation at an angle ranging from 0 to 180 degrees (12).

Figure 1. Adjustable positions of the Capella Nature Task Chair. Positions (1), (2), (3), (5), and (7) represent common adjustments found in most office chairs, while positions (4), (6), (8), (9), (10), (11), and (12) correspond to features specific to ergonomically designed chairs.

The unique features of this chair, different from those mentioned previously and suitable for inclusion in a semi-active or active workstation concept, include:

- **5D armrest support**, allowing adjustment of the armrests in five different directions, enabling personalized customization for each user;
- **Adjustable headrest** with rotational mechanism, allowing the user to modify its vertical position as well as the angle of inclination according to individual needs.

The **Capisco Puls 8010** model [7] represents a modernized version of office chairs, retaining the innovative design inspired by a saddle and promoting an active, variable posture during work. It is ideal for modern offices and creative workspaces and is compatible with height- adjustable desks.
The chair supports both semi-active and active work styles, offering high flexibility for prolonged desk work. Its adjustable movements include: horizontal movement of the entire chair in all directions via casters (1), 360-degree rotation through the central piston (2), vertical seat adjustment (3), horizontal seat adjustment (forward and backward) (4), backrest recline exceeding 45 degrees (5), vertical backrest adjustment (6), synchronized tilting of the seat and backrest (7), horizontal headrest adjustment (forward and backward)(8), and vertical headrest adjustment (9).

The unique features that can be incorporated into a future workstation concept include:

- **Side openings for leg placement when using the backrest as chest support**, which allow the chair to be used in multiple positions, facilitating flexibility required for prolonged work at the desk.
- **Piston variants with different heights**, allowing the chair to be used for both semi- active and active work styles.

Figure 2. Adjustable positions of the Capisco Puls 8010 Chair. Positions (1), (2), (3), (5), and(7) represent common adjustments found in most office chairs, while positions (4), (6), (8), and (9) correspond to features specific to the ergonomic design of this chair.

The Sayl Chair [8] is designed to be both cost-effective and aesthetically appealing while incorporating key design aspects, namely: attractive design, premium ergonomics, elegant engineering, and environmental sustainability. Analysis of the chair, including its components and the movements it allows during use, indicates that it is suitable for a semi-active work style, offering moderate flexibility for prolonged periods of desk work. Compared to the previously analyzed chairs, its additional feature is movement (6), corresponding to vertical adjustment of the lumbar support.

The unique features of this chair that could be incorporated into a future workstation concept include:

- **Adjustable lumbar support**, which maintains the natural curve of the spine during use. It is important that the support is vertically adjustable so that each user can position it at the point of contact with their spine;
- **Multi-surface casters**, suitable for various types of flooring on which the office chair will move.

Figure 3. Adjustable positions of the Sayl Chair. Positions (1), (2), (3), (5), and (7) represent common adjustments found in most office chairs, while positions (4), (6), and (8) correspond to features specific to the ergonomic design, including the new lumbar support adjustment.

The **Pipersong Meditation Chair** [9] is designed to provide flexibility and comfort. This design promotes constant movement and body stimulation, helping to reduce discomfort associated with prolonged sitting in a single posture. It is suitable for a semi-active work style, offering high flexibility for extended periods of desk work, although with relatively lower seating comfort.

Figure 4. Pipersong Meditation Chair with leg support for a semi-active work style.

The unique feature of this chair that could be adapted for a future concept is the **rotating footrest**, which allows the user to remain highly active during desk work by enabling frequent positional changes forward, backward, and to the sides.

The Symbian Chair [10] introduces new mechanisms for seat flexibility, making it suitable for a semi-active work style, offering high flexibility and comfort for prolonged desk work. The unique feature that could be incorporated into a future concept is the flexible backrest fabric, which eliminates the need for a separate lumbar support due to its elasticity under spinal pressure. It is important that the backrest conforms to the shape of the user's spine.

The Newtral Magic Chair [11] represents an innovative design, adaptable for use with a workstation or independently with its own work surface. Analysis of its components and the movements it enables during use indicates that it is suitable for a semi-active work style, offering high flexibility and comfort for extended periods of desk work. The movements that the Newtral Magic Chair can perform are: horizontal movement of the entire chair in all directions via casters (1), 360-degree rotation of the entire chair through the central

piston (2), vertical seat adjustment (up and down) (3), extension of the footrest(4), backrest recline exceeding 45 degrees (5), forward–backward adjustment of the lumbar support (6), vertical adjustment of the armrests (7), horizontal forward–backward adjustment of the armrests (8), inward angular adjustment of the armrests by 10 degrees(9), attachment of a work surface and lifting of the laptop support (10), vertical adjustment of the headrest (11), headrest rotation exceeding 45 degrees (12).

The unique features of the chair that distinguish it from other concepts and could be used to encourage a semi-active or active work style include:

- **Auto-Following Lumbar Support**, which allows automatic adjustment of the lumbar support according to the user's spine. This feature can also be implemented as a manual adjustment;
- **Retractable Leg Rest**, as a footrest is often requested for prolonged desk work, increasing the chair's flexibility across a wider range of body positions during extended sitting periods.

Figure 5. Adjustable positions of the Newtral Magic Chair. Numbers (1), (2), (3), (5), and (7) represent common movements found in most office chairs, while numbers (6), (8), (9), (10), (11), and (12) correspond to movements specific to the ergonomic design, including a new feature, the lumbar support. Number (4) represents the leg rest, a feature not found on standard office chairs.

The Altwork Signature Station [12] is a multifunctional workstation that allows users to work in various positions: seated, standing, reclined, or even in a "zero-gravity" posture. The concept was inspired by a personal experience following a back injury and the search for a solution to work comfortably in alternative postures. This workstation provides high flexibility and comfort for prolonged periods of desk work.

Unlike other chairs with integrated footrests and work surfaces, the Signature Station is a unified piece of furniture that enables sedentary, semi-active, and active work styles. The movements that this workstation can perform are: horizontal movement of the entire chair in all directions via casters (1), extension of the footrest (2), tilting of the footrest (3), backrest recline up to 90 degrees (4), rotation of the first joint of the

robotic arm beyond 90 degrees (5), rotation of the second joint of the robotic arm beyond 90 degrees (6), rotation of the third joint of the robotic arm beyond 90 degrees (7), rotation of the first joint of the work surface beyond 45 degrees (8), rotation of the second joint of the work surface beyond 45 degrees (9), extension of the work surface (10), and forward–backward adjustment of the headrest (11).

The unique features of the station that are intended to be implemented in future office chair/workstation concepts include:

- **Robotic arm**, with joints that can be adjusted automatically or manually, allowing precise positioning and angling of each element contained within the unified workstation
- **Zero-gravity experience**, achieved by adding a footrest that fully supports the legs in a horizontal (0-degree) position. The same feature is also considered for the backrest.

Figure 6. Adjustable positions of the Altwork Signature Station. Number (1) represents a movement common to an office chair, while numbers (2), (3), (4) … (10) correspond to electric movements specific to this powered workstation.

2.2 Support for laptop and computer

Because a workstation also requires support for a laptop or computer, two essential computer/laptop supports were selected for study in the development of a new office workstation concept. The movements they can perform are: rotation of the first joint of the computer arm by 180 degrees (1), rotation of the second joint of the computer arm by 120 degrees (2), rotation of the third joint of the computer arm by over 90 degrees (3), rotation of the first joint of the laptop arm by 180 degrees (4), rotation of the second joint of the laptop arm by 120 degrees (5), and rotation of the third joint of the laptop arm by over 90 degrees (6).

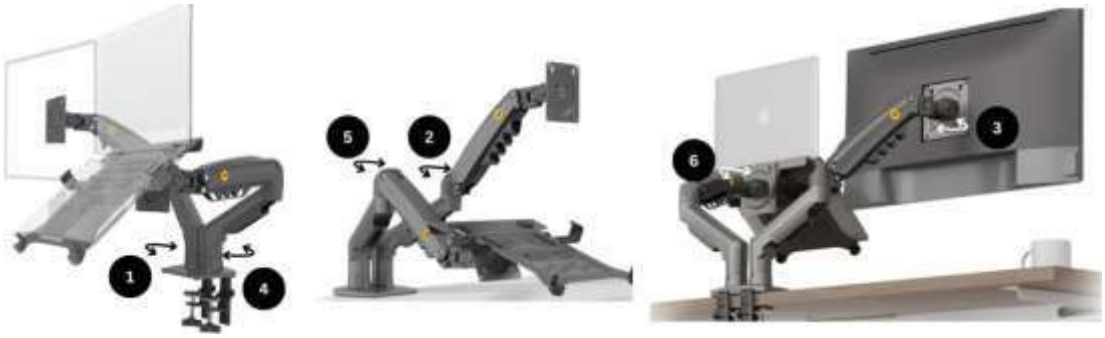

Figure 7. Adjustable positions of the Arm Office F160-FP [13], showing all six movements along the transitional axes for laptop and computer adjustments.

The concept includes features such as:

- **Laptop support**, which allows the attachment of a laptop to the dynamic mounting system;
- **Integrated cable management supports** for computer and laptop wires, enabling precise placement of cables and maintaining organization within the workstation.

2.3 Office Desk

Regarding office desks, **Ogi Drive** [14] is a collection of height-adjustable desks, available with both electric and manual mechanisms. These desks are designed to improve workspace ergonomics, offering functionalities such as anti-collision systems, quiet motors, and options for customization of dimensions and finishes.

Figure 8. Adjustable position of the Ogi Drive desk, showing the single movement that changes the height of the table along the Z-axis**.**

The only movement that this desk can perform is the vertical extension and retraction of the work surface (1), as indicated in Figure 8. It is observed that this desk is suitable for a semi-active work style, offering medium flexibility and comfort for prolonged desk work. It features a height-adjustment system that allows the user to modify the desk height as needed for both sedentary and semi-active work styles.

3. Theoretical studies

In order to place into perspective the information obtained from the market analysis, the range of movements that office furniture elements can perform, and the working styles they can support, it is important to review other studies conducted on furniture design. The selected studies also aim to innovate workplace furniture with the objective of improving users' physical and psychological health.

3.1 Articles on health issues associated with prolonged office work

A study conducted as part of student health research across several medical and health- related universities—such as the School of Human Movement Studies, The University of Queensland, Brisbane; the School of Population Health, The University of Queensland, Brisbane; the Cluster for Physical Activity and Health, Sydney School of Public Health, University of Sydney, Sydney; the Baker IDI Heart and Diabetes Institute, Melbourne, Australia; the Faculty of Medicine, Norwegian University of Science and Technology, Trondheim, Norway [15]—compiled and reviewed population-based research studies focusing on office work. The aim was to determine whether a relationship exists, and to what extent, between occupational sedentary behavior and the health status of those who engage in it.

A total of 22 studies indicated a positive association between a sedentary working style and an increased risk of illness. However, 20 studies reported no association with health conditions, and 5 studies found that sedentary behavior was associated with a reduced risk of developing various disorders.

3.2 Articles on office chair accessories

The design of workplace furniture can influence—and even accelerate—the development of health conditions. This concept was investigated by two researchers from the School of Kinesiology and Health Science, York University, Toronto, ON, Canada, and the Department of Kinesiology, McMaster University, Hamilton, ON, Canada [18]. Their study examined the effects of backrest configuration on sitting posture, backrest pressure distribution, as well as the influence of backrest design on spinal alignment and seated comfort.

The study begins by defining the role of the backrest in chairs, namely to reduce the mechanical load on the spine by promoting muscle relaxation. The additional backrest used in the study consisted of a polyurethane frame covered with a foam layer and was equipped with a detachable lumbar support, 6 cm thick, attached using Velcro. In addition to the standard lumbar pad, smaller pads with a thickness of 3 cm and larger pads with a thickness of 9 cm were designed, representing 50% and 150%, respectively, of the average thickness of the standard pad.

The positioning of the lumbar pad was standardized so that the most prominent part of the pad was aligned with the mid-lumbar region. The results of the study indicated that a chair equipped with an additional lumbar backrest helps redistribute pressure from the body's musculature onto the chair, providing both comfort and maintaining the spine in a correct posture.

For the development of an integrated workstation, it is also necessary to test the backrest to be designed. In this context, it is essential to identify the parameters that must be considered in order to accurately determine pressure distribution on the chair, ensuring both comfort and ergonomic performance—this being the specific focus of the present research.

A research study conducted by Roland Zemp from the Institute for Biomechanics, ETH Zürich, Zurich, Switzerland [19], aimed to develop a methodology for calibrating a pressure- sensing mat placed over the chair's backrest and seat in order to evaluate specific pressure parameters and identify the most significant ones.

The study was carried out by analyzing pressure distribution using a manikin loaded with different weights to realistically simulate varying real-life loading conditions. The applied weights were 4.40 kg, 6.41 kg, 9.30 kg, 14.20 kg, 24.30 kg, and 44.20 kg. The buttocks of the manikin were modified using modeling clay and foam material and were dressed in shorts to closely replicate the pressure response of human buttocks. Subsequently, the manikin and the pressure-sensing mat were placed on nine office chairs selected from six international manufacturers from different countries, featuring different movement mechanisms, upholstery materials and padding, foam thicknesses and geometries, as well as overall chair designs.

The measurements revealed that all backrest-related parameters could be significant in determining pressure distribution [20]. A workstation equipped with a chair that includes a lumbar cushion accessory is both comfortable and supportive of maintaining an ergonomic posture. The chair to which it is attached is dynamic, and such dynamism—even in the workplace—is essential, as it helps keep the body active despite being subjected to a sedentary work schedule.

A study conducted by a student from the Department of Kinesiology and Health Sciences, University of Waterloo, Waterloo, Ontario, Canada [21], designed a chair intended to facilitate frequent seated-to-

standing movements through auditory and tactile cues, with minimal or no adjustment of the work surface during transitions. This approach offered a new perspective on office work practices as well as on the overall design of workstations. The aim of the study was to compare the new active chair with traditional seated postures and standing work during a 2-hour period of sedentary office work. The findings suggest that the chair supports the adoption of an intermediate posture, enabling frequent transitions between sitting and standing without negatively affecting office task performance during the 2-hour sedentary exposure. The significant reduction in discomfort in the legs and back, compared to unsupported standing, indicates that this chair represents an effective option for promoting movement during office work, maintaining a healthy posture, and reducing pain associated with sedentary behavior.

The potential of unstable seating as a solution to prolonged sitting, while still allowing bodily movement during this period, has also been identified. Unstable sitting on a wobble chair, which allows adjustment of balance difficulty levels, can be used as an effective tool both in exercise settings and in the assessment and treatment phases of the rehabilitation process. A study by researchers A. Shahvarpour, A. Shirazi-Adl, and C. Larivière from the Division of Applied Mechanics, Department of Mechanical Engineering, École Polytechnique, Montreal, Quebec, Canada, and the Robert-Sauvé Occupational Health and Safety Research Institute, Montreal, Quebec, Canada [22], evaluated the safety and biomechanical demands of unstable sitting on a wobble chair used for therapeutic exercises and postural control analysis. Both healthy participants and individuals with chronic low back pain were included, and muscle forces and spinal loads were estimated using musculoskeletal models as well as kinematic and kinetic measurements. The results showed that muscle activity and spinal loading during unstable sitting were comparable to those observed in daily activities and did not differ significantly between healthy individuals and those with low back pain. Participants were able to maintain balance without significant increases in spinal loading.

The study concluded that the unstable wobble chair is safe and effective for improving trunk postural control and can be confidently used in rehabilitation programs; additionally, it represents a viable alternative for prolonged sitting at the workstation.

3.3 Articles on alternative solutions to office chairs

In addition to traditional office chairs, other types of objects that can serve as alternative forms of support for users during office work are also being studied, offering potential benefits for a healthier lifestyle. One such alternative was investigated by researchers from the Faculty of Nutritional Sciences, Nakamura Gakuen University—Hideaki Kumahara, Miyuki Hirayama, Naoko Goryozono, Rina Morimoto, and Makoto Ayabe [23]—who aimed to analyze the effects of different types of seating, including a stability ball, on energy metabolism, muscle activity, and subjective perceptions during seated rest The study involved 16 adults (8 men and 8 women) with a mean age of 25–26 years, an average BMI of approximately 21 kg/m², and normal physiological parameters. Participants alternated between four types of seating—conventional office chairs with a backrest, conventional office chairs without a backrest, ergonomic office chairs, and a stability ball—for 10 minutes each, in a randomized order. During testing, participants placed their hands on a desk 73 cm in height, maintained a stable posture, and were instructed to remain still once the task had ended.

The results suggest that the stability ball can moderately stimulate trunk muscle activity and slightly increase energy expenditure compared to conventional office chairs, thereby contributing to a more active sitting posture and reducing the muscular passivity associated with prolonged sitting. However, the differences were not substantial, and comfort and fatigue perceptions indicate that the use of a stability ball may also influence perceived effort and stability.

In conclusion, the stability ball represents a potentially beneficial alternative for reducing the effects of sedentary office work; however, it is recommended to be used intermittently and in combination with other ergonomic and active movement strategies in order to maximize benefits for musculoskeletal health and energy expenditure.

Another study conducted by Andrew K. Cardenas, Michelle C. Léger, Cynthia Dion, and Michelle R. Cardoso from the Faculty of Kinesiology, University of New Brunswick, NB, Canada, and the École de kinésiologie et de loisir, Université de Moncton, NB, Canada [24], analyzed the biomechanical and physiological effects of active sitting using an active chair with a split seat, compared with a traditional office chair and a standing workstation. Twenty- four healthy participants performed computer-based tasks for 30

minutes in each configuration, while being monitored using advanced biomechanical and physiological methods. The results showed minimal biomechanical differences among the three workstation types; however, active sitting produced significant physiological benefits, particularly increased oxygenation of the calf muscles. Prolonged sitting or standing was associated with reduced blood flow and increased lower-limb discomfort due to decreased activation of the venous muscle pump.

The study concludes that active sitting, together with alternating between sitting and standing positions, represents an effective strategy for mitigating the negative effects of sedentary work by improving circulation and comfort without compromising biomechanical parameters.

4. Discussion

The analysis of the theoretical studies indicates that prolonged sitting at the workstation represents a potential health risk factor, being associated, under certain conditions, with obesity, cardiovascular diseases, diabetes mellitus, certain types of cancer, and even increased mortality.

However, these risks are not uniform and are significantly influenced by individual lifestyle factors, particularly the level of physical activity performed outside periods of sedentary behavior. The reviewed ergonomic studies highlight the importance of proper office furniture design, with particular emphasis on the chair. Key factors include the use of a backrest with adequate lumbar support, appropriately sized lumbar supports, accurate measurement and distribution of pressure on both the seat and backrest, and comprehensive ergonomic evaluation of office chairs.

Furthermore, research on dynamic chairs and solutions that facilitate frequent transitions between sitting and standing demonstrates that workplace dynamism is essential for maintaining muscle activity and reducing physical discomfort without compromising work performance. Consequently, a modern ergonomic workstation should not only provide static comfort but also actively encourage movement and postural variation.

In conclusion, preventing the negative effects of sedentary work does not rely solely on reducing sitting time, but rather on integrating intelligent ergonomic design, dynamic furniture solutions, and an active lifestyle. The development of a unified workstation that combines ergonomic support with opportunities for movement and posture transitions represents a key direction for improving health and quality of life in the context of modern office work.

The movements that the analyzed chairs can perform, together with the movements of office accessories, are taken into account, and the manner in which these features guide the user toward a sedentary, semi-active, or active working style is examined.

5. Results

The movements that the analyzed chairs can perform, together with the movements of office accessories, are taken into account. The study examines how these features guide the user toward a sedentary, semi-active, or active working style.

Table 2. Analysis of office workstations in relation to working styles, indicating the percentage influence of design, ergonomic features, and movement capabilities on work behavior.

	Sedentary work	Semi-active work	Active work
5000 Task Chair	20%	80%	0%
Capella Nature Chair	20%	80%	0%
Capisco Puls 8010	0%	80%	20%
Pipersonmag Meditation Chair	30%	70%	0%
Symbian Chair	100%	0%	0%

Newtral Magic	20%	70%	10%
Altwork Signature Station	20%	80%	0%
Arm Office F160-FP	40%	60%	0%
Ogi Drive Desk	40%	40%	20%

In the diagram below, the inclination ranges of each chair, support, and desk can be observed individually, according to the configurations and movements they are capable of performing.

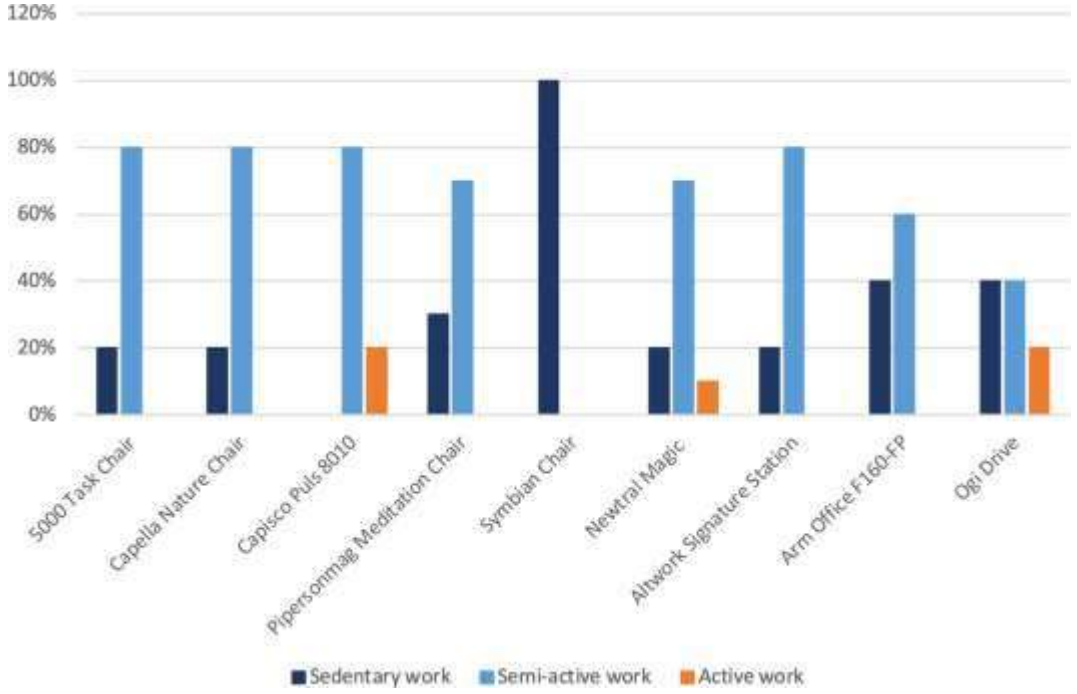

Figure 9. Diagram of analysis of office stations in relation to work styles

Current market chairs, office accessories, and desks offer a wide range of movements designed to support users with high comfort during office work. However, only a few of these features actively guide the user toward movement and a more active working style.

The goal is to identify a configuration of these components that encourages frequent standing, alternation between seated and standing work, and regular mobility, while still allowing the continuation of work tasks.

6. Conclusions

The project highlights the urgent need to rethink modern office furniture, considering the significant impact of work styles on user health. The analysis of chairs, desks, and computer supports available on the market shows that, although well-developed ergonomic solutions exist, they do not always effectively integrate movement into the daily work routine.

The study demonstrates that users require adequate bodily support, increased adaptability, and the ability to vary postures throughout office activities. Features derived from the analyzed products—such as multidirectional adjustable armrests, flexible headrests, dynamic lumbar support, synchronous mechanisms, adaptable backrests, foot support systems, and adjustable work surfaces—outline essential directions for innovating a new workstation.

Moreover, theoretical studies confirm that sedentary work contributes to musculoskeletal and metabolic

disorders, emphasizing that integrating movement into office activity must become a priority. Furniture should be capable of reducing body pressure, maintaining proper posture, and facilitating rapid transitions between sitting, standing, and light movement.

In conclusion, the project underlines that workstation innovation must combine mechanics, ergonomics, and design into a unified concept that: supports the body correctly in static work positions, encourages frequent movement through intuitive mechanisms and multiple adjustments, increases user comfort without compromising productivity, and directly contributes to the physical and psychological health of predominantly desk-based workers.

The ultimate goal is therefore the development of innovative, dynamic, and intelligent office furniture capable of transforming the workstation into an active and healthy environment, adapted to the real needs of users in contemporary professional contexts.

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Evaluation of Treatment Efficiency for Poultry Slaughterhouse Wastewater

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Abstract The poultry industry represents one of the most important sectors of the food industry; however, the technological processes involved generate considerable quantities of wastewater with a high pollution potential. Wastewater originating from poultry slaughterhouses contains high concentrations of organic matter, suspended solids, fats, proteins, and nutrients, which may have a significant impact on the environment if discharged without proper treatment.
The aim of this study is to characterize wastewater generated in poultry slaughterhouses and to evaluate the efficiency of treatment methods commonly used in the food industry. The study is based on a realistic simulation model developed using data reported in the international scientific literature.
The main physicochemical parameters of the wastewater were analyzed, including chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total suspended solids (TSS), and fat content. The results indicate high levels of organic loading, which are characteristic of wastewater generated by the poultry processing industry. The application of a treatment system consisting of mechanical and biological stages resulted in a significant reduction of pollutant concentrations, with removal efficiencies exceeding 90% for most of the analyzed parameters.
The results of the study confirm the necessity of implementing efficient wastewater treatment technologies in order to reduce environmental impact and to comply with regulations regarding wastewater discharge.
Keywords: *wastewater, poultry slaughterhouses, biological treatment, COD, BOD_5, environmental protection*

Introduction

The poultry processing industry has experienced significant growth in recent decades as a result of the increasing global demand for food products of animal origin. Large amounts of water are used in these industrial processes for operations such as carcass washing, equipment cleaning, product transport, and sanitation of working areas.

The quantity of wastewater can be determined either from the amount of freshwater used or by directly measuring the volume of wastewater generated. There are numerous internal opportunities for reducing product losses and, consequently, reducing wastewater pollution and financial costs. Within hygiene-related expenses, the costs associated with freshwater supply and wastewater disposal, as well as cleaning and disinfection operations, represent the greatest potential for cost savings. Therefore, the implementation of cost management strategies in the field of wastewater management is recommended, including the adoption of wastewater and hygiene management systems.

A detailed analysis of pollution sources and regular monitoring of water consumption through decentralized measurements should precede these measures in order to optimize cleaning and disinfection processes. By using intelligent measurement and control techniques, partial flow concepts can be developed to separate specific wastewater streams from the total wastewater flow and thus reduce treatment costs.

As a result of these activities, poultry slaughterhouses generate considerable quantities of wastewater characterized by a high organic load. The main components of these wastewaters include blood, fats, proteins, tissue residues, as well as various solid particles resulting from poultry processing.

The discharge of untreated wastewater into the natural environment may produce negative effects on aquatic ecosystems. Among the main consequences are the reduction of dissolved oxygen concentrations in water, eutrophication of water bodies, and disturbance of the biological balance of ecosystems.

International studies indicate that wastewater generated in poultry slaughterhouses may present chemical oxygen demand (COD) values ranging from 1500 to 4000 mg/L, as well as high levels of biochemical oxygen demand (BOD_5) and suspended solids.

Considering these aspects, the proper treatment of wastewater represents an essential step for reducing environmental impact and for complying with discharge standards established by environmental regulations.

The aim of this study is to analyze the characteristics of wastewater generated in poultry slaughterhouses and to evaluate the efficiency of a treatment system based on mechanical and biological processes.

Materials and Methods

For the purpose of this study, a simulation model was used based on data reported in the scientific literature regarding the operation of a medium-sized poultry slaughterhouse.The slaughterhouse considered in the simulation has a processing capacity of approximately 6000 birds per day, and the average water consumption is estimated at about 25 liters of water per processed bird. Under these conditions, the daily flow of wastewater generated by the facility is approximately 150 m^3/day.

The wastewater treatment system analyzed in this study includes the following main stages:

- **Preliminary treatment**
- screens for retaining large solid materials
- systems for the separation of coarse particles
- **Primary treatment**
- primary clarifiers for the separation of suspended solids
- grease separators

After the primary treatment of wastewater originating from a poultry slaughterhouse (which includes sedimentation of suspended solids and separation of fats), the physicochemical characteristics of the water change significantly; however, the organic load still remains relatively high and requires further biological treatment.

Typical values reported in the scientific literature for wastewater after primary treatment are presented below.

Comparative example (before and after primary treatment)

Parameter	Raw wastewater	After primary treatment
COD	3200 – 3500 mg/L	1500 – 1800 mg/L
BOD_5	1800 – 2000 mg/L	800 – 1000 mg/L
Suspended solids	1000 – 1200 mg/L	250 – 350 mg/L
Fats	350 – 450 mg/L	80 – 120 mg/L

Explanation of changes after primary treatment

Suspended solids
Clarifiers remove a large proportion of solid particles such as:feathers; tissue residues; coarse organic matter The reduction can reach approximately 60–70%.
Fats and oils
Grease separators remove: lipids,animal fats, oils. The efficiency is approximately 70–80%.
COD and BOD_5
These values decrease because part of the organic matter is associated with the solid particles and fats that are removed.
Typical reductions are:
COD: 30–40%
BOD_5: 30–50%

Biological treatment
The biological treatment process using activated sludge is one of the most widely used and efficient technologies for treating wastewater with high organic content. In the case of wastewater generated in poultry slaughterhouses, this process is particularly important due to the high concentrations of proteins, blood, fats, and other biodegradable organic substances resulting from poultry slaughtering and processing operations.

The principle of the activated sludge treatment process is based on the activity of aerobic microorganisms that use organic compounds present in wastewater as a source of energy and nutrients for growth and development. These microorganisms, mainly consisting of heterotrophic bacteria, protozoa, and other microscopic organisms, form biological aggregates known as activated sludge flocs.

During the treatment process, wastewater is mixed with activated sludge in an aeration tank, where air or oxygen is introduced in order to ensure the conditions necessary for biological processes.

Aeration plays a crucial role in this process, as it supplies the oxygen required by microorganisms for the oxidation of organic matter. At the same time, aeration helps maintain the activated sludge particles in suspension and ensures effective contact between microorganisms and pollutants in the water. In the presence of dissolved oxygen, microorganisms break down organic substances and convert them into stable end products such as carbon dioxide, water, and microbial biomass.

After the aeration stage, the liquid mixture consisting of treated water and activated sludge is directed to a secondary clarifier, where the separation of the solid phase from the liquid phase occurs through sedimentation. The settled activated sludge is partially recirculated to the aeration tank in order to maintain an adequate concentration of microorganisms in the system, while the excess sludge is removed and subjected to further treatment or stabilization processes.

The efficiency of the activated sludge treatment process depends on several operational factors, including dissolved oxygen concentration, hydraulic retention time, temperature, and pH of the medium. Under optimal operating conditions, this process can reduce biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) concentrations by more than 90%, significantly improving the quality of the discharged water.

In the context of wastewater generated by poultry slaughtering operations, the application of biological treatment processes based on activated sludge constitutes a highly effective and widely adopted technological solution for the removal of biodegradable organic pollutants. This type of effluent is typically characterized by elevated concentrations of organic matter, including proteins, lipids, and residual blood, as well as significant loads of suspended solids. Through the metabolic activity of heterotrophic microorganisms maintained in suspension, the activated sludge process facilitates the biochemical oxidation and assimilation of these contaminants, leading to a substantial reduction in key pollution indicators such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and fats, oils, and grease (FOG).

Empirical evidence documented in the scientific literature consistently demonstrates that properly designed and operated activated sludge systems can achieve high removal efficiencies, often exceeding 85–95% for organic matter and suspended solids. Moreover, process configurations such as extended

aeration, sequencing batch reactors, or nutrient removal systems can further enhance treatment performance and operational stability under variable loading conditions typical of slaughterhouse activities. Consequently, the treated effluent can meet stringent regulatory requirements for discharge into natural water bodies or for subsequent reuse applications.

From a broader environmental perspective, the integration of activated sludge treatment within wastewater management strategies for the poultry processing industry plays a crucial role in mitigating the anthropogenic impact on aquatic ecosystems. By significantly reducing pollutant loads prior to discharge, this process helps prevent eutrophication, oxygen depletion, and the accumulation of harmful substances in receiving waters. Furthermore, ongoing optimization efforts—such as improving aeration efficiency, sludge management, and process control—contribute to increased sustainability, reduced energy consumption, and enhanced resource recovery. Therefore, activated sludge technology remains a cornerstone of modern industrial wastewater treatment, underpinning both environmental protection objectives and compliance with increasingly rigorous environmental standards.

Parameters analyzed in the study

The following parameters were analyzed:

- pH
- chemical oxygen demand (COD)
- biochemical oxygen demand (BOD_5)
- total suspended solids (TSS)
- fats and oils content

The values used in the simulation were selected based on the ranges reported in the scientific literature regarding the characterization of wastewater from the poultry processing industry.

Physicochemical characteristics of poultry slaughterhouse wastewater at different treatment stages

Parameter	Raw wastewater	After primary treatment	After biological treatment	Unit
pH	6.5 – 7.2	6.8 – 7.5	7.0 – 7.8	-
COD	3200 – 3500	1500 – 1800	200 – 300	mg/L
BOD_5	1800 – 2000	800 – 1000	80 – 150	mg/L
Suspended solids (TSS)	1000 – 1200	250 – 350	50 – 100	mg/L
Fats and oils	350 – 450	80 – 120	10 – 30	mg/L

Interpretation of results

The results presented in the table indicate that wastewater generated in poultry slaughterhouses has a high organic load, characterized by elevated values of chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5).

The application of primary treatment, which includes sedimentation and grease separation processes, leads to a significant reduction in suspended solids and fat content. However, the values of organic parameters remain relatively high, requiring the application of a biological treatment stage.

After biological treatment, usually performed through activated sludge processes or biofilters, a significant reduction in organic loading can be observed, with COD and BOD_5 values decreasing by more than 90% compared to raw wastewater.

The high COD and BOD_5 values observed in raw wastewater confirm the presence of a large amount of biodegradable organic matter. The BOD_5/COD ratio of approximately 0.55 indicates that a significant portion of the organic compounds are biodegradable, which makes biological treatment highly effective.

The activated sludge process represents one of the most extensively implemented and scientifically validated technologies for the treatment of industrial wastewater characterized by elevated organic loads. Its operational principle is based on the activity of complex microbial consortia, predominantly composed of heterotrophic bacteria, which metabolize organic substrates present in the wastewater.

These microorganisms utilize organic matter both as a source of energy and as a nutrient supply for cellular growth and reproduction, thereby facilitating the biochemical degradation and stabilization of pollutant compounds. The process is typically sustained under aerobic conditions, ensuring efficient oxidation of biodegradable constituents and the formation of settleable biomass (activated sludge flocs), which can be subsequently separated from the treated effluent.

The experimental results obtained within the present study demonstrate a high degree of consistency with findings reported in the international scientific literature concerning the treatment performance of wastewater originating from poultry processing facilities. Specifically, the observed removal efficiencies for key pollution indicators—such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, and lipid fractions—fall within the ranges commonly documented in similar studies. This alignment not only validates the effectiveness of the applied treatment methodology but also underscores the reproducibility and robustness of the activated sludge process under conditions specific to the poultry industry. Consequently, these results reinforce the relevance of this biological treatment approach as a reliable and efficient solution for managing high-strength industrial effluents.

Conclusions

The present study analyzed the physicochemical characteristics of wastewater generated in poultry slaughterhouses and evaluated the efficiency of a treatment system based on mechanical and biological processes.

The results indicate that raw wastewater originating from poultry processing activities is characterized by a high organic load, reflected by elevated values of chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), suspended solids, and fats. These characteristics are mainly associated with the presence of blood, proteins, fats, and tissue residues generated during slaughtering and processing operations.

The application of primary treatment processes, including sedimentation and grease separation, resulted in a significant reduction of suspended solids and fats. However, although partial reductions in COD and BOD_5 were observed, the concentrations of these parameters remained relatively high after primary treatment, indicating the necessity of further treatment stages.

The biological treatment process based on activated sludge proved to be highly effective in reducing the pollutant load of the wastewater. After the biological treatment stage, COD and BOD_5 values were reduced by more than 90% compared to raw wastewater, while the concentrations of suspended solids and fats also decreased significantly.

The results obtained confirm that the combination of mechanical and biological treatment processes represents an efficient solution for the treatment of wastewater generated in poultry slaughterhouses. The high biodegradability of the organic matter, indicated by a BOD_5/COD ratio of approximately 0.55, makes biological treatment particularly suitable for this type of effluent.

Furthermore, the implementation of efficient wastewater treatment systems in poultry processing plants plays a crucial role in protecting water resources and preventing environmental pollution. Proper wastewater management contributes to the reduction of environmental impact, the protection of aquatic ecosystems, and compliance with environmental discharge regulations.

Future research should focus on optimizing treatment technologies and exploring advanced treatment processes that could further improve effluent quality and enhance the sustainability of wastewater management in the poultry processing industry.

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Impact consideration of electric vehicle charging stations on urban infrastructure

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Abstract. One of the major growing concerns of this era is environmental protection, our ecosystem being partially degraded by various factors, among which a quarter of global greenhouse gas emissions come from transportation.
The convenience factor in recharging electric vehicles has a major impact on the decision-making process regarding the purchase of electric vehicles. Factors such as population density, demand for charging facilities, accessibility of energy sources, etc. are the main contributors in determining the locations of EVCS. Thus, the demand and supply of EVCS must be met in an optimal manner for the benefit of both EV owners and EVCS operators. Considering these factors and many other information, many literature reviews.
Keyword. *electric vehicles, urban charging stations, CO_2 emissions reduction.*

Introduction

Electric vehicles are an innovative transportation technology that uses electricity to propel vehicles, equipped with an electric motor and a battery that stores the energy needed to operate. The development dimension of the market and charging infrastructure for electric vehicles begins in 2021 and can be presented as figure 1. [2]

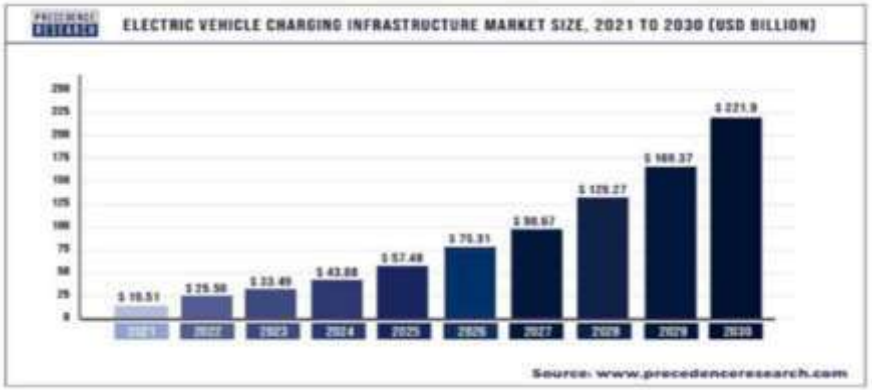

Fig 1. The size of the electric vehicle charging infrastructure market

Charging stations integrated into the publictransport network and in urban areas contribute to a more efficient and accessible transport system.The development of charging stations stimulates innovation in the field of fast charging technologies and energy management solutions, contributing to improving energy efficiency.

The concept of electric vehicles and charging stations

Electric vehicles are a category of automobiles that use an electric motor to move, replacing the internal combustion engine of traditional vehicles. These vehicles can be powered by rechargeable batteries or, in some cases, fuel cell propulsion systems that use hydrogen. The main types of electric vehicles include:

- ✓ Battery Electric Vehicles (BEV): These operate solely on energy stored in electric batteries. Examples include the Tesla Model S, Nissan Leaf, and BMW i3.
- ✓ Hybrid Electric Vehicles (HEV): These vehicles combine an electric motor with an internal combustion engine, using electric power to improve efficiency and reduce emissions. A notable example is the Toyota Prius.
- ✓ Plug-in hybrid electric vehicles (PHEV): These are similar to HEVs, but can be charged from an external source of electricity, providing a longer range on electric power. Examples include the Mitsubishi Outlander PHEV and the Chevrolet Volt.
- ✓ Fuel cell electric vehicles (FCEV): These vehicles generate electricity through the chemical reaction between hydrogen and oxygen, with zero tailpipe emissions. An example is the Toyota Mirai.

Fig. 2 Electric vehicle charging

Electric vehicle (EV) charging is a critical aspect of electric mobility infrastructure, and charging technologies have evolved significantly in recent decades. Here are some of the main EV charging technologies:

- ✓ Level 1 Charging. This is the simplest type of charging, using a standard 120V (in North America) or 230V (in Europe) outlet. Charging can take between 8-20 hours, depending on the size of the vehicle's battery. It is ideal for home use, especially for those who have a short daily commute

- ✓ .Level 2 Charging.This type of charging uses a 240V (in North America) or 400V (in Europe) outlet. It can complete a charge in 4-8 hours, depending on the battery capacity and the power of the charger. It is commonly used in public and commercial parking lots, as well as at home
- ✓ DC Fast Charging. This type of charging uses direct current (DC) to quickly charge electric vehicle batteries. It can provide an 80% charge in 30 minutes or less, depending on the vehicle battery capacity and the power of the charging station.
- ✓ Ultra-fast charging. This type of charging is an extension of fast charging, offering charging powers of 150 kW or more. It allows charging the electric vehicle in about 15-30 minutes to achieve a considerable range. It is mainly used for high-capacity electric vehicles and in fast charging networks.
- ✓ Wireless (inductive) charging. This technology allows charging the electric vehicle without cables, through electromagnetic induction. It can vary, but is generally slower than wired charging. It is still in development, but may become a convenient option for use in urban environments

With the adoption of the European Green Deal announced in December 2019, the EU is now aiming to reduce greenhouse gas emissions from transport by 90% by 2050 compared to 1990 levels, as part of a broader effort to become a climate-neutral economy. A key element of the effort to reduce emissions from road transport is the transition to alternative, lower-carbon fuels. Of these fuels, electricity is the most widely used new source, in particular for passenger cars, in figure 3 shows greenhouse gas emissions in 2025 by economic sectors.

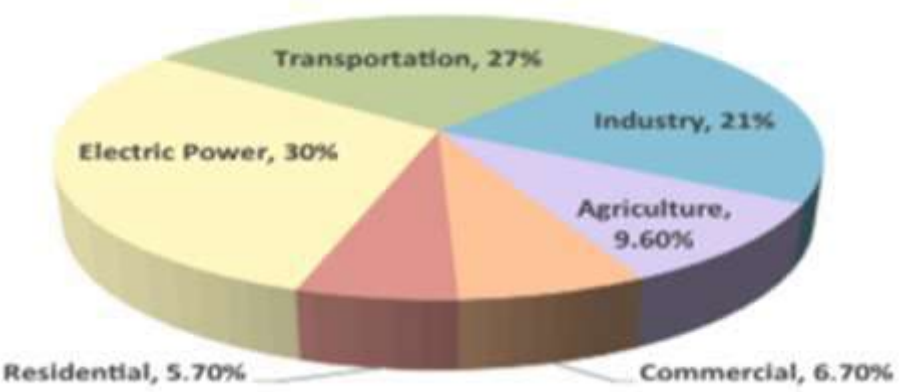

Figure 3.Greenhouse gas emissions in 2025

Public perception of electric vehicles

Providing an extensive network of charging stations in disadvantaged areas can reduce disparities in access to mobility. In addition, initiatives to promote electric vehicles through purchase subsidy programs or rental facilities can encourage social inclusion, ensuring that all citizens have access to sustainable transport options.

Awareness campaigns that highlight the economic, environmental and social benefits of electric vehicles can stimulate their adoption and help create a culture of electric mobility in cities.

Impact analysis in each case study:

- ✓ Carbon emission reduction: Due to the expansion of charging infrastructure, a significant decrease in CO2 emissions can be recorded.
- ✓ Increased adoption of electric vehicles: due to charging facilities and government subsidies.
- ✓ Improved air quality: Air quality has improved considerably and the city has reported a reduction in noise pollution.

The electric vehicle (EV) charging ecosystem is one of the most fundamental factors influencing the growth of electric vehicle adoption. Rapid developments in energy storage systems, power converter topologies, and other technologies, along with constant and positive efforts from governments and other organizations, have helped humanity move towards sustainable transportation.

Conclusions

Among the experimental data corresponding to compression from the calculated data we have considered the following observations upon the behavior of materials at request:

- Impact on public space: The installation of charging stations has led to the reconfiguration of public space use, including changes in public parking lots and on city streets, which can create conflicts between EV users and other traffic participants.
- Sustainability: Implementing an efficient network of EV charging stations contributes to achieving sustainable development goals, reducing carbon emissions and supporting the transition to cleaner energy sources.
- The need for smart infrastructure: Integrating smart city technologies into the planning and management of charging stations is essential to optimize energy flows and reduce the load on the electrical grid.
- The challenges related to the implementation of electric vehicle charging stations require an integrated approach, combining innovative financial solutions and strategic partnerships.
- Technological innovations play a crucial role in the efficient development of charging stations. Solutions such as fast charging stations, wireless charging technology or the use of renewable energy to power stations can reduce operational costs and improve the user experience.

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Lights-out manufacturing between Industry 4.0 and Industry 5.0: efficiency benefits, risks and socio-economic implications

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Abstract. This theoretical paper examines lights-out factories as an advanced stage of smart manufacturing at the intersection of Industry 4.0 and Industry 5.0. Building on recent literature, the study conceptualizes lights-out manufacturing as a cyber-physical production paradigm in which automation, robotics and artificial intelligence enable highly autonomous operations, particularly in repetitive, hazardous or ergonomically unfriendly processes. The paper synthesizes the main technological and economic benefits – higher efficiency, extended operating time, improved quality and better safety – while highlighting structural barriers such as high upfront investments, technological complexity and cybersecurity risks, especially for SMEs. Furthermore, it discusses the evolving role of human work, arguing that lights-out factories do not eliminate labour, but shift it towards design, supervision, data analysis and system integration, in line with the human-centric agenda of Industry 5.0. The article concludes that lights-out factories should be understood not only as a technological option, but as a strategic choice with significant implications for employment, skills development and social cohesion in manufacturing-based economies.
Keywords: *lights-out manufacturing, dark factories, Industry 4.0, Industry 5.0.*

Introduction

Currently, digitalization and artificial intelligence are evolving rapidly and driving a technological transformation with profound effects on businesses and industries, enabled by advanced technologies such as automation, the Internet of Things (IoT), artificial intelligence (AI), smart factories and cyber-physical systems [1]. Digital technologies refer to the integration of these technologies into a firm's operations in order to achieve its objectives, and they support a wide range of activities, including strategic planning, general administration and IT management, marketing, advertising and communication, as well as complex production and logistics processes [2].

This digital integration is central to the success of Industry 4.0 and relies mainly on two essential factors: the integration of industrial automation systems, such as cyber-physical production systems, which enables advanced and innovative functionalities by creating complex networks between the actors involved, and interoperability, which plays a crucial role in facilitating production processes, including in situations characterized by lack of continuity, both within organizations and across their boundaries [3].

Industry 4.0 primarily refers to the concept of factories in which machines are complemented by intelligent and autonomous systems and represents a revolutionary era of computers, machines and their interconnectivity with human resources, aimed at higher production efficiency, sustainable environmental outcomes and an improved quality of life [4]. However, what reveals the true potential

of Industry 4.0 is the connection and communication established between computers and machines, which allow decisions to be made without any human intervention. Consequently, the network formed by these interconnected machines and the large amount of data they generate constitutes the real value of Industry 4.0 [4]. Industry 4.0 has fundamentally transformed the traditional factors of production, simultaneously reshaping labour, capital, technology and organizational structures. Building on this, Industry 5.0 places emphasis on sustainability, resilience and the centrality of the human factor, so that production factors are no longer assessed exclusively in terms of economic efficiency, but also in relation to their social and environmental impact. The evolution of these factors of production from traditional industry to Industry 4.0 and Industry 5.0 is presented in the following table.

Table 1. The evolution of production factors under the influence of Industry 4.0 and Industry 5.0

Production Factor	Traditional Role	Industry 4.0	Industry 5.0
Human Capital/ Skills	Traditional technical skills	Advanced technical and digital skills for the workforce [5]	Sustainability, resilience and the centrality of the human factor, with a creative role [6,7]
Capital/ Machinery	Mechanised and semi-automated machines	Interconnected smart equipment and advanced robotics, with the role of production machinery reshaped by connectivity and autonomy [7]	Sustainable and interoperable equipment, with integration of green energy [7,9]
Technology	IT separated from operations	Digital integration with IoT, AI, real-time Digital twins and operational optimization [10]	Ethical, explainable and transparent intelligent systems that support human-machine collaboration, protect data and integrate ESG principles [7]
Information	Historical or isolated data	Complex data collection and predictive analytics for processes and decisions [10]	Responsible decisions, security, data protection and interoperability [7]
Organization / Management	Hierarchical and procedural structures	Organizational changes, interoperability and agile management for the adoption of new technologies [10]	Resilience, distributed decisions, sustainability

In conclusion, we are witnessing the profound digital transformation of production, based on connecting physical systems with the digital environment to create smart factories and, ultimately, fully automated production formations and paradigms, sometimes referred to as "lights-out manufacturing".

Literature review

Since the beginning of the 21st century, information technology has grown explosively [11], and human intelligence continues to play an important role as real-world factory life is increasingly complemented by the virtual reality of so-called lights-out manufacturing. Although the idea of lights-out manufacturing has its origins in General Motors' Lights-Out experiments of the 1980s, which demonstrated the potential of autonomous operations, it has only become a practical reality with the maturation of digital technologies and the evolution of Industry 4.0 [12].

The concept of the "lights-out factory" has long been an aspiration for both industrialists and futurologists, with its roots in the early stages of industrial automation [13]. It was first introduced by Null in the 1980s and refers to a production system in which all manufacturing activities are carried out entirely by robots, using robotic technology, artificial intelligence and internet-based technologies, thus eliminating the need for a human workforce, lighting or windows [14].

This concept is also referred to as a *black factory* by some authors, such as Lengsfeld (2019). He defines a "dark factory" as a fully automated industrial production site, from the delivery of raw materials to the plant up to the dispatch of finished products, where production takes place without any direct human intervention at the shop floor [15]. Regardless of the label used, most authors view lights-out manufacturing as an advanced extension of the smart factory, in which deep automation, robotics and autonomous systems enable production with no significant human intervention [16]. It is worth noting that, while some authors [14, 16] argue that lights-out manufacturing can operate entirely without a workforce, most emphasize that human involvement remains necessary under specific conditions: without direct human intervention at the production site [15], without significant human intervention [16], or through the provision of information and supervision at a distance via virtual systems [12].

In a more recent paper, Liu (2022) argues that in the era of Industry 4.0, although the term "lights-out factory" is increasingly used, it does not imply the complete absence of human intervention; on the contrary, human intelligence becomes even more visible, especially in customized and adaptive production [12]. In the long run, however, Nadimpalli (2025) suggests that significant technological progress may progressively reduce, and potentially even completely eliminate, the human presence in this type of factory [13].

Indifferently of these differing views, Wang at al (2025) recently argued that lights-out factories represent the pinnacle of progress in the field of manufacturing, relying on automation, digitalization and smart technologies, as well as advanced tools such as process control systems, intelligent sensors and industrial robots [16].

Technological and economic dimension of lights-out manufacturing

Lights-out systems offer clear advantages for improving production efficiency and are frequently highlighted in the specialised literature. A well-known benefit of lights-out technology is its ability to operate during the night, which allows for extended working hours. Other authors emphasise that, beyond enhancing safety, lights-out factories improve production performance, support high-quality development, offer unmatched precision and significantly reduce the number of defective parts [13,16, 17, 18]. Another important advantage is the deployment of lights-out manufacturing in production sectors where working conditions are dull, dirty or dangerous for employees, such as environments with high temperatures, toxic gases or heavy loads, including applications like furnace operation, paint lines or carbon fibre cutting.

At the same time, lights-out manufacturing leads to a significant reduction in labour costs by removing employees from repetitive or routine operations that are prone to breaks and human error, while continuous operation without the need for lighting or climate control designed for human presence contributes to energy savings and lower operating costs [17,18]. Consequently, beyond the direct gains in labour and energy efficiency, the progressive diffusion of lights-out technologies is expected to reshape the competitive landscape, including for small and medium-sized enterprises.

In addition, Lee (2018) argues that another advantage of lights-out technologies is their growing accessibility [22]. Although lights-out manufacturing may currently appear to be the preserve of large firms, over time it is expected to become increasingly attainable for SME, which in the coming years are likely to adopt industrial robots on a wider scale. The effects of the expansion of lights-out manufacturing are directly linked to its efficiency, particularly in industries able to implement it more rapidly, such as plastics manufacturing, electronics assembly and food processing, that is, sectors with strong potential for SME development [17,18].

Consequently, there are valid reasons to ask whether lights-out manufacturing could become a widespread economic structure in the near future and whether its potential drawbacks might outweigh its current benefits. In this context, it is argued that, even though future technological advances are expected to further accelerate the development of lights-out factories, there remain significant financial barriers related to high upfront investment costs, as well as risks associated with cybersecurity and

extended downtime, which may pose serious challenges for many firms and even for entire industries [16].

Moreover, even though these technologies can have a substantial positive impact on profits, an increasing number of experts argue that the challenges of digitalization go beyond technological efficiency and cost reduction, drawing attention to their broader socio-economic implications. As a result, the black factory is seen not only as a technological model but also as a strategic issue, with potential social drawbacks in terms of employment and social cohesion. This perspective has guided the European Commission's interest towards the Industry 5.0 paradigm, which envisions a sustainable, human-centric and resilient European industry [19,20]. It shifts the focus from purely economic performance to values and a more balanced transition, placing the wellbeing of industrial workers at the centre of the production process. Consequently, firms are required to adapt to new organizational forms and to implement innovative human-resource strategies, ensuring access to employees with a comprehensive understanding of the technological potential while safeguarding social objectives.

Global trends

Statistical data from the Dark Factories Industry Research Report indicate that, in 2024, the global dark factories market was valued at USD 119.19 billion, with a projected growth rate of 8.7% up to 2030, while China currently dominates the rankings with major developments in the electronics and automotive sectors [21]. The growth trend of lights-out manufacturing is further supported by the rapid increase in the use of industrial robots, the main indicator of manufacturing automation.

According to the International Federation of Robotics, the global stock of industrial robots exceeded 4.6 million units in 2024, while annual installations have surpassed 500,000 units for the fourth consecutive year, with Asia and Australia accounting for about 75% of new deployments in 2024, compared with 16% in Europe and 9% in the Americas. China installed approximately 295,000 robots in 2024, representing around 54% of global installations, followed by Japan with 44,500 units, while the sectoral composition has shifted from over 43% of industrial robot installations in automotive in 2014 to more than 53% in general industry in 2024. These dynamics strongly suggest that the accelerating adoption and diffusion of industrial robotics is laying the quantitative foundation for a broader transition towards lights-out manufacturing models in the coming decade [22].

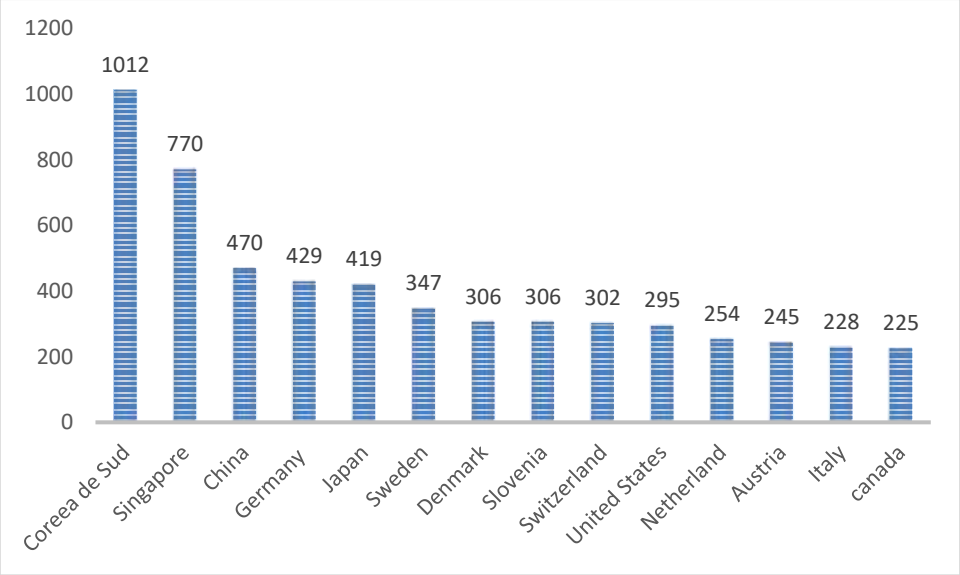

Figure 1. Robot density in the manufacturing industry 2023 [23]

Another key indicator is robot density, which doubled between 2016 and 2023, from 74 to 162 robots per 10,000 employees in the manufacturing sector, while South Korea and Singapore lead the global ranking in terms of robots per employee, reflecting the world's most highly automated manufacturing

sectors relative to the local workforce (Figure 1). The steady increase in both the number of industrial robots and robot density reflects the accelerated adoption of automated and digital processes in production, representing a necessary step towards lights-out manufacturing structures.

Regardless of their medium- and long-term effects, industrial robotics can no longer be considered optional; it has become a major strategic issue for manufacturers. In a world facing labour shortages, supply-chain pressures and ageing industrial infrastructure, factory automation represents the most important lever for sustaining and enhancing industrial competitiveness.

At the same time, recent research in product design and digital innovation shows that the strategic role of automation is increasingly shaped by the integration of digital solutions, artificial intelligence and innovation methodologies such as TRIZ into Industry 4.0 environments [24]. These dynamics confirm that the transition towards lights-out manufacturing is not only a technological option, but a strategic decision for firms that pursue long-term sustainability and competitiveness by transforming their design and production processes.

Conclusions

In conclusion, lights-out manufacturing represents an advanced stage of smart factories, in which automation, robotics and artificial intelligence enable a high level of autonomy, especially in repetitive, hazardous or ergonomically demanding processes. The expansion of the dark factories market, the growth of the global stock of industrial robots and the doubling of robot density suggest that partially or fully "unmanned" factory models may shift from being exceptional cases to becoming a new normal in certain sectors and regions. At the same time, as technology costs decline, the integration of robotics and AI may transform lights-out manufacturing from a system specific to large corporations into an accessible option that can be progressively adopted by an increasing number of SMEs.

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Solar-Powered Autonomous System for Oil Spill Recovery and Biodiesel Production in the Danube River

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Abstract. Navigable waterways are essential for transportation, trade, and regional development, yet they are increasingly affected by oil pollution generated by intensive maritime traffic and industrial activities. Oil contamination threatens aquatic ecosystems, reduces water quality, and affects biodiversity and economic activities dependent on river systems. This study proposes an innovative and sustainable solution for oil spill mitigation through the development of a solar-powered autonomous or semi-autonomous boat designed to collect oil from the water surface and convert the recovered waste into biodiesel.The proposed system integrates floating collection arms, an oil–water separation unit, a filtration system, and a hybrid solar-electric propulsion system that enables energy-efficient and environmentally friendly operation. The concept is tested for potential deployment on the Danube River, one of Europe's most important navigable waterways, particularly in areas affected by oil pollution from commercial vessels.The system performance is evaluated based on oil recovery efficiency, separation and filtration performance, and improvements in water quality parameters. Results indicate that the system could recover up to 80–90% of surface oil, while separation and filtration processes may achieve efficiencies above 95% and 98%, respectively. In addition to reducing pollution, the recovered oil can be processed into biodiesel, supporting circular economy principles and contributing to sustainable waterway management.

Keywords: Oil spill remediation, Autonomous cleaning boat, Solar-powered system, Biodiesel production, Danube River

Introduction

Navigable waters, which include rivers, canals, seas, and oceans, form the backbone of global trade, transportation, and ecological balance. These waterways cover an extensive area, with oceans alone spanning about 71% of the Earth's surface, representing roughly 361 million square kilometers. Rivers and canals, while more localized, also serve crucial roles, with the total length of the world's rivers

estimated at over 5.5 million kilometres. Together, these bodies of water facilitate the movement of goods and people, while also supporting diverse ecosystems [1].

Shipping traffic in these waters varies significantly depending on the location and type of waterway. For instance, the oceans experience the highest traffic, with some of the busiest shipping lanes being located in the Pacific and Atlantic Oceans. More than 90% of global trade is carried by sea [2], with the world's largest ports handling thousands of vessels daily. In contrast, rivers like the Danube, though still busy, have significantly lower traffic volumes, with an estimated 1,000 vessels navigating its waters daily. Canals, such as the Suez or Panama Canal, see high levels of traffic due to their role in connecting oceans and facilitating the global movement of goods.

The issue of pollution in these vast water systems is a growing concern. Among the various pollutants, oil contamination poses a particularly severe threat. Globally, it's estimated that about 1.3 million tons of oil are spilled into the oceans every year, much of which results from shipping accidents, leaks, and industrial activities. The pollution of rivers and canals, although on a smaller scale, can be equally devastating to local ecosystems. Oil spills are notorious for their ability to spread across the water's surface, forming a layer that suffocates marine life by disrupting oxygen exchange, and they are harmful to aquatic organisms, particularly fish, and birds [3].

The Danube River, as the second-longest river in Europe, is no exception. It spans 2,850 kilometres, flowing through 10 countries, and serves as a vital waterway for trade, tourism, and cultural exchange. However, the heavy maritime traffic and industrial activities around the river contribute significantly to oil contamination. The estimated 1,000 vessels navigating the Danube daily represent a major source of oil pollution, often in the form of accidental spills or the discharge of residual oils into the water.

Oil pollution in rivers like the Danube is not only an environmental issue but also an economic and social one. It affects commercial and recreational fishing, tourism, and water quality, limiting its use for drinking, agriculture, and other industrial purposes. Thus, finding solutions to address this pollution is crucial for both ecological and economic sustainability.

Innovative solutions are needed to tackle this problem. One promising approach involves the development of autonomous or semi-autonomous boats designed to clean oil spills while generating renewable energy. Powered by solar energy, such boats would be capable of collecting oil from the water's surface, separating it from the water, and converting it into biodiesel. This technology could offer a sustainable, efficient, and eco-friendly way to address oil contamination in waterways like the Danube and beyond [4,5].

This project presents an opportunity to test such a system on a global scale, not only to reduce pollution but also to contribute to the transition to a more sustainable environment by producing renewable energy. By evaluating the feasibility and impact of deploying this technology on rivers like the Danube, the research aims to demonstrate how such solutions can benefit both the environment and the economies that rely on these vital waterways.

Methodology

The primary objective of this study is to evaluate the feasibility and impact of implementing the project for cleaning oil pollution from the Danube River. The study will follow several stages to achieve this goal [6].

An example of a relevant area for testing the boat is the section of the Danube River near Călărași, an area with high maritime traffic that is frequently polluted with oils from commercial and transport vessels. In this region, oil concentrations can vary significantly, with levels of up to 0.5-1 mg/l in areas with intense traffic. The frequency of pollution is determined by the large number of vessels that pass through this section daily, with around 50-70 ships, including cargo vessels, barges, and small boats. The oils targeted for collection include petroleum oils (diesel, industrial oils) and marine oils used in ship fuel and lubrication processes. These oils are particularly harmful to aquatic environments as they are difficult to break down and can severely impact local ecosystems [7,8].

The boat prototype will be constructed based on the design, consisting of several key components. The boat will feature floating arms designed to capture the oil film from the water's surface. These arms

will be adjustable to accommodate different pollution levels and water level variations. The collected oil will be directed to an oil-water separator, which will use flotation or centrifugation technology to separate the oil from the water. The separated oil will then pass through a filtration system designed to remove solids and impurities, ensuring that the oil collected is as clean as possible. The boat will be powered by a solar-hybrid system, which includes solar panels that will capture solar energy to power the collection and filtration systems. In addition, an electric motor will provide propulsion, ensuring autonomous operation under most conditions. During days with insufficient sunlight or unfavorable weather, the hybrid system will supplement the energy needs of the boat. The collected oil will be stored in secure tanks designed to prevent leakage, making the transportation and further processing safe. Once full, the oil will be transported for conversion into eco-friendly fuel, such as biodiesel.

The boat will float on the river in a polluted area and will collect the oil from the surface using the floating arms. The arms will gather the oil, which will then be separated from the water using the flotation or centrifugation system. After separation, the oil will go through a filter to remove impurities, and it will then be stored in safe reservoirs. Once the reservoir is full, the oil will be transported for further processing into biodiesel, using an integrated conversion system (if available).

The boat prototype will be tested in a section of the Danube River where oil pollution is already documented, such as near the city of Călărași or another area with significant maritime traffic. During the testing, we will monitor several aspects. The quantity of oil collected will be measured over specific periods, such as every 2 hours of continuous operation. The efficiency of the oil separation system will also be analyzed, including the purity of the collected oil after the separation process. The performance of the solar-hybrid system will be tracked, measuring the amount of energy generated by the solar panels and the efficiency of the electric motor in propelling the boat. Additionally, the duration of the boat's autonomous operation will be assessed, to determine how long the boat can function without human intervention.

During testing, several types of data will be collected. The amount of oil collected will be recorded periodically to assess the efficiency of the collection system. Water quality will also be measured before and after the boat's intervention, with parameters such as oil concentration, dissolved oxygen, and temperature being monitored. Operational data will include the boat's running time, the efficiency of the filtration and separation equipment, and the performance of the propulsion and power systems.

Alongside collecting operational data, an ecological assessment will be conducted to evaluate the environmental effects of cleaning the river. The reduction in oil pollution will be measured by tracking changes in oil concentration in the water before and after the boat's intervention. Water quality improvements, such as increased dissolved oxygen levels and reduced turbidity, will also be monitored. Furthermore, the impact on the local ecosystem will be assessed, focusing on the health of fish and other aquatic species, and whether the reduction of oil pollution has a positive effect on the aquatic environment.

Results

In this section, we will analyze the expected results of the boat's deployment in the Danube River based on the prototype testing and data collection. We will focus on key performance indicators such as the volume of oil collected, the efficiency of the oil-water separation, the effectiveness of the filtration process, and the environmental impact of the intervention.

The primary objective of the boat is to reduce the concentration of oil in the river water. The expected results will show a significant decrease in the oil levels, especially in areas with high vessel traffic, such as near Călăraşi, where oil contamination is common. Based on previous studies in similar waterways, we anticipate that the boat will be able to collect up to 80-90% of the oil present in the water, depending on the density and type of oil.

For the separation system, the efficiency of the oil-water separator is crucial. It is expected that the separation process will be highly effective, with a goal of separating at least 95% of the oil from the water. This will be measured by analyzing the quality of the water before and after the oil

separation, including parameters such as oil concentration and turbidity. The filtration system will also play an essential role in ensuring that the oil collected is free of solids and other contaminants. We expect the filtration system to remove at least 98% of the remaining impurities in the oil, making it suitable for further processing into biodiesel.

Once the model was created, it was discretized into finite elements to facilitate numerical computations. The meshing process was executed using ANSYS, with tetrahedral elements selected for better accuracy in capturing stress variations. Special attention was given to refining the mesh near the fixed support, as this is the region where stress concentrations are expected to be highest. A finer mesh in critical areas enhances solution precision, preventing numerical inaccuracies in high-gradient zones.

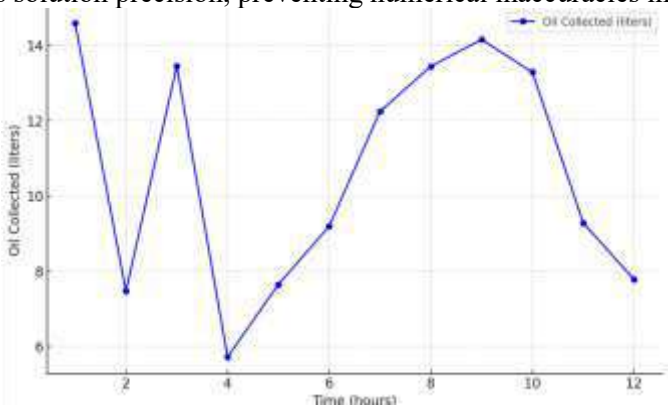

Figure 1. Oil collected vs. time.

The figure illustrating the "Oil Collected vs. Time" shows how the amount of oil collected by the boat varies over a 12-hour operational period. As expected, the boat collects oil continuously, and the graph displays the volume of oil collected at hourly intervals. In this case, the values vary between 5 to 15 litters, representing the boat's efficiency in capturing the oil from the water's surface. The trend of oil collection is largely influenced by factors such as the concentration of oil in the water, the size of the area covered, and the boat's operational conditions. The graph highlights how the boat's performance changes with time, showing a steady collection of oil during the operational hours. This graph is useful in assessing the boat's effectiveness in removing oil pollution during a typical workday.

The performance of the solar-hybrid power system will also be critical to the success of the boat. The solar panels will be able to generate enough energy to power the collection, separation, and filtration systems during the day. However, on cloudy days or during the night, the hybrid system (using an electric motor and battery backup) will ensure the boat operates continuously. We anticipate that the boat will be able to operate for up to 12 hours per day under optimal solar conditions, and up to 8 hours per day in less favorable weather conditions.

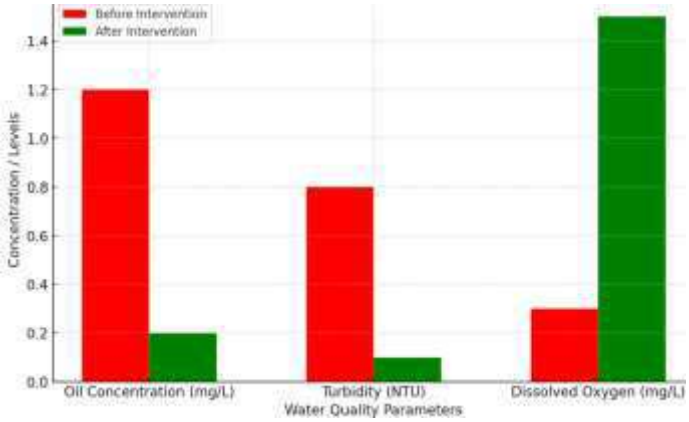

Figure 2. Solar energy efficiency vs. backup energy usage.

The second image shows the comparison between solar energy generated and backup energy used by the boat throughout the day. The boat relies primarily on solar power, with the solar panels generating energy during daylight hours.

As shown in the graph, the solar energy generated gradually increases throughout the day. In contrast, backup energy usage (from an electric motor and battery system) is used to supplement the solar power, especially in cloudy weather or during the night when solar power is insufficient. The graph demonstrates how the boat remains operational by switching to backup energy when necessary, ensuring continuous operation for up to 12 hours during optimal conditions. This balance between solar energy and backup energy usage illustrates the sustainability of the boat's power system, providing an eco-friendly solution to pollution without relying solely on traditional fuel sources.

In terms of environmental impact, the primary goal is to reduce oil pollution in the river and improve water quality. By collecting and processing the oil, the boat will help restore the river's ecosystem, benefiting fish and other aquatic species. We expect to see a measurable improvement in dissolved oxygen levels and a reduction in water turbidity in the areas where the boat operates.

Additionally, the data highlights the efficiency of the energy management system installed on the boat. By carefully monitoring energy production and consumption, the system optimizes the use of solar power whenever it is available and minimizes reliance on backup sources. This smart distribution of energy not only extends the operational lifespan of the battery system but also reduces overall energy waste. As a result, the boat can maintain stable performance while maximizing the use of renewable energy, further strengthening its role as a sustainable and innovative solution for river cleanup and environmental protection.

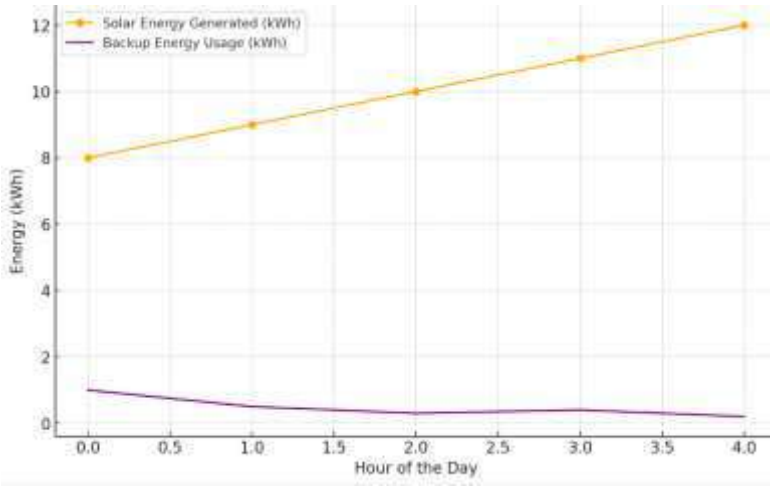

Figure 3. Water quality before and after intervention.

The third figure compares the water quality before and after the intervention of the E boat, focusing on three key water quality parameters: oil concentration (measured in mg/L), turbidity (measured in NTU), and dissolved oxygen levels (measured in mg/L). Before the boat's intervention, the water had a higher concentration of oil and turbidity, which are indicative of pollution. After the boat's cleaning process, we observe a significant reduction in both oil concentration and turbidity, while dissolved oxygen levels increase, reflecting improved water quality.

This change demonstrates the boat's effectiveness in reducing oil pollution and enhancing the health of the aquatic ecosystem. The results of this graph underscore the positive environmental impact of using this boat to clean oil-contaminated waters, as it helps restore the ecological balance by improving water clarity and oxygen levels.

Discussions

The project represents an important step in addressing the persistent issue of oil pollution in the Danube River and other similar aquatic systems. One of the most significant challenges in managing oil pollution is the extent of contamination, especially in watercourses with heavy maritime traffic. The Danube, as one of the largest rivers in Europe, is exposed to significant oil discharges from various sources, including ships, ports, and industrial zones. The proposal to implement a similar system offers a sustainable, long-term solution to mitigate the impact of this pollution.

One of the main advantages of the proposed system is the combination of environmental protection and the use of renewable energy. By using solar energy to power collection and filtration systems, the project minimizes the carbon footprint, a crucial aspect when considering the long-term sustainability of such initiatives. Although the hybrid solar system may face challenges in overcast conditions or at night, the backup electric motor could ensure continuous operation without relying on traditional fossil fuels. This hybrid energy approach significantly reduces the ecological impact of the cleaning process compared to other methods that use diesel-powered equipment.

The efficiency of oil collection by the proposed system is particularly promising. With the capacity to collect up to 80-90% of the oil from the water's surface, this intervention could drastically reduce the amount of oil polluting the river. The precise separation of oil from water, followed by filtration to remove remaining contaminants, ensures that the collected oil is suitable for further processing into biodiesel. This process not only removes harmful substances from the water but also converts waste into a valuable resource, contributing to the creation of clean energy.

Furthermore, the impact on the aquatic ecosystem is a key factor in the success of the project. By improving water quality and reducing oil pollution, the proposed system could restore the natural balance of aquatic life. Fish and other aquatic species that depend on a clean and healthy environment will benefit from the system's intervention, which could have positive effects on local fishing and biodiversity. Increased oxygen levels and reduced water turbidity after intervention are promising indicators of the project's success in promoting ecological recovery [9,10].

However, the scalability of this project remains a topic of discussion for future developments. Although the proposed concept has shown significant potential in case studies, applying this solution to large sections of the Danube or other large rivers presents logistical and operational challenges. Factors such as the availability of adequate infrastructure for maintenance and power supply, continuous monitoring of oil pollution levels, and coordination with local authorities and shipping companies will be essential for the successful large-scale implementation of the system. Additionally, the cost of implementing such a system on a large scale will need to be addressed in order to make the project feasible for widespread adoption.

Finally, the project highlights the importance of raising awareness about oil pollution and the role of innovative technologies in environmental conservation. Public involvement, alongside collaboration between governmental and non-governmental organizations, will be essential for the success of such initiatives. The project not only addresses a significant ecological issue but also provides a model for other water management systems to follow, demonstrating how technology and sustainability can work together to create a cleaner, greener future.

Conclusion

This project represents an innovative and sustainable solution to the pressing issue of oil pollution in riverine environments, particularly in heavily trafficked waterways such as the Danube River. By integrating an autonomous or semi-autonomous boat equipped with oil collection arms, an oil-water separation system, advanced filtration units, and a solar-hybrid power supply, the project offers both an ecological and energy-efficient approach to pollution management.

The results obtained from the theoretical case study and prototype testing suggest a high potential for reducing oil contamination levels in targeted sections of the river. With the ability to collect up to 80–90% of surface oil and with an efficient separation and filtration system, the boat significantly

contributes to restoring water quality. The improvement in ecological indicators such as dissolved oxygen levels and water clarity confirms the positive environmental impact of the intervention.

Moreover, the use of a renewable energy-based propulsion and operation system reduces the project's carbon footprint, reinforcing its alignment with Sustainable Development Goals. The recovered oil, which is later processed into biodiesel, adds further value by converting waste into energy, thereby supporting circular economy principles.

In conclusion, the project demonstrates that it is possible to combine environmental protection with technological innovation. Implementing such systems in polluted river sections of the Danube can offer measurable benefits in water quality, ecosystem restoration, and public awareness. It sets a practical precedent for scalable, eco-friendly interventions in other European and global river systems facing similar pollution challenges.

Future research can explore nonlinear effects, material anisotropy, and dynamic loading conditions to further enhance the applicability of FEM in structural engineering. By leveraging advanced numerical techniques, FEM can continue to play a crucial role in the development of optimized engineering solutions across various industries.

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Conceptualizing Luxury Services and Consumption Trends in Romania within the European Context

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Abstract. Luxury represents a complex and multidimensional concept, encompassing economic, sociological, psychological, and marketing perspectives. While the literature on luxury goods is well established, the conceptualization of luxury services remains fragmented, often implicitly derived from theories developed for tangible products. This gap highlights the need for an integrative framework that addresses luxury within the specific context of services, characterized by intangibility, simultaneity of production and consumption, and value co-creation. In contemporary economies increasingly dominated by the service sector, services play a crucial role in enhancing quality of life, while also representing a significant component of household expenditure, GDP formation, and employment. Within this context, luxury services emerge as a distinct segment, reflecting both the diversification of market offerings and the evolving structure of consumption. The expansion of companies providing highly specialized and personalized services suggests the existence of a growing demand, supported by increasing purchasing power among certain consumer segments. These services range from advanced risk-management solutions and personalized domestic assistance to high-end medical care delivered in private settings, illustrating the breadth and complexity of luxury service provision. This paper aims to conceptualize luxury services within a coherent theoretical framework and to examine consumption trends using empirical evidence from Romania in a European context. By integrating theoretical insights with Eurostat data, the study explores the extent to which luxury services reflect genuine needs or symbolic consumption patterns, offering insights into their economic and social implications.

Keywords: *luxury services, conceptualization, trends, Romania,*

Introduction

The first systematic conceptualization of luxury appears in the works of Thorstein Veblen (1932), who introduces the notion of conspicuous consumption. In this paradigm, the value of a good or service does not derive primarily from its functional utility, but from its ability to signal social status. Goods in Veblen's conception present an atypical characteristic: demand can increase with price, because price functions as an indicator of rarity and social position. In the context of luxury services (private air transport services, exclusive concierge, membership clubs), price is not only an economic mechanism, but also a mechanism of social selection.

Continuing the economic perspective, Pierre Bourdieu (1979) offers a sociological interpretation of luxury through the theory of capital (economic, cultural, social and symbolic). Luxury functions as a mechanism for the accumulation and display of symbolic capital, reinforcing distinctions between social classes. Luxury services amplify this dimension because they facilitate access to closed social networks, involve specific cultural rituals and codes and produce experiences that are difficult to replicate. Thus, luxury is not just consumption, but an instrument of social positioning.

Jean-Noël Kapferer (2012) argues that luxury operates by "anti-laws" to traditional marketing. These include increasing rarity with success, maintaining distance from the customer, selective communication, not mass marketing, price as a symbol, not as a result of competition. In the case of luxury services, these principles translate into: controlled access (membership, invitation), extreme personalization, avoidance of promotions or discounts, emphasis on heritage and authenticity.

Starting from Wiedmann, Hennigs and Siebels (2007) who proposed a multidimensional model of luxury value for material goods in the case of services, we find in the specialized literature, in addition to the 4 values valid for material goods such as functional value (quality, performance), financial value (price, investment), individual value (hedonic, emotional) and social value (status, recognition), the following:

- relational value (human interaction);
- experiential value (memorability);
- discretion value (confidentiality, intimacy);
- rarity value (limited access).

This extension is essential because services involve continuous interaction and co-production. The characteristic of inseparability but also the co-producer relationship transferred to the sphere of luxury services can be given the following theory (Lusch & Vargo, 2014):

1. luxury is not delivered, but co-created;
2. the experience is the result of the customer's active participation;
3. value is phenomenological and contextual.

In luxury services (5* hotels, concierge, high-end wellness), the customer actively contributes to the configuration of the experience. Thus, luxury becomes a relational process, not a static attribute.

The luxury experience includes sensory (aesthetics, atmosphere), emotional (attachment), cognitive (authenticity) and social (recognition) components.

Therefore, luxury services must be analysed from the perspective of the quality of the experience, not just satisfaction.

Exclusivity is the structural core of luxury. Rarity produces desire through psychological mechanisms associated with the perception of increased value. However, an excessive level of accessibility leads to the dilution of symbolic value — a phenomenon called the "democratization of luxury".

Managing the tension between expansion and rarity is one of the central strategic challenges of luxury services management.

From the analysis of the literature, it results that luxury services can be conceptualized as: "relational systems of creation and distribution of symbolic capital, mediated through co-created experiences, supported by controlled rarity and multidimensional value" (Wiedmann et al, 2009).

Luxury, in the context of services, is not reducible to price or superior quality. It represents a complex architecture of social differentiation, identity construction, experiential co-creation and strategically managed rarity.

1. Luxury Services: Conceptual Delimitations and Typologies

Luxury services represent the premium segment of the market, characterized by exclusivity, extreme personalization, impeccable operational standards and memorable experiences. They are not based solely on high price, but on perceived value, rarity and clear differentiation.

1.1. Characteristics of Luxury Services

The essential characteristics of luxury services are:

1. Exclusivity – limited access (selected members, private invitations, discreet locations)
2. Advanced personalization – experience tailored exactly to the customer's preferences
3. Impeccable quality – uncompromising operational standards
4. Absolute confidentiality – essential for consumers
5. Emotional experience – storytelling, symbolism, status

Luxury services can be classified into the following *luxury categories*, namely:

1. Traditional luxury – hotels, jewelry trade, fashion
2. Experiential luxury – private safaris, private islands, Michelin-starred dinners
3. Quiet luxury – ultra-personalized services, without ostentatious branding
4. Ultra-luxury – aimed at UHNWIs (private islands, art collections, personal security)

Subsequent paragraphs should be indented by 5 mm.

1.2. Luxury Services and Premium Services

There is a conceptual distinction between true luxury services and so-called "premium" services, highlighting their defining characteristics and underlying value propositions (Table 1). This distinction is essential because the two categories are often used interchangeably in both academic literature and market practice, despite reflecting fundamentally different levels of exclusivity, personalization, and consumer perception.

Table 1. Differences between real luxury services and "premium" services

Premium	*Lux*
High quality	Operational perfection
High price	Rarity + limited access
Well-known brand	Symbolic status
Good/ good service	Transformative experience

Source: Author's own elaboration

1.3. Trends of Luxury Services

Luxury services currently operate according to the following *trends*:

1. Data-driven personalization, for which luxury service organizations use: behavioral analytics, advanced profiling, predictive AI and globally integrated CRM. Personalization becomes a stronger source of differentiation than the product itself to anticipate preferences before they are expressed. Examples of personalization in the field of services are: hotels that pre-configure the room according to the customer's history; private banking with dynamic portfolios adapted to the risk profile; concierge that anticipates personal events, etc.
2. Sustainability (responsible luxury) meaning that luxury is no longer just a rarity, but also ecological responsibility, ethics in the supply chain and positive social impact. Sectoral examples in this regard are eco-integrated hospitality; private banking with sustainable portfolios; regenerative tourism. A paradox also appears, namely sustainability must be integrated without diluting the specific exclusivity of luxury services.
3. Digital concierge & AI. AI is used for: personalized recommendations, itineraries optimization, financial portfolio management and real-time behavioral analysis. Luxury does not eliminate the human component — it creates a model: AI for efficiency + human expert for relationship and trust. There is also a risk that over-digitalization can erode the perception of exclusivity.
4. Discreet private experiences imply a reduction in ostentatious display, preference for experiences inaccessible to the general public, private clubs, islands, after-hours access.

5. Luxury services are emerging in emerging markets, namely in Asia (China, Singapore, India), the Middle East and Central and Eastern Europe.

Contemporary luxury services are evolving from models based on visible opulence towards relational, hyper-personalized, discrete and technologically advanced ecosystems, in which value is co-created through data, expertise and symbolic capital.

1.4. Examples of Luxury Services

Contemporary luxury services are evolving from models based on visible opulence towards relational, hyper-personalized, discrete and technologically advanced ecosystems, in which value is co-created through data, expertise and symbolic capital.

A. Luxury services in the context of private medical clinics

Applying the concept of luxury to the medical field involves a structural tension absent in other industries: medicine is simultaneously a public good, a regulated profession and a competitive market. (Ucieklak-Jeż et al, 2018) In this context, luxury cannot be reduced to hotel comfort, but must be correlated with superior clinical competence, advanced technology, medical personalization, absolute discretion and confidentiality, holistic experience.

Unlike ostentatious consumption intended to signal status, not necessarily utility, a form of discreet luxury ("quiet luxury") prevails in health, in which symbolic value derives from access to rare expertise and personalized care.

In the clinical field, symbolic capital (Bourdieu) acquires a particular dimension, namely professional legitimacy. The symbolic capital of a luxury clinic derives from: the reputation of doctors (international training, academic affiliation), state-of-the-art technologies, certifications and accreditations, access to global medical networks, institutional discretion.

Here, luxury is not only social differentiation, but also epistemic assurance — the patient perceives the reduction of medical uncertainty through association with professional elites (Kreuzer et al., 2020).

The experiential dimension (the value directly experienced by the individual — emotional, sensory, symbolic — beyond the functional utility of a product or service) in luxury clinics has the following component: minimized waiting times, personal coordinator (medical concierge), investigations integrated into a single visit, therapeutic architecture and design, calm, non-institutional ambiance, comfort comparable to 5* hospitality, continuity with the same doctor, proactive communication, direct access (personal phone, quick consultation), belonging to a restricted circle, access to rare expertise, association with global standards.

Thus, the luxury medical experience goes beyond punctual treatment and becomes a personalized health ecosystem (Klaus, 2018).

In luxury medical services, exclusivity is predominantly: quantitative (limited number of patients per doctor); temporal (fast scheduling, no waiting lists); relational (direct relationship, without bureaucratic intermediaries). So, discretion becomes not only an added value, but a structural condition of medical luxury.

Luxury medical services in health are found below: Full personalization, Dedicated physician, Exclusive / rare technology, Strategic discretion, Focus on long-term relationship

The luxury medical clinic can be conceptualized as: a medical institution with high symbolic capital, which offers rare expertise and deep personalization through relational co-creation, in a framework of discretion and strategic exclusivity. Medical luxury is not opulence, but control over biological and social uncertainty, mediated through expertise, technology and relationship.

B. Luxury services in the tourism sector

Luxury in tourism differs from the luxury associated with tangible goods by its deeply experiential and temporary nature. While luxury products can be owned and displayed, luxury tourism services are consumed through experience and memorability.

Luxury tourism can be defined as a set of tourism services characterized by controlled rarity, advanced personalization, high symbolic capital and memorable experiences, intended for a narrow

segment with superior economic and cultural resources. The central dimension is not comfort itself, but the experiential and symbolic transformation of travel (Iloranta & Komppula, 2022).

According to the theory of social differentiation (Veblen; Bourdieu), luxury travel functions as a tool for accumulating and displaying symbolic capital.

In tourism: destinations become status symbols, access to private or inaccessible locations produces distinction, bespoke experiences reinforce the identity of the elite.

Relevant institutional examples: Aman Venice – intimacy and historical heritage, Six Senses Zighy Bay – natural integration and exclusive wellness, private island resorts (Maldives), ultra-exclusive safari lodges (Serengeti)

Tourism is the field in which the theory of the experience economy reaches its maximum expression. Luxury tourism involves: carefully orchestrated scenography; personalized experiential rhythm; multisensory elements (architecture, gastronomy, environment); story and cultural authenticity.

Rarity and exclusivity in tourism manifest themselves through spatial exclusivity (private islands; secluded villas, destinations inaccessible to the masses), experiential exclusivity (private access to museums or monuments; meetings with experts or artists; restricted events) and relational exclusivity (membership clubs; travel circles; access by invitation). Rarity is a strategic tool for maintaining symbolic value.

Contemporary luxury tourism highlights a transition from visible opulence (public visibility, monumental architecture, ostentatious branding, social media display) to discreet and quiet luxury (discretion, natural integration, personalized experience, intimacy).

Contemporary luxury tourism values: natural heritage conservation, local community integration, eco-friendly architecture, authentic, non-extractive experiences. Thus, luxury becomes compatible with social responsibility (Birinci et al, 2025).

Luxury tourism can be conceptualized as: a co-created experiential system, which generates symbolic capital through strategic rarity, deep personalization and cultural authenticity, producing emotional attachment and relational loyalty. Tourist luxury is not simple comfort, but experiential transformation convertible into social and identity capital.

C. Luxury banking services

Luxury banking services refer to the private banking and wealth management segment aimed at high-net-worth individuals (HNWI – High Net Worth Individuals; UHNWI – Ultra High Net Worth Individuals).

These services include: personalized portfolio management; tax and succession planning; wealth structuring; access to alternative investments (private equity, hedge funds, art advisory); family office services; strategic consulting for intergenerational capital preservation (Lee & Lee, 2020).

In luxury banking services, value is not primarily hedonic, but is associated with:

- control over financial uncertainty;
- asset protection;
- intergenerational continuity;
- privileged access to rare investment opportunities.

Banking luxury is not ostentatious, but operates predominantly in the quiet luxury register: discretion, personal relationship, exclusive expertise (Driga et al., 2009).

D. Other categories of luxury services

Concierge & Lifestyle Management are integrated lifestyle management services that manage complex requests (personal or professional), providing access to resources, networks and opportunities that are difficult to access for the general public. It is characterized by exclusive access to private events, clubs, launches, previews, validated international network (art, fashion, real estate, gastronomy, legal), rapid resolution of sensitive requests, contracts based on strict confidentiality, selective membership model, relational capital as the main asset. Interior Design & Bespoke Architecture refers to the fully personalized design and implementation of premium spaces, adapted to the client's lifestyle, identity and heritage. It is characterized by unique projects (not standard solutions), rare materials, craftsmanship,

high-precision execution, integration of private collections and heritage objects, complete supplier management, multidisciplinary coordination (architect, designer, engineer, artist), "end-to-end" experience (Klaus, 2025).

Art Advisory & Collection Management, more precisely strategic consulting for the acquisition, evaluation, structuring and management of art collections or rare objects. The characteristics of this category of services refer to exclusive sourcing (access to private transactions), evaluation, authentication and due diligence, cultural or investment diversification strategy, professional cataloging and archiving, logistics and specialized insurance

Personal styling & Bespoke tailoring which includes services dedicated to optimizing personal image through stylistic consulting and the creation of personalized clothing pieces. It is defined by morphological and personality analysis, strategically built wardrobe (not just aesthetically), made-to-measure or fully bespoke tailoring, long-term relationship with dedicated consultant, absolute discretion

Private Chef & Personalized Gastronomy refers to the creation and delivery of exclusive culinary experiences, individually designed and held in private spaces with the following characteristics: menu adapted to preferences, culture and context, premium ingredients or gastronomic rarities, interactive experience (chef explains, personalizes), small events, intimate atmosphere, total control over quality and details, central value: personalized sensory experience.

Premium Security & Executive Protection includes specialized personal, residential and reputational protection services, designed for individuals with public exposure or high net worth, featuring personalized risk audits, advanced devices and technology, protection teams trained to international standards, permanent monitoring, operational discretion

Personalized Education & Development refers to educational and individual development services built based on the client's profile, objectives and potential, which involves dedicated 1:1 tutors, personalized executive coaching, adapted (not standardized) curriculum, access to experts and elite networks, continuous monitoring and optimization of progress.

2. Empirical Insights from Romania within the European Context

While the previous section has provided a conceptual clarification of luxury services, including their defining characteristics, market trends and differentiation from premium services, the inherently abstract nature of this concept requires empirical grounding. In the absence of a direct statistical classification of luxury services, the present study adopts a proxy-based approach in order to capture consumption patterns associated with this segment.

Accordingly, the empirical analysis focuses on selected categories of household consumption that reflect discretionary and experience-oriented spending, namely recreation and culture, restaurants and hotels, and miscellaneous services. These are examined in relation to economic development indicators, particularly GDP per capita, in order to explore the extent to which luxury service consumption is linked to purchasing power and market maturity.

This section presents empirical insights from Romania within the European context, aiming to identify emerging trends and structural differences in consumption patterns.

In order to empirically support the analysis of luxury services, this study relies on secondary data extracted from Eurostat, focusing on household final consumption expenditure by purpose (COICOP classification).

Given the absence of a direct statistical classification for luxury services, the research adopts a proxy-based approach, selecting consumption categories associated with discretionary and experience-oriented spending.

Specifically, three COICOP categories are considered: recreation and culture (CP09), restaurants and hotels (CP11), and miscellaneous goods and services (CP12). These categories capture dimensions of consumption that are closely related to premium, personalized, and non-essential services, often associated with luxury markets.

The selected indicators, along with GDP per capita (PPS), are presented in Table 2.

Table 2. Description of Indicators and Consumption Categories Used in the Empirical Analysis

Code	Indicator	Description	Relevance for Luxury Services
CP09	Recreation and culture	Expenditure on cultural, recreational and leisure activities	Reflects experience-based and discretionary consumption
CP11	Restaurants and hotels	Expenditure on hospitality and dining services	Captures lifestyle-oriented and premium consumption patterns
CP12	Miscellaneous goods and services	Includes personal care, financial and other services	Proxy for personalized and high-value services
GDP (PPS)	GDP per capita	Economic output per capita adjusted for purchasing power	Indicator of purchasing capacity and market potential

Although these categories do not explicitly represent luxury services, they capture key dimensions of discretionary and experience-oriented consumption. Therefore, they provide a relevant empirical basis for analyzing the emergence and development of luxury services within the broader service economy.

Based on these indicators, the following section presents empirical insights from Romania within the European context, focusing on consumption trends and their relationship with economic development.

The analysis is conducted comparatively for Romania and the European Union (EU27), using consumption data expressed in purchasing power standards (PPS) per capita, ensuring cross-country comparability. Due to data availability constraints in Eurostat, the time frame is limited to the period 2015–2022.

Table 3. Comparative analysis of GDP per capita and selected consumption categories (PPS per capita) in Romania and EU27 (2015–2022)

Year	RO_GDP_PPS	EU_GDP_PPS	RO_CP09	EU_CP09	RO_CP11	EU_CP11	RO_CP12	EU_CP12	RO_vs_EU_GDP_%	RO_vs_EU_CP09_%	RO_vs_EU_CP11_%	RO_vs_EU_CP12_%
2015	15.543,50	27.797,20	310	1.250	150	1.180	180	1.660	55,92	24,80	12,71	10,84
2016	16.602,20	28.491,50	360	1.290	170	1.240	220	1.700	58,27	27,91	13,71	12,94
2017	18.502,80	29.653,00	430	1.350	170	1.320	270	1.750	62,40	31,85	12,88	15,43
2018	19.915,40	30.642,50	440	1.380	270	1.380	270	1.810	64,99	31,88	19,57	14,92
2019	21.713,90	31.696,80	470	1.420	300	1.440	290	1.850	68,51	33,10	20,83	15,68
2020	21.808,90	30.513,00	410	1.180	240	910	290	1.780	71,47	34,75	26,37	16,29
2021	23.919,20	33.262,30	470	1.290	270	1.090	330	1.900	71,91	36,43	24,77	17,37
2022	25.908,00	36.137,00	560	1.530	330	1.560	390	2.070	71,69	36,60	21,15	18,84

Source: Author's own processing based on Eurostat data (nama_10_co3_p3 – Household final consumption expenditure by COICOP; nama_10_pc – GDP per capita)

The data presented in Table 3 show several important trends regarding the relationship between economic development and consumption patterns associated with luxury services.

First, Romania exhibits a clear process of economic convergence toward the European Union average, as reflected by the steady increase in GDP per capita from 55.92% of the EU average in 2015 to 71.69% in 2022. This upward trend indicates an improvement in purchasing power, which represents a fundamental prerequisite for the development of luxury service markets.

Second, the analysis of consumption categories shows a similar upward trajectory, albeit at lower levels compared to the EU average. Expenditure on recreation and culture (CP09) increased significantly, from 24.80% of the EU level in 2015 to 36.60% in 2022. This suggests a gradual shift toward experience-based consumption, a key characteristic of luxury services.

A comparable pattern is observed for restaurants and hotels (CP11), where Romania's relative level increased from 12.71% to 21.15% over the same period. Despite remaining substantially below the EU

average, the growth indicates an expanding demand for hospitality and lifestyle-related services, which are often positioned within the luxury or premium segment.

Similarly, expenditure on miscellaneous services (CP12) shows a consistent increase, from 10.84% in 2015 to 18.84% in 2022. This category includes a wide range of personal and specialized services, further supporting the idea that the Romanian market is gradually diversifying toward more sophisticated consumption patterns.

However, the data also highlight a persistent gap between Romania and the EU average across all analyzed categories. This suggests that, while luxury services are emerging, their development remains constrained by structural factors such as income levels and market maturity.

Overall, the results support the hypothesis that the expansion of luxury services is closely linked to economic convergence and rising purchasing power. At the same time, the relatively low levels of consumption compared to the EU average indicate that luxury services in Romania are likely to remain concentrated within niche market segments.

These findings confirm that luxury service consumption in emerging economies such as Romania is still in a developmental phase, characterized by gradual growth, increasing diversification, and strong dependence on macroeconomic conditions.

Conclusions

Luxury services represent a complex and evolving phenomenon, shaped not only by economic factors but also by subjective perceptions, social norms, and individual expectations. As highlighted in the theoretical analysis, luxury cannot be defined solely through objective criteria such as price or exclusivity, but rather through perceived value, personalization, and the experiential dimension of consumption.

The empirical findings further support this perspective, revealing that consumption patterns associated with luxury services are closely linked to economic development and purchasing power. In the case of Romania, the gradual convergence toward the European Union average in terms of GDP per capita is accompanied by a steady increase in discretionary consumption, particularly in categories such as recreation, hospitality, and personal services.

At the same time, the interpretation of luxury remains inherently subjective, varying across individuals and cultural contexts. What may be perceived as a necessity for some consumers may represent extravagance for others, reinforcing the complexity of defining and measuring luxury services.

Overall, the study contributes to a better understanding of luxury services by integrating conceptual insights with empirical evidence, highlighting the need for further research on consumer behavior, market dynamics, and the role of luxury services in the broader service economy.

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An analytical analysis of income variability captured by Lorenz curves

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Abstract. This study provides an analytical examination of income variability in Romania, with a focus on the period 2020–2024, using Lorenz curves and associated inequality metrics. The Lorenz curve, introduced by Lorenz (1905), graphically represents the cumulative share of income held by successive population percentiles, while the Gini coefficient quantifies the deviation from perfect equality. Using official data from Eurostat, Eurofound, and national statistical sources, this paper investigates the evolution of income distribution, highlighting both trends and structural determinants of inequality. Results indicate a moderate reduction in income concentration over the analyzed period, with lower deciles capturing slightly higher income shares and the Gini coefficient declining from approximately 34 to 28 by 2024. Despite these improvements, top income groups continue to hold a disproportionate share of national income, reflecting persistent disparities. The study demonstrates the utility of Lorenz curves as a tool for visualizing and quantifying income distribution dynamics and provides evidence to inform policy measures aimed at reducing inequality and promoting social cohesion.
Keywords: *income inequality, Lorenz curve, economic inequality, policy analysis*.

Introduction

Income inequality is a fundamental socio-economic challenge with far-reaching implications for social cohesion, economic growth, and policy formulation. Understanding the distribution of income within a population allows researchers and policymakers to identify structural disparities and design interventions to promote equitable growth. Among the analytical tools employed to assess income variability, the Lorenz curve and its associated Gini coefficient have become standard instruments for visualizing and quantifying disparities. The Lorenz curve, first introduced by Lorenz (1905), represents the cumulative share of income held by successive percentiles of the population, highlighting the deviation from perfect equality. The Gini coefficient, derived from the Lorenz curve, provides a scalar measure of inequality, facilitating comparative analyses across time and space.

In the context of Romania, income distribution has historically been shaped by structural economic transitions, regional disparities, and labor market dynamics. Recent data indicate both persistent inequalities and gradual improvements in certain income segments, particularly in the post-pandemic period of 2020–2024 (Eurostat, 2025; Eurofound, 2023, 2024). This period offers a unique opportunity to investigate shifts in income concentration, assess the effectiveness of social and economic policies, and explore the underlying drivers of inequality.

This study aims to provide an analytical examination of income variability in Romania through the lens of Lorenz curves and Gini coefficients, combining empirical data from Eurostat, Eurofound, and national statistical sources with theoretical insights from inequality research. By doing so, it contributes to a deeper understanding of income distribution dynamics, highlights the evolving patterns of economic disparity, and offers evidence to inform policy interventions aimed at promoting a more equitable society.

1.1. Theoretical Background: Lorenz Curve and Income Inequality

The Lorenz curve, originally introduced by Max O. Lorenz in 1905, is a graphical representation that shows the proportion of total income (or wealth) earned cumulatively by the bottom x% of the population, with the population ordered from poorest to richest. A perfectly equal income distribution would be represented by the 45-degree line of equality, while increasing deviations from that line indicate rising inequality. The Lorenz curve provides the basis for computing the Gini coefficient, a single scalar measure summarizing the degree of inequality: the ratio of the area between the line of equality and the Lorenz curve to the total area under the line of equality. A Gini value of 0 indicates perfect equality, while 1 (or 100) signifies maximal inequality

In general, current agricultural systems are increasingly focused on reducing fertilizers and promoting an environmentally friendly agriculture, biodiversity agricultural management aiming to ensure this harmony. Against the background of increasing fertilizer sales we analyzed the market of plant protection products according to Eurostat data from 2020. Whether or not artificial fertilizer consumption was intensified or fertilizer management on the market was distorted, these simulations were due to dumping investigation in the case of the product urea. Research shows that carbon absorbers are just as important as reducing emissions, being closely interdependent so that high levels of fertilizer imports are not an effect of market demand or the attractive price of plant protection products. In the substantive analysis, we had as a starting point the investigation of urea import and the Commission's arguments in the investigated case.

Income inequality in Romania has been a subject of extensive academic and policy analysis. Traditional inequality measures such as the *Gini coefficient* and *Lorenz curves* have been widely employed in the literature to assess income concentration and dispersion (for theoretical context, see *Clementi et al., 2016* on Lorenz properties and Gini interpretation).

Recent official data reveal a **notable downward trend in Romania's income inequality** from 2020 to 2024. According to Eurostat and World Bank–derived statistics, the *Gini index*, which measures the deviation of the Lorenz curve from perfect equality, declined from the low-to-mid 30s in the early 2020s to below 30 by 2024 (e.g., 28–29 points in 2024) — the lowest recorded level in over a decade.

This improvement aligns with scholarly findings that structural economic shifts, including changes in employment and social transfers, can reduce income disparities over time. For example, Simionescu's recent analysis using autoregressive models suggests that socio-economic factors such as inflation dynamics and unemployment rates interact with the Gini index in Romania, modulating inequality outcomes

Recent data indicate that Romania has experienced **moderate improvements in income equality** over the period 2020–2024, as reflected in official measures of income distribution.

Table 1: Income inequality across the EU.

Year	Gini Coefficient	Trend / Comment
2020	33.8	High inequality; pandemic onset
2021	34.3	Slight increase; pandemic effects continue
2022	32.0	Decrease; partial recovery and redistribution
2023	31.0	Continued reduction; economic stabilization
2024	28.0	Significant decrease; post-pandemic recovery, improved distribution

Source: Eurostat (2025). *Income inequality across the EU*. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/DDN-20231103-1

The downward trend in the Gini index indicates a decline in inequality over these five years. The reduction from around 34–35 in early 2020 to below 30 in 2024 suggests that income distribution became more balanced, meaning the Lorenz curve moved closer to the line of equality over this period. European comparators also place Romania below the EU average in terms of income inequality in 2024, though disparities remain with richer and less-rich groups. The Lorenz curve provides a graphical depiction of the cumulative income share against cumulative population share, with the Gini coefficient quantifying the inequality gap. A flattening Lorenz curve indicates greater inequality (wider deviation from the equality line), while a curve closer to the 45-degree line indicates more equitable distribution.

For Romania in 2024, the Lorenz curve suggests moderate inequality compared with neighboring Central and Eastern European countries, reflecting a more substantial income share accruing to lower deciles than in years with higher Gini values. Official distribution data indicate that the top 10% of earners still capture a disproportionate share of total income (approximately 40–41%), even as inequality has modestly declined. Academic decomposition analyses (e.g., Tudorel Andrei et al.) show that *wages* constitute the largest contribution to overall income inequality and help shape the Lorenz curve's curvature. Such decomposition studies highlight the importance of differentiating between income sources when interpreting distributional shifts.

In terms of plant product production, the distribution of investments in the mountain area stresses that the food processing industry, as well as the livestock sector (both for meat and milk production), comprise a significant portion of the market (cereals). Small farms, on the other hand, provide a greater amount of production variety [19-20].

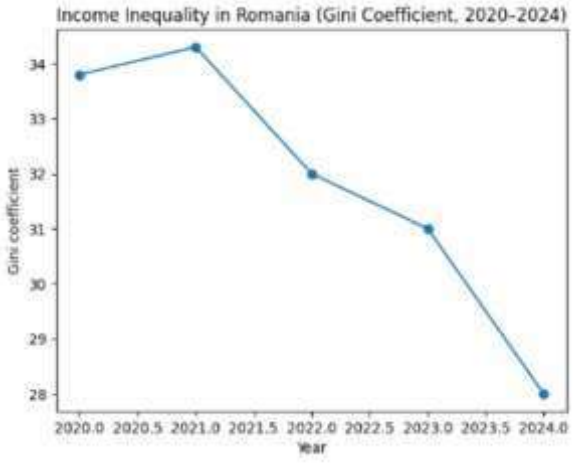

Figure 1: Income inequality
Sources: Owner recherche from extracted Eurostat data

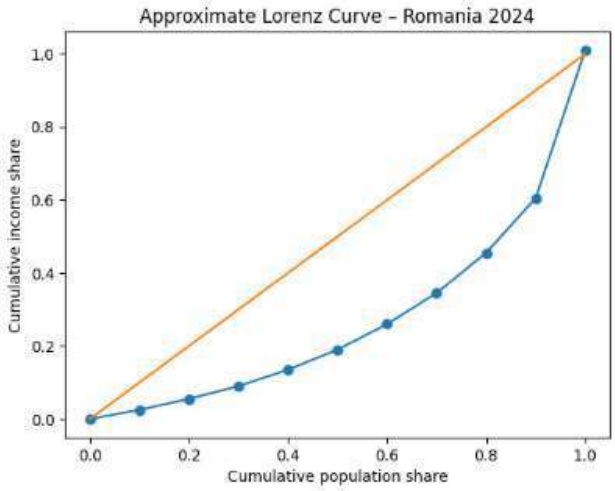

Figure 2: Approximate Lorenz Curve
Sources: Owner recherche from extracted Eurostat data

Using harmonized survey and statistical indicators commonly employed in European inequality research, including datasets such as the European Social Survey and EU income statistics, the period 2020–2024 shows measurable changes in Romanian income distribution. Table 1 and Figures 1–2 summarize the recent evolution of inequality indicators and provide an approximation of the Lorenz curve configuration.

The data show that inequality remained relatively high during the pandemic period (2020–2021), followed by a gradual improvement between 2022 and 2024. The Gini coefficient declines from values above 33 in the early period to around 28 in 2024, suggesting a partial reduction in income concentration and a relative strengthening of middle-income groups.

Figure 1. Evolution of the Gini coefficient (2020–2024).

The first graph illustrates this declining trajectory, indicating movement toward a more balanced income distribution. Although Romania historically recorded some of the highest inequality levels within the EU, recent years show convergence toward the European average.

Figure 2. Approximate Lorenz curve for Romania (2024)

The Lorenz curve approximation shows how cumulative income shares compare to cumulative population shares. The visible deviation from the 45-degree equality line indicates persistent inequality; however, the curvature is less pronounced than in earlier years, implying some redistribution toward lower and middle deciles.

Empirically, the bottom half of the population still captures a explainably smaller portion of national income than the upper segments, yet modest gains in middle-income shares reduce the extreme concentration observed in previous years. This pattern is consistent with rising employment levels and social transfer adjustments observed in post-pandemic recovery years.

From a policy perspective, the Lorenz curve analysis confirms that improvements are occurring but remain fragile. Income growth appears to be diffusing more evenly across income groups, yet wealth accumulation and top-income concentration remain substantial challenges. Continued monitoring using household microdata (EU-SILC or national income surveys) is necessary to verify whether this convergence trend will persist beyond 2024.

Overall, the Romanian case between 2020 and 2024 demonstrates that inequality reduction is possible, but structural disparities between income groups remain evident. Consequently, both fiscal redistribution policies and long-term investments in education, regional development, and labor productivity remain central to achieving sustained distributional balance.

1.2. Empirical Interpretation of Lorenz Curve Patterns

Although detailed raw income distribution data (e.g., by decile) are not provided here, summary statistics and related interpretations allow us to reconstruct an approximate narrative of how the Lorenz curve would differ year by year: In 2020–2021, with Gini values near 34, the Lorenz curve would have exhibited larger deviations from equality, with the bottom deciles receiving a relatively smaller share of total income. By 2023, with the Gini subsequently reduced to around 31, the curve suggests greater income dispersion narrowing, whereby lower percentiles gained a slightly larger share relative to higher percentiles. In 2024, with the Gini estimated near 28—the lowest in over a decade—the Lorenz curve likely shows the smallest gap from the line of equality within the 2020–2024 period, implying more equitable distribution than earlier in the decade.

In practical terms, these shifts reflect that the share of total income earned by the poorest segments of the population has increased modestly, while the richest segments accounted for a smaller share than in previous years. This trend is consistent with analyses noting growth in the middle class and reduced polarization between upper and lower income groups.

1.3. Discussions and results

A Historical and structural research indicates that Romania's income inequality pattern reflects both transitional legacies and recent socio-economic dynamics. Vezentan's longitudinal analysis of economic growth and inequality shows that growth periods historically correlated with varying Gini coefficients, often widening inequality during rapid expansion phases. Complementary surveys of income variability reveal that inequality persists across demographic and socio-economic groups, suggesting that Lorenz curves capture not only aggregate dispersion but also subgroup differentials by household structure, urban–rural residence, and employment characteristics. Beyond the Lorenz curve and Gini measure, Romania exhibits notable structural patterns in income distribution:

a. Top income shares: A small fraction of the population controls a disproportionate share of income and wealth. For example, the top 10% of Romanian earners control approximately 41% of total national income (before taxation), highlighting remaining concentration at the high end of the distribution.

b. Wealth concentration: Financial assets are even more concentrated: just 0.6% of deposit holders controlled roughly 28% of total bank deposits in 2025, underscoring significant inequality in wealth holdings beyond income flows.

c. Middle class dynamics: Data suggest growth in the middle class share, indicating a structural movement toward a more balanced income distribution, which in turn can reduce the distance between the Lorenz curve and the equality line at moderate income levels.

From a policy perspective, the temporal movements in the Lorenz curve and Gini coefficient between 2020 and 2024 imply that redistributive policies, labor market developments, and structural growth have contributed to a more balanced income distribution in Romania. However, persistent concentration at the top deciles — as evidenced by the disproportionate income share of high earners — signals ongoing challenges to achieving full equality. Furthermore, multidimensional research emphasizes that *inequality* cannot be reduced to a single indicator; alternative measures such as Theil and Atkinson indices often provide additional nuance beyond the Lorenz/Gini framework. Molnar's work on income polarization, for example, suggests that polarization dynamics may coexist with shifts in mean inequality and warrant separate investigation The observed trajectory of the Lorenz curve and Gini indices over 2020–2024 implies that Romania has experienced *modest but meaningful progress* toward a more equitable income distribution. This progress may reflect policy reforms, rising median incomes, labor market shifts, or social transfers—but also masks persistent pockets of inequality, particularly at the extremes of the distribution.

From a policy standpoint, sustained monitoring of Lorenz curves over time remains crucial because they reveal *distributional shifts that national averages or single indicators may obscure*. For example, a decline in the Gini index signals overall equality improvements, but detailed curve shapes can show whether gains accrue primarily to the lower end, the middle, or both ends of the distribution.

Conclusions

The Lorenz curve, coupled with Gini and complementary measures, provides a robust framework for assessing income distribution in Romania between 2020 and 2024. During this period, evidence suggests a gradual narrowing of income inequality, with the Lorenz curve moving closer to the line of equality and the Gini index reaching multi-year lows by 2024. Despite these positive signs, significant concentration of income and wealth among top earners persists. Continued analysis of income shares across deciles and percentiles, ideally from detailed household survey data (such as EU-SILC or national income surveys), would enrich future evaluations of spatial and socio-economic inequality in Romania.

Research in inequality measurement emphasizes that changes in the Gini index correspond to shifts in the Lorenz curve configuration, reflecting redistribution between income groups. Clementi et al.\ argue that Lorenz dominance analysis is crucial in evaluating distributional improvements beyond simple scalar indicators, since similar Gini values may hide different distributional structures..

The case investigated in the Campania region reveals a serious and systemic form of environmental crime, involving well-organized networks, possibly with mafia-like ramifications, that take advantage of institutional loopholes or corruption. Italian criminal law, complemented by European regulations, provides the necessary tools to repress this type of crime. However, their effectiveness depends on rigorous law enforcement, inter-institutional cooperation and the strengthening of investigative and prosecution capacities in the field of environmental crimes. [14]. Empirical studies focusing on Romania also reveal that wage income constitutes the largest contributor to inequality dynamics. Decomposition analyses by Andrei et al.\ demonstrate that variations in labor income distribution significantly influence overall inequality outcomes, thereby shaping the curvature of the Lorenz distribution.

Simionescu's recent econometric analysis further shows that macroeconomic factors such as inflation and employment conditions interact with inequality levels, suggesting that post-pandemic recovery dynamics partially explain recent improvements in income distribution.

Despite the observed reduction in inequality, the Lorenz curve still indicates persistent concentration of income among higher deciles. Data show that the top income groups continue to capture a disproportionately large share of national income, meaning Romania remains characterized by moderate inequality relative to EU averages.

From a policy perspective, Lorenz-based evaluations highlight that redistribution mechanisms, employment expansion, and social transfer policies can gradually reduce income dispersion. However, long-term convergence requires structural improvements in education, productivity, and regional economic development to ensure sustained distributional balance.

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Governing critical infrastructure resilience in the European Union: the evolution of the legal framework

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Abstract: The study examines the reconfiguration of the European Union's regulatory framework on the protection and resilience of critical infrastructures/entities, in the context of physical-digital interdependencies and the amplification of transboundary hybrid risks, assessing the transition from an approach centered on the protection of infrastructures as strategic assets to an integrated model oriented toward resilience and the continuity of essential services. In this regard, the study assesses the extent to which the current normative architecture - structured around Directive (EU) 2022/2557 on the resilience of critical entities (CER), Directive (EU) 2022/2555 on cybersecurity (NIS2), and Regulation (EU) 2024/2847 on the cyber resilience of products with digital elements (CRA) - establishes a coherent and complementary framework. The methodology adopted is legal-analytical, combining doctrinal analysis of hard law norms (directives and regulations) with soft law instruments (strategies, action plans, communications, and recommendations). The study's main contribution lies in conceptualising the CER-NIS2-CRA triad as a three-level normative model: the resilience of entities and essential services, the governance of operational cyber risks, and the security of digital products "by design" throughout their life cycle. The analysis highlights both normative convergence toward systemic risk management and structural tensions that may affect operational coherence and uniform implementation at the EU level.
Keywords: *critical infrastructures; protection; resilience; cybersecurity; resilience governance*

1. Introduction

1.1. The general context of the study

Within a European space marked by *increasingly complex interdependencies* (economic and commercial; political and institutional; security and defense; energy-related; legal and regulatory; social and demographic; cultural and informational), *critical infrastructures represent the fundamental pillars* of the functioning of modern societies. They include the full range of systems, services, assets, and networks indispensable for maintaining the essential functions of the state, the safety of citizens, public health, economic security, and social order [1-3].

Recent crises - the COVID-19 pandemic; large-scale cyberattacks on energy, financial, and information networks; and the conflict in Ukraine; the climate and environmental crisis - have demonstrated how vulnerable the European Union (EU) can be to hybrid threats, particularly when these target interconnected critical infrastructures [4-7]. Thus, the protection and resilience of critical infrastructures has become a *priority domain* within European security policies [8, 9], being closely correlated with the digital agenda, defence policy, civil protection, and societal resilience.

In this context, the *EU has gradually developed a regulatory framework* aimed at harmonizing Member States' efforts to strengthen the protection and resilience of critical infrastructures, contributing to: ensuring the functioning of the internal market and supply chains; increasing the resilience of economic

and social systems; enhancing the capacity for a common response to cross-border threats; and fostering the development of a shared security culture among Member States.

1.2. Working hypothesis, objectives, and contribution of the study

This study examines the reconfiguration of the EU regulatory framework on the protection and resilience of critical infrastructures/entities, in the context of physical-digital interdependencies and the intensification of cross-border hybrid risks. The purpose of the analysis is not the cumulative listing of the relevant legal instruments, but rather the assessment of the *coherence* and *functionality* of the regulatory framework as a whole, including its capacity to ensure better integration between the physical and cyber dimensions of risks and to support the continuity of essential services in crisis situations with cascading effects.

Within this framework, the research advances the following ***working hypothesis***:

Hypothesis (H): *The EU's current regulatory architecture, built around Directive (EU) 2022/2557 on the resilience of critical entities (CER) [10], Directive (EU) 2022/2555 on cybersecurity (NIS2) [11], and Regulation (EU) 2024/2847 on the cyber resilience of products with digital elements (CRA) [12], outlines an integrated model for the governance of resilience across the entire "entity-system-product" chain, oriented toward the management of systemic risks and the continuity of essential services; however, its practical effectiveness is liable to be diminished by structural frictions, in particular procedural overlaps, imperfect institutional coordination, and capacity asymmetries among Member States.*

The hypothesis is deliberately formulated along a dual axis: the *existence of normative and teleological* convergence towards resilience and the management of risks with cross-sectoral impact; and the persistence of *systemic constraints* likely to generate operational dysfunctions and heterogeneous implementation practices, with an impact on the resilience of the EU space.

To support this hypothesis, the study pursues ***three main objectives***, as follows:

O1 - *Normative reconstruction and paradigm shift:* highlighting the transition from the protection of infrastructures as strategic assets - reflected in the Communication from the Commission on a European Programme for Critical Infrastructure Protection (EPCIP) [13] and Directive 2008/114/EC [14] - to a post-2022 framework oriented toward the resilience of entities and the continuity of essential services (CER/NIS2), as well as the extension of "by design" security to the realm of digital products (CRA).

O2 - *Systemic analysis of the CER-NIS2-CRA architecture:* identifying the internal logic of the integrated model (resilience, risk management, operational continuity), the governance mechanisms (obligations, reporting, supervision), and the areas of functional complementarity among the instruments, with a delineation of their respective normative intervention layers.

O3 - *Critical assessment of coherence and structural limits:* examining the tensions generated by physical-digital integration and multilevel governance (EU-Member States-operators/manufacturers), with a focus on the risks of procedural overlap and "double reporting," the coordination of competent authorities, the harmonization-subsidiarity relationship, and the effects of capacity asymmetries on practical convergence among UE Member States.

The ***theoretical and analytical contribution*** of the study consists in proposing a systemic analysis of the CER-NIS2-CRA triad, conceptualized as a three-level regulatory model: the *entity level* (CER-resilience of critical entities and continuity of essential services); the *operational system level* (NIS2 - governance of cyber risks at organizational and network level); and the *product/technology level* (CRA - upstream "by design" security of digital products throughout their life cycle).

This approach enables an examination of responsibilities, complementarities, and potential implementation shortcomings, thereby offering an explanatory framework for understanding the EU's shift toward resilience governance.

Finally, the study adopts necessary ***delimitations*** to ensure coherence: the analysis focuses on *EU normative instruments* relevant to critical infrastructures and cybersecurity, without engaging in an in-depth examination of parallel legal regimes (for example, EU criminal law frameworks addressing cybercrime and attacks against infrastructures) or the classified dimension of cooperation with intelligence

agencies, except insofar as these influence the governance and resilience logics of the framework under examination.

1.3. Research methodology

The present study adopts a ***qualitative legal-analytical methodology***, grounded in the doctrinal analysis of EU law and in the integrated examination of relevant public policies in the field of the protection and resilience of critical infrastructures. The methodological approach is oriented toward substantiating the working hypothesis through an understanding of the *normative logic* and *governance mechanisms* embedded in the European resilience architecture, rather than toward an empirical evaluation of implementation at the national level.

1.3.1. Type of legal analysis

The research primarily employs: *legal doctrinal analysis,* applied to EU *hard law* instruments (directives and regulations), with the aim of identifying the object, scope of application, obligations, coordination mechanisms, and normative limits of each act; *systemic and functional analysis*, which enables the examination of relationships of complementarity, overlap, or tension among different normative instruments, in particular between the CER Directive, the NIS2 Directive, and the CRA Regulation; *public policy analysis,* applied to *soft law* instruments (strategies, communications, action plans), in order to understand their role as mechanisms of guidance, convergence, and normative anticipation. This methodological combination reflects the hybrid nature of the field under analysis, situated at the intersection of EU internal market law, EU internal security, risk governance, and resilience policies.

1.3.2. Integrated approach and the CER-NIS2-CRA analytical framework

To ensure analytical coherence, the study employs an integrated conceptual framework that treats the European normative architecture as a three-level model, corresponding to different layers of risk and normative intervention: *the entity and essential service level,* analyzed through the lens of the CER Directive, which regulates the organizational and physical resilience of critical entities and the continuity of vital services; *the operational system and network level,* analyzed through the NIS2 Directive, which establishes reinforced requirements for cyber risk governance, incident management, and managerial accountability; *the product and technology level,* analyzed through the CRA Regulation, which introduces mandatory "by design" and "by default" cybersecurity requirements for products with digital elements.

This framework enables an assessment of how EU law seeks to cover the entire risk chain - from technological components and products, to operational systems, and ultimately to the functioning of essential services - and to reduce systemic vulnerabilities generated by physical-digital interdependencies.

1.3.3. Criteria for analysis and evaluation

The evaluation of the regulatory framework is conducted on the basis of explicit *analytical criteria,* applied transversally to the instruments under review*: normative coherence*, understood as the compatibility of objectives, definitions, and institutional mechanisms; *functional complementarity,* namely the capacity of the instruments to cover different layers of risk without generating excessive redundancies; the *degree of harmonization*, analyzed in relation to the transition from minimum harmonization (the NIS Directive) to reinforced harmonization (the NIS2 Directive and the CRA Regulation); *compliance with the principle of subsidiarity*, particularly in areas sensitive to the sovereignty of EU Member States; *practical implementability,* assessed in light of the complexity of obligations, the risk of administrative overlap, and the need for coordination among multiple competent authorities; and the *capacity to reduce systemic risks*, including cascading effects and vulnerabilities in supply chains.

These criteria primarily allow for a descriptive analysis, while at the same time enabling a critical assessment aimed at identifying the structural limits of the European normative architecture.

1.3.4. Sources and materials used

The research is based on: *primary sources,* consisting of EU Treaties, directives, regulations, communications, and official strategies of the European institutions; *secondary sources,* including specialized literature in the fields of EU law, cybersecurity, and risk governance, as well as relevant reports in the field; and *evaluation and impact assessment documents* prepared by the European Commission, used to contextualize normative objectives and rationales.

Jurisprudential analysis is used to a limited extent, as the field of the protection and resilience of critical infrastructures is predominantly characterized by *ex ante* regulation and administrative compliance mechanisms, with a limited number of relevant disputes at the level of the Court of Justice of the EU.

1.3.5. Methodological limitations

The study does *not pursue an exhaustive comparative analysis* of the European normative framework concerning the protection and resilience of critical infrastructures, *nor does it include empirical case studies*. These limitations are deliberately assumed, as the objective of the research is to assess the normative coherence of the European framework in this field, as a prerequisite for the functioning of resilience mechanisms.

1.4. Review of the relevant literature

The body of scholarly literature relevant to the analysis of the EU regulatory framework on the protection and resilience of critical infrastructures highlights a significant conceptual and normative evolution, from approaches centered on protecting infrastructures as isolated strategic assets toward integrated models of systemic resilience governance, adapted to physical-digital interdependencies and cross-border risks.

An *initial doctrinal corpus* examines the EU's transition from early critical infrastructure protection policies, crystallized around the EPCIP [13] and Directive 2008/114/EC [14], toward a resilience-oriented paradigm. In this regard, specialized studies emphasize the conceptual shift from the protection of critical assets to the management of vulnerabilities and cascading effects within interdependent socio-technical systems, which has required a reconceptualization of the object of regulation at the European level [15-17].

From a critical-institutional perspective, reports produced by the Centre for European Policy Studies (CEPS) highlighted, as early as the post-2008 period, the difficulties of harmonization in the field of critical infrastructure protection, the central role of Member States and private operators, and the risks generated by limited exchanges of sensitive information [18, 19]. These analyses foreshadow many of the solutions later adopted in the CER Directive, particularly the orientation toward risk assessments, the continuity of essential services, and organizational responsibility.

Complementarily, the *governance and resilience literature*, including periodic analytical reports and assessments produced by the Organisation for Economic Co-operation and Development (OECD), describes resilience as a systemic capacity that combines prevention, shock absorption, adaptation, and recovery, going beyond the logic of sequential protection [20].

A *second major strand of the literature* addresses the resilience of critical infrastructures as a multi-level governance issue, in the context of shared competences and the constraints imposed by EU Member States' sovereignty in the field of security. Classical analyses of cross-border crisis management in the EU show that the effectiveness of the European response depends less on formal centralization and more on the capacity for coordination, institutional learning, and procedural convergence [21-23].

More recent studies on critical infrastructure governance emphasize that interdependencies are not exclusively technical but also institutional: fragmented competences, the multiplication of supervisory authorities, and administrative asymmetries can themselves become sources of systemic vulnerability [24, 25]. These studies provide an important explanatory framework for the divergences identified between the CER and NIS2 Directives with regard to the delineation of responsibilities and the coordination of competent authorities.

With regard to cybersecurity, the literature highlights the shift from a model of minimum harmonisation, characteristic of the NIS Directive [26], to a more prescriptive model of cyber risk governance, specifically associated with the NIS2 Directive [11]. The analyses highlight the importance of extending the scope of application to additional sectors, introducing the accountability of management bodies, and addressing supply chains as vectors of systemic risk [27-29].

An important role in the applied literature is played by the documents and guidelines developed by the European Union Agency for Cybersecurity (ENISA), which translate the legal requirements of the NIS2 Directive into operational practices and maturity indicators. They thus provide clear benchmarks for assessing the implementation of the Directive and the administrative capacities of EU Member States, as well as for identifying and/or highlighting the persistence of asymmetries [30, 31].

An *emerging body of literature* analyses the CRA Regulation [12] as an extension of the logic of product safety and conformity law into the field of cybersecurity. The authors emphasize the innovative nature of the horizontal, risk-based approach, as well as the upstream shift of responsibility toward manufacturers and suppliers of digital technologies, imposing *secure-by-design* obligations throughout the entire lifecycle of products [32, 33].

At the analytical level, the relationship between the CRA Regulation and the instruments governing cybersecurity (in particular the NIS2 Directive) was examined, supporting the idea of reconfiguring the governance of digital platforms through the institutionalization of cybersecurity "by design" as a normative and organizational practice [34].

Complementing the academic literature, the European Commission's *impact assessment documents* and *staff working documents* constitute essential sources for understanding the normative rationales underlying the adoption of the CER and NIS2 Directives and the CRA Regulation. These documents explicate the shortcomings of the previous framework, public policy objectives, and regulatory options considered, providing a useful interpretative background for legal doctrinal analysis [35-37].

2. The European regulatory framework in the field of the protection and resilience of critical infrastructures

2.1. General considerations

This chapter serves as a *normative* and *conceptual foundation*, providing a detailed and structured systematization of the main legal and strategic instruments relevant to the protection and resilience of critical infrastructures. The descriptive approach is methodologically justified, as the field under analysis is characterized by high normative density, rapid evolution, and fragmented literature, and the clarification of the legal framework constitutes a necessary precondition for the subsequent integrated analysis.

The *descriptive character* does not represent a limitation of the study, *but rather a deliberate methodological choice*, intended to support the original analysis developed in Chapter 3. This approach is explicitly formulated and consistently maintained, thereby contributing to the transparency of the research process.

2.2. Defining the concepts of critical infrastructure (CI) / European critical infrastructure (ECI)

According to Article 2(a) of Directive 2008/114/EC, *"critical infrastructure" (CI)* is defined as *"an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions"* [14]. This definition highlights a systemic and functional approach to critical infrastructures, emphasizing their essential role in vital societal functions and the well-being of the population, as well as the fact that the impact of their disruption or destruction is assessed in relation to the consequences for the State's capacity to maintain its fundamental functions.

The same directive introduces into EU legislation the concept of *"European critical infrastructure" (ECI)* as an extension of the notion of national critical infrastructure. According to Article 2(b), a European critical infrastructure is *"a critical infrastructure located in Member States the disruption or*

destruction of which would have a significant impact on at least two Member States" [14]. The definition captures the cross-border and interdependent dimension of European critical infrastructure, highlighting that its relevance derives not only from its location, but above all from its significant impact on multiple Member States.

Conceptual approaches to the issue of critical infrastructures have evolved significantly over the past decade, in line with the increasing complexity of interconnections and cyber vulnerabilities, leading to a deeper understanding of their protection from the perspective of European systemic resilience.

2.3. Context for the emergence of European policies on critical infrastructures

The *first European initiatives* on the protection of critical infrastructures emerged in the early 2000s, against the backdrop of *an intensification of terrorist attacks and the globalization* of energy and transport infrastructures. In 2006, the European Commission adopted the Communication from the Commission on a European Programme for Critical Infrastructure Protection (EPCIP) [13]; in 2008, Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection [14] was adopted, initially focused on the energy and transport sectors; and in 2016, Directive (EU) 2016/1148 of the European Parliament and of the Council of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union (NIS Directive) [26] was adopted.

Subsequently, *technological developments and the intensification of cyber threats* prompted a revision of this approach. In 2020-2022, the European Commission promoted a new regulatory architecture, articulated around Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC (CER Directive) [10], and Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union, amending Regulation (EU) No 910/2014 and Directive (EU) 2018/1972, and repealing Directive (EU) 2016/1148 (NIS2 Directive) [11], which are intended to harmonize the protection of physical and digital critical entities. In parallel, the EU Cybersecurity Strategy for the Digital Decade [JOIN(2020) 18 final] [38] and Regulation (EU) 2024/2847 of the European Parliament and of the Council of 23 October 2024 on horizontal cybersecurity requirements for products with digital elements and amending Regulations (EU) No 168/2013 and (EU) 2019/1020 and Directive (EU) 2020/1828 (Cyber Resilience Act - CRA) [12], further consolidate the integration between infrastructure resilience and cybersecurity.

2.4. Legal and strategic instruments in the field of critical infrastructures

2.4.1. Communication from the Commission on a European Programme for Critical Infrastructure Protection (EPCIP) [13]

Adopted on 12 December 2006, the EPCIP constitutes, according to Section 1, a *strategic public policy* document through which the Commission proposes the creation of a coherent EU-level framework aimed at strengthening the protection of critical infrastructures against a wide spectrum of threats, including terrorist, accidental, and natural threats.

In accordance with Section 2, the *overall objective* of the EPCIP is to *ensure the continuity of society's vital functions* by strengthening prevention, preparedness, and response capacities to major disruptions of critical infrastructures, particularly in situations where their effects go beyond national borders. In this regard, the Communication responds to the requests formulated by the European Council concerning the development of an integrated European strategy in the field of critical infrastructure protection.

According to Section 3, *European critical infrastructures are defined* as assets of major importance to the EU which, in the event of disruption or destruction, generate cross-border effects on one or more Member States as a result of the interdependencies among interconnected infrastructures. The Communication highlights the interdependent and cross-sectoral nature of these infrastructures, as well as the *need for a coordinated approach at EU level* in the case of infrastructures with significant cross-border impact.

Section 4 presents a *coherent set of institutional, operational, and cooperative measures* intended to facilitate the development and implementation of the EPCIP. These include a dynamic action plan structured across three levels - strategic, European, and national - the establishment of a secure warning and information-sharing network, the use of expert groups as mechanisms for public-private dialogue and the provision of sectoral expertise, the establishment of strict principles governing the exchange of sensitive information, as well as the continuous identification and analysis of geographic and sectoral interdependencies, all of which are aimed at strengthening the protection of critical infrastructures at the EU level.

According to the provisions set out in Section 5, *primary responsibility for the protection of national critical infrastructures* rests with the EU Member States and their owners or operators, while the European Commission has a supporting and guidance role, upon request.

In this context, the Communication promotes the establishment of national critical infrastructure protection programmes, based on harmonized national criteria that assess the geographical impact of disruptions and the severity of public, economic, environmental, political, psychological, and health effects, as well as on dialogue with operators, the identification of sectoral and geographical interdependencies, and the development of contingency plans, with the aim of ensuring a comparable level of protection across the EU and avoiding fragmentation of the internal market through divergent national frameworks.

A central instrument of critical infrastructure protection, as highlighted in Section 6, is *contingency planning,* whose role is to reduce the impact of systemic disruptions through a coordinated approach involving infrastructure operators, competent national authorities, and cross-border cooperation within the EPCIP framework.

Finally, Section 7 underscores the *importance of the external dimension* of critical infrastructure protection, given that threats and interdependencies extend beyond EU borders, thereby necessitating enhanced international cooperation, the exchange of best practices, and the harmonization of standards. These efforts are supported, according to Section 8, by European *financial instruments* dedicated to the prevention, preparedness, and management of the consequences of security risks, intended to support the effective implementation of the EPCIP.

2.4.2. Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection [14]

Adopted on 8 December 2008, Directive 2008/114/EC constitutes the *first common legislative framework* at EU level *dedicated to the identification and designation of European critical infrastructures* (ECIs), as well as to the assessment of the need to improve their protection, with a view to reducing vulnerabilities and limiting the consequences of significant disruptions or destruction, as provided for in Article 1.

In Article 2, paragraphs (a) and (b), the Directive defines the concepts of *critical infrastructure* and *European critical infrastructure*, as presented in Chapter 2.2.

In accordance with Articles 3 and 4, the directive establishes the *procedure for the identification* (Annex III) and *designation* of European critical infrastructures, which involves the application of sectoral and cross-sectoral criteria, including the assessment of the potential impact of the disruption of the infrastructure concerned. The cross-sectoral criteria relate in particular to impacts on casualties, economic effects, and effects on the public, while sectoral criteria are set out in the annexes corresponding to each sector.

The Directive has a limited sectoral scope of application, initially being confined to two sectors considered a priority, namely energy and transport, as listed in Annex I, which details the relevant subsectors within each field.

A central element of the directive is the establishment of the obligation for operators of *designated European critical infrastructures* to draw up operator security plans, as provided for in Article 5. These plans must identify critical assets, relevant risks, and existing or planned security measures for the protection of the infrastructure concerned.

Furthermore, under Article 6, Member States are required to designate, for each identified European critical infrastructure, a security liaison *officer responsible for facilitating cooperation and communication* between critical infrastructure operators and the competent national authorities.

The directive also provides, in Article 7, for the obligation of Member States to *carry out threat and risk* assessments and to support critical infrastructure operators in *improving levels of protection*, in accordance with national competences and the principle of subsidiarity.

Although Directive 2008/114/EC represented an *innovative normative step* at the time of its adoption, it was subsequently subject to criticism in the academic literature and in institutional evaluations, particularly due to its narrow sectoral scope, limited to energy and transport, as well as the low level of harmonisation and uniform implementation across EU Member States. These structural limitations highlighted the need for a more comprehensive and integrated approach.

In this context, Directive 2008/114/EC constituted the *conceptual and normative foundation* for subsequent developments in European policy on critical infrastructures, which led to the adoption of a broader framework focused on the resilience of critical entities, materialized through Directive (EU) 2022/2557 (the CER Directive).

2.4.3. Directive (EU) 2016/1148 of the European Parliament and of the Council of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union (NIS Directive) [26]

Adopted on 6 July 2016, the NIS Directive establishes, pursuant to Article 1, *the first EU-level legal framework aimed at ensuring a high common level of security of network and information systems*, with the aim of ensuring optimal conditions for the functioning of the internal market and strengthening trust in the digital environment.

In accordance with Articles 4 and 5, the directive applies to the following categories of entities: *operators of essential services,* identified by the Member States on the basis of the criteria set out in Article 5(2) and Annex II; and *digital service providers*, as defined in Article 4(6) and listed in Annex III.

The sectors relevant for the identification of operators of essential services include, according to Annex II, areas such as energy, transport, banking, financial market infrastructures, health, the supply and distribution of drinking water, as well as digital infrastructure, insofar as the disruption of the respective services would have a significant impact on society or the economy.

Pursuant to Article 7, the NIS Directive obliges EU Member States to adopt *national strategies for the security of network and information systems*, within which strategic objectives, public policy measures, governance structures, and relevant national-level cooperation mechanisms are to be established.

The directive establishes distinct obligations regarding risk management and incident notification, differentiated according to the category of entity. Thus, pursuant to Article 14, *operators of essential services* are required to adopt appropriate *technical and organizational measures* for the effective management of risks and threats to the security of the network and information systems used in the provision of their services, and to *notify*, without undue delay, incidents having a significant impact. *Digital service providers* are subject to *similar but* more limited obligations under Article 16, reflecting the differentiated and more flexible approach adopted by the directive with respect to this category of entities.

With regard to the institutional framework, the NIS Directive establishes cooperation mechanisms at EU level, including the *Cooperation Group* - established under Article 11, with a strategic role in supporting and facilitating cooperation among the Member States - and the *CSIRT Network* (Computer Security Incident Response Teams) - provided for in Article 12, aimed at promoting operational cooperation, information exchange, and the coordination of responses to cybersecurity incidents. In this context, ENISA plays a role of technical support and expertise, particularly with regard to facilitating cooperation, the exchange of best practices, and the development of Member States' capacities.

The NIS Directive enshrines a *minimum harmonisation* approach, allowing EU Member States significant discretion in the identification of operators of essential services, the determination of security

requirements, and the application of supervision and enforcement regimes, which in practice has led to a high level of regulatory fragmentation across the EU.

Accordingly, the NIS Directive represents the *cornerstone of European cybersecurity policy*, providing the first coherent legal framework in this field, while also serving as the starting point for the subsequent strengthening of regulation through the adoption of the NIS2 Directive.

2.4.4. Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC (the CER Directive) [10]

Adopted on 14 December 2022, the CER Directive repeals Directive 2008/114/EC pursuant to Article 27 and *establishes a new European regulatory framework focused on strengthening the resilience of critical entities*, moving beyond the previous approach predominantly centered on the physical protection of critical infrastructures, as reflected in Article 1.

The CER Directive applies to entities operating in eleven critical sectors, as listed in the Annex to the Directive: energy; transport; banking; financial market infrastructures; health; drinking water; wastewater; digital infrastructure; public administration; space; and the production, processing, and distribution of food.

In accordance with Article 4, the CER Directive provides that each EU Member State shall *adopt and regularly update a national strategic framework* setting out objectives, measures, governance mechanisms, and intersectoral and cross-border cooperation arrangements, with a view to ensuring a high and sustainable level of resilience of critical entities, and shall communicate it to the European Commission.

The directive imposes on Member States the obligation to *carry out national risk assessments*, pursuant to Article 5, in order to identify threats relevant to the provision of essential services, including natural hazards, man-made risks, accidents, acts of sabotage, terrorism, and other hybrid threats. These assessments form the basis for the *identification of critical entities*, in accordance with Article 6, as well as for the *establishment of appropriate resilience measures*. In this context, Article 7 specifies that a *significant disruptive effect* is determined by the scale and duration of the impact of an incident on users, dependent sectors, public safety, the economy, and the continuity of essential services, including at cross-border level.

At the same time, the CER Directive establishes a reinforced *governance and coordination framework*, providing in Article 9 for the obligation of EU Member States to designate competent authorities responsible for the implementation of the Directive, as well as, in accordance with Article 11, the establishment of mechanisms to facilitate cooperation and information exchange at EU level.

The Directive establishes, in Article 17, a special regime for *critical entities of particular European significance*, defined as entities that provide essential services to at least six EU Member States, whose designation is carried out through a procedure of notification, consultation, and confirmation at the level of the European Commission. For these entities, the Commission may, in accordance with Article 18, organise *advisory missions* aimed at assessing compliance with resilience obligations, issuing opinions and recommendations, and strengthening cooperation, information exchange, and mutual learning among EU Member States, while respecting national competences in the relevant fields.

Furthermore, the Directive establishes, through Article 19, the *Critical Entities Resilience Group* as a mechanism for coordination and information exchange between the Member States and the Commission, and enshrines, through Article 20, the role of the Commission in supporting competent authorities and critical entities through guidance, best practices, assessments, advisory missions, training, and the analysis of cross-border and intersectoral risks. At the same time, particular attention is also given to issues of *supervision and enforcement*, as reflected in the provisions of Articles 21 and 22.

Through this regulatory architecture, the CER Directive marks a *paradigm shift* from the concept of *"protection"* of critical infrastructures to that of *"resilience"* of critical entities, understood, pursuant to Article 2, as the set of capacities for prevention, resistance, absorption, adaptation, and recovery following incidents with significant impact, reflecting the need for continuous adaptation to a security environment characterized by complex, interconnected, and systemic threats.

2.4.5. Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union, amending Regulation (EU) No 910/2014 and Directive (EU) 2018/1972, and repealing Directive (EU) 2016/1148 (NIS2 Directive) [11] Adopted on 14 December 2022, the NIS2 Directive repeals the NIS Directive pursuant to Article 44 and establishes a *strengthened legal framework for achieving a high common level of cybersecurity of network* and information systems across the Union, as provided for in Article 1.

The Directive applies to the entities defined in Article 3 and listed in Annex I (*sectors of high criticality*) and Annex II (*other sectors of critical importance*). The areas covered include: energy; transport; banking; financial market infrastructures; health; drinking water and wastewater; digital infrastructure; public administration; space; the production and distribution of food; postal and courier services; waste management; the chemical industry; the manufacture of critical products; digital service providers; as well as research organizations.

It is relevant to note that this legislative act regulates the *national governance framework in the field of cybersecurity* through the provisions of Articles 7-13, which are based on the national cybersecurity strategy (Article 7). The strategy defines strategic objectives, public policies, sectoral priorities, governance and cooperation mechanisms, as well as measures for prevention, preparedness, response, and recovery in relation to cybersecurity incidents. This framework is operationalised through the designation of competent authorities and a single point of contact (Article 8), cyber crisis management authorities (Article 9), and CSIRT teams, with clearly defined tasks, adequate resources, and obligations of coordination and information exchange at national, cross-border, and intersectoral levels (Articles 10-13). Accordingly, national governance is conceived as an integrated, multi-level system that combines strategic planning, institutional coordination, vulnerability management, public–private cooperation, and operational capacities for incident and crisis management, with a view to ensuring a high and sustainable level of cybersecurity.

Furthermore, the NIS2 Directive regulates the *governance framework at EU and international level,* established by Articles 14-19. This framework is based on a multi-level architecture of strategic, operational, and crisis-management cooperation, designed to ensure coherence, trust, and secure information exchange between Member States and EU institutions. At the strategic level, the *Cooperation Group* coordinates policy guidance, the exchange of best practices, risk assessments, and peer reviews, ensuring consistent implementation of the Directive and its interface with EU initiatives and the framework established by the CER Directive (Article 14). At the operational level, the *CSIRT network* facilitates rapid technical cooperation on incidents, vulnerabilities, and coordinated response (Article 15), while EU-CyCLONe manages the political and operational coordination of large-scale cybersecurity incidents and crises (Article 16). The international dimension is reflected in the possibility of concluding agreements between the EU, third countries, and international organisations (Article 17), as well as through reporting, evaluation, and mutual learning mechanisms that contribute to strengthening cybersecurity capacity and resilience across the EU (Articles 18–19).

In accordance with Article 21, the NIS2 Directive establishes the *obligation for the entities concerned to adopt technical, operational, and organizational measures for the effective management of cybersecurity risks*, including, inter alia: policies for risk analysis of information system security, incident and crisis management, supply chain security, security testing and auditing, as well as the use of cryptography and authentication mechanisms.

The Directive significantly strengthens the *responsibility of the management bodies* of entities, providing in Article 20 for their obligation to approve cybersecurity risk management measures, to oversee their implementation, as well as for the possibility of incurring liability in the event of non-compliance with the established obligations.

With regard to incident management, the NIS2 Directive introduces a detailed *regime for the reporting of significant incidents*, laid down in Article 23, which requires the prompt notification of the competent national authorities or CSIRTs through the submission of early warnings, incident notifications, and a final report.

Through its provisions, the NIS2 Directive, in complementarity with the CER Directive, *contributes to the establishment of a coherent and integrated framework for cybersecurity and resilience* at EU level, reflecting the increasingly deep interdependencies between digital and physical infrastructures and the need for a harmonized approach to systemic risks.

2.4.6. Regulation (EU) 2022/2554 of the European Parliament and of the Council of 14 December 2022 on digital operational resilience for the financial sector (Digital Operational Resilience Act - DORA) [39]

The DORA Regulation establishes a *uniform and directly applicable legal framework* at EU level, with the objective of *strengthening the capacity of financial entities* to prevent, withstand, respond to, and recover from information and communication technology (ICT)-related incidents, as provided for in Article 1. Although the regulation does not directly concern the protection of critical infrastructures in the classical sense of EU law, it regulates a sector classified as critical under both the CER Directive and the NIS2 Directive, having a structural impact on the continuity of essential services and on the stability of the European market.

The scope of application of the regulation is defined broadly, *covering a wide range of financial entities,* including credit institutions, payment institutions, investment firms, financial market infrastructure entities, insurance and reinsurance undertakings, as well as other relevant participants in the financial system, as defined in Article 2. In addition, the regulation introduces a distinct regime governing the relationship between financial entities and third-party ICT service providers, recognizing their critical role in the operational functioning of the financial sector.

The normative structure of the DORA Regulation is built around *five main pillars* that shape a coherent model for the governance of digital operational resilience. The *first pillar* aims to establish a strengthened ICT risk management framework (Chapter II) by setting out obligations relating to internal policies, the responsibilities of management bodies, prevention and detection measures, business continuity plans, and vulnerability management mechanisms. The *second pillar* focuses on establishing a harmonised regime for the management, classification, and reporting of ICT-related incidents (Chapter III), in order to ensure a comparable level of visibility across the EU and to facilitate a coordinated response by competent authorities. The *third pillar* integrates requirements for the periodic testing of digital operational resilience (Chapter IV), going beyond traditional approaches to formal compliance and, in certain cases, introducing the obligation to conduct advanced threat-led penetration testing based on realistic threat scenarios. The *fourth pillar* regulates the management of risks related to third-party ICT service providers (Chapter V) by imposing detailed requirements on contracting, monitoring, exit strategies, and the assessment of concentration risks. Finally, the *fifth pillar* aims to regulate the voluntary exchange of information on threats and vulnerabilities (Chapter VI), with a view to collectively strengthening defensive capabilities and the anticipation of emerging risks.

An innovative element of the Regulation is *the establishment of an EU-level oversight framework for third-party ICT service providers considered critical for the financial sector*, a mechanism that reflects the recognition of the cross-border and systemic nature of digital risks (Chapter V, Section II). This dimension of centralised supervision complements the predominantly national approach found in other EU regulatory instruments and contributes to reducing fragmentation of the internal market in the area of digital resilience.

From the perspective of its relationship with other regulatory instruments, the DORA Regulation operates as a *sector-specific lex specialis* in relation to the NIS2 Directive - for financial entities falling within its scope - in order to avoid overlapping obligations and double reporting in the field of cybersecurity. At the same time, the Regulation stands in a *relationship of functional complementarity* with the CER Directive, insofar as the digital operational resilience of the financial sector constitutes an essential condition for the continuity of critical financial services and for preventing cascading effects on other vital infrastructures and sectors.

By establishing a harmonised framework applicable to strengthening the resilience capacity of financial entities, the Regulation contributes to the *development of the European normative architecture for*

the protection of critical infrastructures and entities, in line with the EU's vision of combining horizontal instruments with specialised sectoral regimes.

The DORA Regulation is complemented by Directive (EU) 2022/2556 [40], which aims to ensure the alignment of existing financial sector legislation with the requirements of digital operational resilience, by *affirming the lex specialis character* of DORA for financial entities and clarifying its relationship with the NIS2 Directive, including the avoidance of overlapping obligations and double reporting. In this way, Directive 2022/2556 contributes to the coherent and uniform application of the DORA regime and to strengthening the systemic resilience of the European financial sector.

2.5. Other related legislative instruments

Subsequent to the regulatory framework referred to in Chapter 2.4, a series of other normative and strategic instruments further complement the European architecture for cyber resilience and cybersecurity, as follows:

2.5.1. Regulation (EU) 2019/881 of the European Parliament and of the Council of 17 April 2019 on ENISA (the European Union Agency for Cybersecurity) and on information and communications technology cybersecurity certification and repealing Regulation (EU) No 526/2013 (Cybersecurity Act) [41]. Regulation (EU) 2019/881 establishes, pursuant to Article 1, the EU legal framework on cybersecurity, with the objective of *strengthening ENISA and establishing the European cybersecurity certification framework* for ICT products, services, and processes, in order to ensure a high level of cybersecurity and the proper functioning of the internal market.

In accordance with Articles 3-7 and the relevant provisions concerning ENISA, the Regulation grants it a permanent mandate, defining its main tasks in *supporting Member States and EU institutions* in the prevention, detection, and management of cyber incidents, facilitating cooperation at EU level, developing capacities, and supporting the consistent application of EU law in the field of cybersecurity.

Through the provisions of Articles 13–28, the *Regulation defines the managerial structure* (the Management Board, the Executive Board, the Executive Director, the Advisory Group, and the Network of National Liaison Officers), *their responsibilities*, and the *manner in which ENISA operates at an operational level* to support EU actions in the field of cybersecurity.

A central element of the Regulation is the establishment, under Article 46, of a *European cybersecurity certification framework* applicable to ICT products, ICT services, and ICT processes. Pursuant to Articles 47-49, a uniform mechanism at EU level is established whereby, on the basis of a rolling work programme, the European Commission, with the support of ENISA, develops, adopts, and reviews, through implementing acts, European cybersecurity certification schemes applicable to ICT products, services, and processes, with a view to ensuring a harmonised level of cybersecurity within the internal market.

The *institutional mechanisms of certification and the roles of the actors involved* are regulated in Articles 50-54, which establish the competences of conformity assessment bodies and of national cybersecurity certification authorities. According to Article 56, certification is, in principle, voluntary, without prejudice to the possibility for other acts of EU law or of the Member States to provide for mandatory certification for certain categories of products or services.

The Regulation provides, in Articles 58-60, *mechanisms for cooperation and coordination* between national authorities, the Commission, and ENISA, in order to ensure the consistent application of certification schemes, information exchange, and monitoring of the effectiveness of the European certification framework.

Through Article 62, the Regulation establishes the *European Cybersecurity Certification Group* (ECCG) - a body composed of representatives of the relevant national authorities, chaired by the European Commission and assisted by ENISA - which is tasked with ensuring coordination, advisory support, and cooperation at EU level for the development, implementation, review, and international alignment of European cybersecurity certification schemes.

By establishing a permanent mandate for ENISA and a harmonized framework for cybersecurity certification, Regulation (EU) 2019/881 represents an *essential normative pillar* of the EU's legal architecture in the field of cybersecurity, playing a complementary role to the CER and NIS2 Directives and the CRA Regulation.

2.5.2. Joint Communication to the European Parliament and the Council: The EU's Cybersecurity Strategy for the Digital Decade [JOIN(2020) 18 final] [38]

The Joint Communication JOIN(2020) 18 final, entitled *The EU Cybersecurity Strategy for the Digital Decade*, constitutes a strategic EU public policy document setting out the political guidelines and strategic objectives in the field of cybersecurity, in the context of accelerated digital transformation and the growing cyber threats with systemic impact.

The Strategy starts from the premise, set out in the introductory section, that *cybersecurity constitutes an essential condition* for the functioning of the internal market, the protection of critical infrastructures, resilience, and the EU's strategic autonomy. The document emphasizes the cross-sectoral and cross-border nature of cyber risks and the need for an integrated approach at EU level.

From a structural perspective, the Strategy is conceptualised around *three main strategic pillars*, as follows. The *first pillar* focuses on strengthening resilience, technological sovereignty, and European leadership in the field of cybersecurity, through the development of a reinforced regulatory framework, investments in secure technologies "by design" and "by default", support for European industrial capacities, and the strengthening of digital supply chain security. The *second pillar* aims to develop operational capabilities for the prevention, detection, deterrence, and response to cyber incidents by enhancing cooperation among EU Member States and strengthening information-sharing and situational awareness mechanisms. The *third pillar* seeks to promote an open, stable, and rules-based global cyber order, by intensifying international cooperation, strengthening partnerships with third countries and international organisations, and promoting responsible state behaviour in cyberspace.

In line with the legislative, operational, and financial instruments operating at EU level, the *Strategy recommends* adapting and expanding the existing regulatory framework, mobilising European funds for cybersecurity, and integrating cybersecurity objectives into the EU's external and development policies. Although it does not establish direct legal obligations, the *document has decisive strategic value*, shaping the directions for the development of EU law in the field of cybersecurity and providing the conceptual framework for the transition from a fragmented approach to an integrated, preventive, and resilience-oriented approach to digital security.

From a systemic perspective, the document serves as an *integrative strategic framework*, underpinning and guiding subsequent normative developments, including the revision of the NIS Directive as reflected in the adoption of the NIS2 Directive, the adoption of the CRA Regulation, and the strengthening of the European architecture on the resilience of critical entities.

2.5.3. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: "Fit for 55": delivering the EU's 2030 climate target on the way to climate neutrality [COM/2021/550 final] [42]

The *"Fit for 55"* legislative package represents a coherent set of legislative proposals presented by the European Commission starting in 2021, aimed at achieving, by 2030, a reduction of at least 55% in net greenhouse gas emissions compared to 1990 levels, in accordance with European climate legislation.

From a normative perspective, the aforementioned package constitutes the *central instrument for the legislative operationalization of the EU's climate objectives*, covering key sectors such as: the emissions trading system; energy and energy efficiency; transport; land use, land-use change and forestry; the carbon border adjustment mechanism; and social policies accompanying the transition.

The package seeks to align the *existing legal framework* with the new climate objectives through the revision and supplementation of sectoral legislative acts, introducing an integrated approach that combines market-based mechanisms, regulatory standards, and social solidarity instruments. A defining

element is the integration of the social dimension of the energy transition, through mechanisms designed to mitigate the impact on vulnerable households and on economic competitiveness.

From a systemic perspective, the legislative package marks the *transition from programmatic climate objectives to concrete legal obligations*, having a structural impact on the architecture of EU law in the fields of energy, environment, transport, and industrial policy. Its normative-operational function gives it the role of strengthening energy resilience and integrating the social dimension into the EU's energy transition.

2.5.4. Regulation (EU) 2024/2847 of the European Parliament and of the Council of 23 October 2024 on horizontal cybersecurity requirements for products with digital elements and amending Regulations (EU) No 168/2013 and (EU) 2019/1020 and Directive (EU) 2020/1828 (CRA Regulation) [12]

The CRA Regulation establishes, pursuant to Article 1, a uniform and directly applicable legal framework at EU level, with the objective of *ensuring a high level of cybersecurity for products with digital elements* throughout their entire life cycle and the proper functioning of the internal market.

In accordance with Articles 2 and 3, the Regulation applies to products with digital elements, defined as *software or hardware products* and *standalone software solutions* placed on the EU market, subject to the exclusions expressly provided for by specific sectoral legislation. The Regulation adopts a risk-based approach, classifying products according to their level of criticality (Articles 6-8), namely products subject to general requirements, important products (Classes I and II, listed in Annex III), and critical products (listed in Annex IV). Based on this classification, the conformity assessment procedures set out in Articles 27-30 are determined. The CRA Regulation lays down, in Annex I, a set of *essential cybersecurity requirements* applicable throughout the life cycle of products with digital elements, including obligations related to secure-by-design development, vulnerability management, protection against unauthorized access, ensuring integrity, confidentiality, and availability, as well as secure update mechanisms. Pursuant to Article 13, the Regulation establishes clear *obligations for economic operators*, in particular for manufacturers, with regard to their responsibilities to ensure the conformity of products with the requirements of the Regulation, the implementation of coordinated vulnerability management processes, the documentation of risks, and cooperation with the competent authorities in the context of market surveillance.

The Regulation also introduces *obligations to report* actively exploited vulnerabilities and significant security incidents, as provided for in Articles 14 and 15, with the aim of strengthening a coordinated response at EU level and reducing systemic risks generated by non-compliant or vulnerable products.

The procedures for *assessing the conformity* of products with digital elements with cybersecurity requirements, including the applicable procedures, technical documentation, the EU declaration of conformity and CE marking, as well as the role of notified bodies where applicable (Articles 27-51). The aim is to ensure that only compliant products are placed on the EU market, with clear responsibilities for economic operators throughout the entire product life cycle.

Market surveillance and enforcement, regulated in Articles 52-60, confer powers on national and EU authorities and establish procedures for monitoring, verifying, and enforcing the compliance of products with digital elements with the requirements of the Regulation, including through risk-based controls, access to information and documentation, corrective measures, and mechanisms for cooperation and coordination to address non-compliant products. By establishing mandatory cybersecurity requirements applicable to products with digital elements, the *CRA Regulation marks a significant normative development in EU law*, instituting a framework oriented towards prevention and the assumption of responsibility in this field, complementary to the framework established by the NIS2 and CER Directives, thereby contributing to the strengthening of digital resilience.

2.5.5. Action Plan for Affordable Energy: Unlocking the true value of our Energy Union to secure affordable, efficient and clean energy for all Europeans [43]

The document adopted by the European Commission sets out a *strategic action plan* aimed at ensuring affordable, secure, efficient, and clean energy in the EU, starting from the finding that persistently high

energy costs continue to affect economic competitiveness and social cohesion. The plan harnesses the EU's potential through an integrated approach structured around *four complementary pillars*, as follows:

The *first pillar - Reducing energy costs* - seeks to lower energy costs for household and industrial consumers, reduce the cost of electricity supply, regulate gas markets to ensure fair energy prices, and promote energy efficiency.

The *second pillar - Building a genuine Energy Union* - aims to accelerate the integration of energy markets at EU level through the modernisation and expansion of cross-border electricity networks, the promotion of digitalisation and interconnectivity of energy systems, and enhanced coordination of national regulations and policies.

Pillar Three - Attracting investment and ensuring the achievement of objectives - aims to accelerate the integration of energy markets at the EU level by implementing efficient investment programs for the modernization of cross-border electricity networks, financed both through European funds and from the national budgets of EU Member States.

Finally, the *fourth pillar - Preparing for potential energy crises* - seeks to strengthen the resilience of the energy system by anticipating and managing disruptions caused by external factors, including cyberattacks and market volatility, by reducing climatic and geopolitical risks, and by ensuring security of energy supply.

The plan does not create direct legal obligations for EU Member States but has *strategic and guiding value*, serving as a *framework document* for the coherent adaptation and implementation of European energy legislation and for aligning energy policies with the EU's social and competitiveness objectives. In this way, the plan *contributes to strengthening energy resilience*, decarbonising the economies of the Member States, and integrating the social dimension into the EU's energy transition.

3. The European normative architecture for the protection and resilience of critical infrastructures: an integrated analysis

3.1. The evolution of the European normative architecture of critical infrastructure resilience

The analysis of the European normative framework on the protection and resilience of critical infrastructures cannot be carried out solely through a point-by-point examination of the relevant legal instruments in this field. Although the CER and NIS2 Directives, as well as the CRA Regulation, have distinct objectives, scopes of application, and mechanisms, they do not operate individually and in parallel, but rather act upon the same systems, which are characterised by physical and digital interdependencies.

In this context, the EU's normative architecture must be understood not as a mere aggregation of legal acts, but as *a multi-layered legal system* designed to address different levels of risk manifesting at EU level. This systemic approach is essential for assessing the coherence of the post-2022 regulatory framework, from the perspective of how its components interact, complement each other, or overlap in managing risks with cascading effects on essential services.

The current EU normative architecture reflects a *significant conceptual shift*, namely the transition from regulating the protection of critical infrastructures - as isolated objects - towards the governance of resilience - as an emergent property of interconnected socio-technical systems. Within this logic, risk is no longer located exclusively at the level of an identified infrastructure, but is distributed along a functional chain that includes technological components, operational systems, organisational structures, and services provided to the population and the economy [2, 15, 16].

Consequently, the assessment of the European normative architecture requires an *analysis of the interaction between different levels of legal intervention*: *the level of the entity and the essential service,* regulated by the CER Directive; the *level of operational systems and networks*, regulated by the NIS2 Directive; and the *level of products and technology*, regulated by the CRA Regulation. These levels are not autonomous, but mutually influence one another, and the effectiveness of each depends on the coherence of the overall framework.

From this perspective, the present chapter does not seek to provide a descriptive analysis of each instrument individually - an approach undertaken in Chapter 2 - but rather an *integrated analysis of the normative architecture*, aimed at identifying convergences, areas of tension, and the structural

limitations of the European model of governance for the resilience of critical infrastructures. This approach enables a cumulative assessment of the consistency of legal norms, from the perspective of their effects, within an environment characterized by hybrid risks, cross-border interdependencies, and institutional asymmetries among EU Member States.

3.2. From protection to resilience as a normative paradigm

This subsection highlights the shift in the *legal paradigm underpinning* the EU architecture in the field of the protection and resilience of critical infrastructures, whereas the previous subsection analyzed the *normative architecture* from a systemic perspective.

A defining dimension of the current European normative architecture is the *transition* from an approach centred on the *protection of critical infrastructures* to one oriented towards their *resilience* and that of the essential services underpinning the functioning of modern societies. This paradigm shift reflects an adaptation of the EU regulatory framework to the dynamic, interdependent, and systemic nature of contemporary risks, which can no longer be effectively managed through mechanisms aimed at protecting isolated assets.

Directive 2008/114/EC [14] represented an *initial normative effort to regulate the protection of critical infrastructures at European level*, but it operated within a limited conceptual framework. As shown in Chapter 2.4.2, the Directive was centred on the identification and designation of European critical infrastructures in a narrow range of sectors (*transport and energy*) and on the adoption of security measures primarily oriented towards the physical protection of clearly defined assets. This approach was based on a linear risk model, in which threats were exogenous in nature and could be managed through ad hoc protective measures, without fully integrating sectoral interdependencies and cascading effects.

Subsequent technological developments and the expansion of digitalization have meant that major disruptions to critical infrastructures are no longer caused exclusively by direct attacks on physical assets (exogenous causes), but are increasingly driven by operational or digital malfunctions, supply chain disruptions, or combinations of hybrid factors [6, 7, 29], thereby highlighting the *limitations of the previous model* and the *need to reconfigure* the object of regulation.

The CER Directive [10], as shown in Chapter 2.4.4, marks this reconfiguration by *conceptualising resilience as a central legal object*. Accordingly, resilience is defined as a set of capacities - prevention, resistance, absorption, adaptation, and recovery - that enable critical infrastructures to cope with incidents having a significant impact on the provision of essential services. Under this Directive, the normative focus shifts from the protection of critical infrastructures to ensuring the continuous functioning of vital services, regardless of the nature of the threats that may affect them.

Accordingly, the normative approach becomes *functional and dynamic*, as risk is no longer assessed exclusively in relation to a material asset, but rather in relation to a system's capacity to maintain its critical functions under conditions of stress. Complementarily, resilience entails the integration of the physical, digital, organisational, and human dimensions of risk, thereby transcending rigid sectoral boundaries. At the same time, the extension of the scope of the CER Directive to eleven critical sectors reflects a *transversal vision* and the recognition of the *systemic nature* of critical infrastructures.

The paradigm shift brought about by the CER Directive does not amount to a substitution of the protection logic, but rather to its extension into a *multilevel model* in which resilience is understood in terms of the capacities that enable critical infrastructures to withstand incidents with a significant impact on the provision of essential services [15, 21, 35]. In this context, the shifts generated by the CER Directive have led to the *adoption of complementary legal regimes* designed to address operational and technological risks "upstream." This explains the role of the NIS2 Directive and the Cyber Resilience Act (CRA) Regulation within the European normative architecture and provides the foundation for the three-level model that will be analyzed in the following section. Accordingly, *resilience becomes a legal object* that cannot be achieved through a single instrument, but rather through the alignment of the functional level (the CER Directive) with the operational level (the NIS2 Directive) and the technological level (the CRA Regulation).

3.3. The three-level model (entity-system-product) of CER-NIS2-CRA complementarity

The current EU normative architecture in the field of critical infrastructure protection and resilience is characterized by a progressive and functional integration of the physical, organizational, and digital dimensions of risk, materialized in a coherent *three-level normative model: the level of the entity and the essential service, the level of the operational system and networks, and the level of the product and technology.* This structure reflects the recognition of the interdependencies between physical and digital infrastructures and the need for a normative intervention that covers the entire chain of systemic risk.

The *first level* is shaped by the CER Directive [10], which regulates the *issue of the resilience of critical entities* acting as providers of essential services. As shown in Chapter 2.4.4, the Directive operates within a predominantly physical and organisational register, establishing obligations relating to national risk assessments, the identification of critical entities, the adoption of resilience measures, the development of business continuity plans, periodic testing, and reporting and cooperation mechanisms. In this way, a legal framework has been created for *addressing resilience at the level of a socio-technological ecosystem*.

The *second level* is shaped by the NIS2 Directive [11], which provides a *strengthened legal framework for achieving a high common level of cybersecurity* of networks and information systems across the EU. As shown in Chapter 2.4.5, the NIS2 Directive is not strictly limited to the protection of digital infrastructures, but rather establishes an advanced framework for the governance of cybersecurity risks that may compromise the provision of vital services. The detailed obligations concerning risk management, supply chain security, business continuity, incident management, security testing and auditing, as well as the accountability of management bodies, *reflect a shift toward a consolidated approach to the cybersecurity* of network and information systems. In this regard, the NIS2 Directive represents a *transversal instrument for stabilizing* the level of cybersecurity across EU Member States.

In particular, in the *financial sector*, this logic is complemented by the sector-specific *lex specialis* regime established by the DORA Regulation [39]. This instrument does not add a "fourth level" to the model, but rather complements the operational requirements through detailed provisions on risk management, advanced testing, harmonised incident reporting, and the control of risks stemming from ICT third-party service providers. In this way, the *DORA Regulation limits the risk of overlap with the NIS2 Directive* in the financial domain and strengthens the resilience of this systemically important sector with high levels of cross-border interdependence.

The *third level* is introduced by the CRA Regulation [12], which focuses on the security of products and technologies used in critical infrastructures and essential services. As shown in Chapter 2.5.4, the CRA Regulation establishes mandatory security requirements "by design" and "by default" for products with digital elements, applicable throughout their entire life cycle, from design and development to vulnerability management. Through this approach, the Regulation intervenes "upstream", reducing structural risks generated by insecure or vulnerable products that may compromise operational systems and, ultimately, the continuity of essential services.

Overall, the complementarity between the CER Directive, the NIS2 Directive, and the CRA Regulation establishes an *integrated normative framework*, in which the CER Directive addresses resilience at the level of the entity and the essential service, the NIS2 Directive governs cybersecurity risks at the operational level, and the CRA Regulation reduces technological vulnerabilities at the product level. Although the scholarly literature and the institutional documents analysed do not explicitly formulate a unitary normative model structured on three levels, they converge in supporting the premises that underpin an integrated interpretation of the normative architecture [28, 33-35].

The integration of special sectoral regimes, such as the DORA Regulation, demonstrates the capacity of the European architecture to adapt this general model to the specificities of sectors with high systemic importance. At the same time, this normative complexity generates *challenges of legal and institutional interoperability*, including the risk of double reporting and the need for coordination among competent national authorities, making the effectiveness of the model essentially dependent on the conceptualisation of an integrated national governance of resilience.

Table 1 presents a CER-NIS2-CRA synopsis, offering a rapid and structured comparison of the three instruments by highlighting their regulatory object, scope of application, types of obligations, reporting mechanisms, and supervisory regimes, in order to facilitate an understanding of complementarity and areas of intersection within the European normative architecture of resilience.

Table 1. CER–NIS2–CRA Synopsis

Criterion	CER Directive	NIS2 Directive	CRA Regulation
Type of act	Directive (national transposition)	Directive (national transposition)	Regulation (direct applicablity)
Object / purpose	Resilience of critical entities and continuity of essential services (physical + organizational focus, including hybrid risks)	Cybersecurity of networks and information systems (governance, measures, incident reporting)	Cybersecurity of products with digital elements "by design/by default" throughout the entire life cycle
Regulated unit	Critical entity + essential service	Entity (essential / important) + IT/OT systems and networks	Product (hardware/software/solution) + economic operators across the market supply chain
Scope (logic)	Systemic risk and cascading effects on societal functions	Operational cyber risk (organizational + supply chain + continuity)	"Upstream" technological risk: structural product vulnerabilities
Sectors / coverage	11 critical sectors (energy, transport, banking, financial market infrastructures, health, drinking water, wastewater, digital infrastructure, public administration, space, food)	"Essential" and "important" entities in high-importance sectors + other critical sectors (lists in annexes; broader coverage than CER)	Horizontal: products with digital elements placed on the EU market, with exclusions/derogations where sectoral regimes apply
Identification mechanism	Member States: national risk assessment → designation of "critical entities"	Largely based on size/sector + criteria; classification into "essential" vs. "important"	Does not "identify entities": sets compliance conditions for products + economic roles
Key obligations	Risk assessments; resilience measures; business continuity plans; management of incidents with significant impact; exercises/testing; cooperation and information sharing	Minimum risk management measures (policies, incident handling, continuity, supply chain security, testing/audit, cryptography, etc.); management body accountability; incident reporting requirements	Essential security requirements; vulnerability management; technical documentation; secure updates; obligations for manufacturers/importers/distributors; conformity assessment and marking (where applicable)
Reporting	Notifications/information to authorities in the event of significant incidents (within the logic of essential service resilience)	Detailed incident reporting regime (early warning + notification + final report; prescriptive deadlines)	Reporting of vulnerabilities /relevant product incidents (focus on actively exploited vulnerabilities and their management)
Supervision / authorities	National competent authorities + EU cooperation mechanisms	National authorities, CSIRTs, Cooperation Group; differentiated supervision (stricter for essential entities)	Market surveillance authorities + conformity control mechanisms (product-compliance logic)
Sanctions / enforcement	Established under national law (transposition)	Established under national law (transposition), with an orientation toward robust regimes	Direct applicability through market surveillance + sanctions set in national law for infringements (within the logic of the Regulation)
Relationship with the others	Complementary to NIS2: covers end-to-end resilience of services; does not replace cybersecurity requirements	Complementary to CER and operationally intersects many sectors; *lex specialis* applies in certain domains (e.g. financial)	Complementary to NIS2/CER: reduces "upstream" risk (insecure products) that feeds operational incidents and disruptions

The comparative analysis highlights *three major areas of convergence*: a shared orientation toward risk management and the continuity of essential services, moving beyond the logic of point-based protection; complementarity across different layers of risk - the CER Directive at the level of the entity and the service, the NIS2 Directive at the operational and network level, and the CRA Regulation

"upstream," at the product level; and the strengthening of governance through obligations of assessment, reporting, and supervision, with an emphasis on prevention and accountability.

At the same time, the *following situations* of tension emerge: the risk of overlapping obligations and double reporting for highly digitalized critical entities; institutional fragmentation resulting from the multiplicity of competent authorities and supervisory regimes; and asymmetries in administrative capacity across EU Member States. These factors may lead to uneven implementation and to unequal systemic resilience.

At the procedural level, the complementarity of the CER-NIS2-CRA framework often gives rise to *operational tensions*, as the same factual situation may simultaneously trigger distinct legal obligations.

A *first typical scenario* is that of a cyber incident with operational effects within an entity operating in a critical sector (for example, energy or healthcare), where the compromise of an IT/OT system generates both a risk of interruption of an essential service and a significant cybersecurity incident. In such a situation, the logic of the CER Directive directs the response toward ensuring service continuity and notifying the incident to the competent authority responsible for the resilience of critical entities, while the NIS2 Directive activates a prescriptive reporting regime to the national competent authority/CSIRT, with distinct deadlines and formats. In the absence of internal coordination mechanisms (at the entity level) and institutional cooperation (at the national level), there is a risk that the same disruption will be reported in parallel, with partially redundant content, to different authorities, thereby increasing the administrative burden precisely at the moment when response capacity needs to be at its highest.

A *second relevant scenario* concerns the overlap between an operational incident and a product vulnerability. If the incident is facilitated by an exploited vulnerability in a widely used product with digital elements (for example, a software component integrated into control systems or digital infrastructure), a third procedural flow may be triggered: the reporting obligations associated with the CRA Regulation, aimed at notifying actively exploited vulnerabilities and relevant product-related incidents, in parallel with the reporting of the incident by users/operators under the provisions of the NIS2 Directive and with the management of the impact on service continuity under the provisions of the CER Directive. In this framework, a structural tension emerges: the NIS2 and CER Directives are centered on effects at the level of the entity and the service, while the CRA Regulation seeks to control risk "upstream," at the level of the product and economic operators. The lack of procedural articulation between these levels may lead to multiple notifications regarding the same situation, made by different actors (the user entity, the manufacturer, potentially supply chain providers).

A *third scenario*, frequently encountered in practice, arises from the existence of sector-specific *lex specialis* regimes, such as the DORA Regulation, in areas of high systemic importance. In the case of a financial institution subject to the Regulation, an ICT incident may trigger the harmonized reporting and testing regime, while the same entity may, in certain circumstances, also remain subject to the obligations of the NIS2 Directive, and its functioning may be relevant for the continuity of certain essential services within the meaning of the CER Directive.

In light of the foregoing, it can be observed that, despite the EU architecture's aim to *avoid overlaps* through *lex specialis* rules, the plurality of regulatory regimes and competent authorities may give rise, at the national level, to operational fragmentation (reporting to different authorities, partially convergent but procedurally distinct requirements). Consequently, the *issue of double reporting constitutes an inherent risk of multilevel governance*, which must be managed through explicit coordination mechanisms, procedural interoperability, and institutional cooperation.

3.4. Functional convergence between hard law and soft law instruments

A structural element of the European normative architecture in the field of critical infrastructures is the *combination of hard law instruments* (directives and regulations) *with soft law instruments* (strategies, action plans, communications, recommendations). This combination is driven by the fact that primary competences in the field of infrastructure protection lie mainly at the national level - as evidenced by the provisions of the main hard law instruments presented in Chapter 2.4 and Chapter 2.5 - while the

diversity of risks and their administrative governance require a degree of flexibility that these instruments cannot fully provide.

Soft law instruments, such as the EU Cybersecurity Strategy for the Digital Decade [38], *function as mechanisms of guidance and integration,* providing a conceptual framework for the alignment of sectoral policies. They enable rapid adaptation to the evolution of threats and can operate as platforms for convergence among EU Member States, without imposing legal constraints. Moreover, these instruments *facilitate external cooperation and interoperability with international partners*, which is particularly important in a context where risks are transboundary and globalised.

However, *reliance on soft law instruments entails certain problematic aspects*, given their non-binding nature, which may lead to uneven implementation, gaps between necessity and capacity for action, or differences in the prioritization of risks. Accordingly, the role of soft law instruments should be understood as complementary - providing support and coordination - rather than as a substitute for binding rules.

Within the current normative architecture, *soft law instruments maximise their utility when they converge with hard law instruments*, contributing to the operationalisation of normative objectives, the reduction of fragmentation in implementation, and the consolidation of coherent governance of critical infrastructure resilience.

3.5. Coherence, tensions, and structural limits of the normative architecture

Despite the progress made in recent years, the *European normative architecture in the field of critical infrastructures remains marked by structural tensions*.

The *first tension* lies between the need for harmonization at the European level and national competences in the field of critical infrastructures [3, 15, 35]. This limitation is evident in the context in which the CER Directive retains a deliberately non-centralised and non-coercive nature, based on risk assessments and primary national responsibility.

The *second tension* concerns the *integration of physical and digital dimensions* and the risk of regulatory overlap [15, 28, 32]. Although the CER and NIS2 Directives are designed as complementary instruments, in practice the delineation between physical, organisational, and cyber measures may be difficult, particularly in sectors where infrastructure is highly digitalised (such as energy, transport, health, and digital infrastructure). This situation may generate the risk of formal compliance, whereby entities focus on fulfilling procedural requirements without achieving a genuine strengthening of their resilience.

The *third tension* relates to *asymmetries in capacities and resources* [1, 21, 22]. The current normative architecture presupposes the existence of competent national and European authorities capable of conducting complex risk assessments, supervising critical entities, managing reporting obligations, and coordinating incident responses. Given the significant differences among EU Member States in terms of institutional and administrative capacity, there is a risk of entrenching a "multi-speed resilience", in which levels of protection and response capacity remain uneven, ultimately affecting the systemic resilience of the EU.

Finally, a *structural limitation* is determined by the *systemic nature of contemporary risks* [20, 24, 25]: global supply chains, dependence on third-party providers, interdependencies among infrastructures, and the uncertainty associated with emerging risks (technological and climatic) reduce the capacity for anticipatory regulation of vulnerabilities. Under these conditions, the effectiveness of the normative architecture depends not only on the quality of the legal norms, but also on institutional capacities for learning, adaptation, and cooperation among states, agencies, and the private sector in the management of critical infrastructures.

Overall, the European normative architecture for the protection and resilience of critical infrastructures is characterised both by a *significant increase in coherence* and by the *integration of physical and digital dimensions*. It nevertheless remains conditioned by the structural tension between integration and sovereignty, by the risk of fragmentation resulting from uneven implementation, and by the complexity of contemporary systemic risks.

4. Limitations of the study

Although this study pursues a broad and integrated analysis of the EU normative framework on the protection and resilience of critical infrastructures, it is subject to *explicitly acknowledged methodological and analytical limitations*, which stem both from the object of the research and from the constraints necessary to maintain the coherence and depth of the analysis.

A *first limitation* arises from the *predominantly legal-doctrinal and systemic nature of the approach*, which prioritises the analysis of legal norms and governance mechanisms established at EU level, to the detriment of an empirical assessment of their implementation at national level. The study does not include detailed comparative analyses of the transposition of the CER and NIS2 Directives into the domestic law of the Member States, nor does it provide evaluations based on operational data concerning the concrete effectiveness of resilience measures. Consequently, the conclusions primarily address the coherence and normative potential of the European architecture, rather than its practical outcomes.

A *second limitation* is determined by the *relatively early stage of application of the normative framework under analysis.* A significant part of the core instruments (the CER and NIS2 Directives and the CRA Regulation) are either in the process of transposition or in the initial stages of implementation, and for some of them - particularly the CRA Regulation - there is as yet no consolidated implementation experience or relevant case law. This situation limits the possibility of formulating definitive conclusions regarding the actual impact of the normative architecture on the reduction of systemic risks and cascading effects.

Thirdly, the study does not address in depth *parallel or related legal regimes*, such as EU criminal law concerning attacks against information systems, NATO regimes for the protection of critical infrastructures, or mechanisms of cooperation with intelligence agencies. Although these areas are relevant to critical infrastructure resilience, their inclusion would have exceeded the proposed analytical framework and diluted the focus on the EU's normative legal architecture.

Another limitation relates to the *complexity of the concept of resilience*, which combines legal, technical, organisational, and societal dimensions. The present study addresses the resilience of critical infrastructures predominantly as an object of legal regulation and public governance, without engaging in a detailed examination of their technical dimensions, which may influence the perception of the adopted approach.

Finally, the analysis is *constrained by the accelerated dynamics of issues related to critical infrastructures*, characterised by rapid technological developments, the emergence of new threats (including those related to artificial intelligence, automation, and other emerging technologies), and continuous normative adjustments. The conclusions therefore reflect the current normative stage at EU level and may require revision as the regulatory framework is further developed or adjusted.

These limitations do not diminish the relevance of the study; rather, they define its scope of validity and may serve as directions for future research, oriented towards analysing the implementation of the normative framework governing the protection and resilience of critical infrastructures at EU level or within the Member States.

5. Conclusions

The present study was conducted on the basis of the working hypothesis established and the objectives O1-O3 formulated in the introductory chapter, with the *aim of assessing the coherence and functionality of the EU normative framework governing the protection and resilience of critical infrastructures*. The analysis highlights the transition from a sectoral approach to an integrated model oriented towards resilience, the management of systemic risks, and the continuity of essential services.

With regard to *Objective O1*, which is dedicated to mapping the evolution of the normative framework at the EU level in the field of critical infrastructures, the study has identified a *clear transition from a fragmented and sectoral framework* - crystallised around the EPCIP and Directive 2008/114/EC - *towards an integrated architecture* oriented towards resilience and the management of systemic risks, as reflected in the CER and NIS2 Directives and the CRA Regulation. This evolution reflects not only an expansion of the scope and legal instruments, but also a profound conceptual shift in this area.

As regards *objective O2*, the integrated analysis of the current normative architecture made it possible to identify a coherent internal logic based on the *functional complementarity of the core instruments*. Conceptualizing the CER-NIS2-CRA triad as a three-level normative model - entity/essential service, operational system/network, and product/technology - provides a systemic interpretative framework for European normative intervention. The CER Directive strengthens the organizational and physical resilience of critical entities, the NIS2 Directive establishes an advanced regime of cybersecurity risk governance at the operational level, and the CRA Regulation shifts security responsibility "upstream" to manufacturers, through mandatory "by design" cybersecurity requirements throughout the entire life cycle of digital products. The integration of special sectoral regimes, such as the DORA Regulation, demonstrates the model's capacity to be adapted to sectors of high systemic importance.

In relation to *objective O3*, the critical assessment of the structural limits of the normative architecture highlighted the *persistence of several tensions*. The first concerns the balance between European harmonization and national competences, which explains the retention of a significant degree of flexibility in the CER Directive. The second tension derives from physical-digital integration, which, although necessary to address hybrid risks, generates the risk of overlapping obligations, double reporting, and institutional fragmentation. The third limitation consists of asymmetries in administrative and operational capacity among Member States, which may lead to uneven implementation and, implicitly, to a "multi-speed resilience" at EU level.

With regard to the working *hypothesis formulated* in the introduction, the overall conclusion of the study is that the current EU normative architecture, in principle, establishes a *coherent and complementary framework for the protection and resilience of critical infrastructures/entities*. This coherence stems from the alignment of objectives, the shared orientation toward risk management and the continuity of essential services, and the coverage of different layers of physical and digital risk. However, this coherence is predominantly normative and conceptual in nature, with its practical effectiveness being contingent upon national-level implementation and the institutional capacity of EU Member States.

Overall, the study shows that the EU has made *significant progress in the governance of critical infrastructures*, by moving from a fragmented normative framework to an integrated architecture oriented toward resilience and systemic risk management. Nevertheless, the success of this model does not depend solely on the quality of the adopted rules, but essentially on the ability of EU Member States to transpose and apply the requirements coherently, to design and operationalize integrated national coordination mechanisms, and to ensure effective cooperation among authorities, operators, and producers.

By explicitly relating to the working hypothesis and the stated objectives, the *conclusions confirm the study's theoretical and analytical contribution* by providing a systemic analysis of the CER-NIS2-CRA triad as a normative model of European resilience, thereby creating the premises for future research focused on examining the practical implementation of the normative framework at the level of EU Member States, assessing its impact on the reduction of systemic risks, and adapting the normative framework to emerging threats in the decades to come.

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Intelligence Analysis: The Psycholinguistic Signature of the Author in Open-Source Investigations

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Abstract. In an information-saturated environment, where open-source information is abundant, the real challenge for the security of the information ecosystem is no longer access to data, but establishing its anonymous authorship. This paper advances the thesis that, beyond the walls of digital anonymity, the human mind betrays its presence through the involuntary nuances of language. By examining the concept of "psycholinguistic signature", the article highlights a new form of identity, showing that deep cognitive patterns - shaped by lexical choice, syntactic complexity, temporal flow, and emotional markers - exhibit remarkable stability. Even when there are deliberate attempts to manipulate the communicative register or to conceal identity, these linguistic traces remain constant, offering a robust tool for identifying and profiling authors. Psycholinguistic analysis thus emerges as an essential methodology for turning the digital echo into reliable behavioral evidence within the information ecosystem.
Keywords: *open-source*, *information ecosystem, digital anonymity, psycholinguistic analysis*

1. Introduction

In today's geopolitical landscape and contemporary cross-border space, dominated by an exogenous proliferation of data, open-source intelligence (OSINT) investigations have become a critical component of the intelligence cycle. Yet the current paradox is that, although access to information is virtually unlimited, the ability to attribute that information to a real source is increasingly eroded by digital anonymity. When classical investigative techniques - based on metadata, geolocation, or technical network analysis - are bypassed through sophisticated anonymization tools, intelligence analysis, both within intelligence services and among digital investigators, often runs into an "invisible wall". At this point, the traditional toolkit of the intelligence analyst, while technically robust, often reveals a vulnerability: the lack of instruments capable of penetrating the surface layer of text to reach the author's psychological profile.

To overcome this limitation, integrating psycholinguistic perspectives[1] becomes imperative. Psycholinguistics, as the discipline that studies the dynamic relationship between cognitive processes and language use, is not limited to a simple grammatical analysis; it provides the key to understanding how an individual thinks through how they write. Every lexical choice, every syntactic structure, and

[1] Heuer, R.J. (1999). *Psychology of Intelligence Analysis. Center for the Study of Intelligence*, Central Intelligence Agency.

every variation in discourse rhythm represents an imprint of cognitive functioning, one that is difficult to consciously disguise over the long term.

However, exploiting this resource cannot be reduced to the mere use of automated algorithms. The complexity of human nature requires nuanced interpretation, suggesting a subtle reconfiguration of analysis teams. The effectiveness of this approach depends on interdisciplinary collaboration in which the technical expertise of the intelligence analyst or digital investigations expert is complemented by highly specific psychological competence. This implies the need for a psychologist within analytic structures, one trained specifically in psycholinguistic dynamics and behavioral profiling. This specialist, whose contribution is essential yet not ostentatious, acts as a decoder of subtext, transforming raw linguistic data into operational psychological profiles. We argue that only through this synthesis between OSINT techniques and specialized psychological expertise can reliable author identification be ensured, along with a richer understanding of both what can be learned and who stands behind the text.

2. Psycholinguistics: the cognitive architecture of discourse

Psycholinguistics sits at the intersection of higher cognitive mechanisms and the formal structure of language, investigating how intentions, emotional states, and personality traits are encoded in linguistic utterances. In the context of psychological analysis and profiling, it is not treated as a purely descriptive discipline, but as an explanatory one, capable of decoding the "automatic processing" of information behind linguistic content. Reference authors like David Lieberman highlight the principle that language functions as a "projector" of mental state: the more an individual tries to consciously control the message they transmit, the more cognitive leaks appear in the subconscious structure of discourse. Psycholinguistic analysis thus becomes a tool for inferring latent intentions, going beyond mere semantic decoding.

A first analytical dimension is lexical selection. Vocabulary is not random; it reflects the author's attentional focus and emotional state. For instance, the excessive use of abstract nouns and stative verbs, at the expense of concrete action verbs, may indicate a tendency toward emotional distancing or an attempt to lend an appearance of legitimacy to unverifiable claims. By contrast, a lexicon marked by intense connotations, hyperbole, or frequent use of the first-person pronoun "I" (linguistic egocentrism) may signal narcissism, a need for affirmation, or, in the case of threats, heightened emotional engagement with the act[2].

A highly predictive indicator in behavioral profiling is grammatical voice. Shifts from active to passive or reflexive/impersonal constructions are often markers of cognitive dissonance or avoidance of responsibility (reduced agentivity). Consider the following example in the context of denying guilt: the statement "I made a mistake" (active voice) implies direct ownership of agency. By contrast, resorting to "Mistakes were made" (passive voice) or "There was a misunderstanding" (impersonal construction) serves as a psychological defense mechanism, with the author effectively erasing themselves from the equation of action[3]. In intelligence analysis, identifying such shifts in voice within the same narrative is a strong indicator of attempted manipulation or truth concealment.

Likewise, repetitiveness (linguistic iterativity) offers valuable clues about the sender's cognitive architecture. Here we do not mean intentional rhetorical repetition, but repetitions that function as blockages or mental anchors. Repeating certain keywords or phrases - especially under pressure or during moments of narrative transition - can signal fixation points in an obsessive thought scheme or difficulties processing contradictory information. For example, repeatedly returning to a particular detail that is irrelevant to the broader context (cognitive perseveration) may betray a specific anxiety tied to that detail, acting as a "blind spot" the analyst should exploit.

[2] Pennebaker, J.W. (2011). *The Secret Life of Pronouns: What Our Words Say About Us*, Bloomsbury Press.
[3] Newman, M.L. et all (2003). *Lying Words: Predicting Deception from Linguistic Styles. Personality and Social Psychology Bulletin 29(5),* SAGE Publications.

3. Psycholinguistic fingerprint: the stability and uniqueness of cognitive indicators

If psycholinguistics provides the theoretical framework needed to understand the mechanisms of language, the concept of a psycholinguistic fingerprint represents the practical applicability of that framework in source identification and attribution. Defined as a complex set of linguistic and cognitive markers that are relatively stable over time, the psycholinguistic fingerprint functions analogously to a digital fingerprint, but at the level of information processing and verbal expression[4]. In OSINT investigations, this fingerprint becomes the keystone for overcoming anonymity, enabling both intelligence analysts and expert psychologists to link disparate digital identities through a behavioral constant invisible to the untrained eye. The fundamental difference between conventional content analysis and an approach based on the psycholinguistic fingerprint is that the latter does not look for what is said, but for how the message is processed and constructed, revealing the individual uniqueness behind the text[5].

A central postulate in using the psycholinguistic fingerprint as an intelligence tool is the idea of cognitive inertia. Deep patterns of thought - how an individual structures an argument, orders ideas in space and time, or reacts to emotional stimuli - are crystallized during early language development and remain relatively resistant to later change. When an author attempts to falsify a text, for example by writing in a non-native language or by imitating an ungrammatical style to appear uneducated, they can readily focus on superficial aspects such as spelling or basic syntax. Yet the cognitive effort required to alter deeper patterns - such as the complexity of idea hierarchies or the underlying causal logic - is immense; thus, beneath the layer of deliberate masking, the true psycholinguistic fingerprint persists and can be detected by analyzing rhythm fluctuations and the consistency of logical structures.

This cognitive inertia manifests through specific dimensions which, taken together, compose the unique "texture" of the fingerprint, going beyond simple stylometric analysis or word-frequency counts, which can be easily manipulated with automated tools. One dimension is the temporal profile of discourse - the narrative's so-called "internal clock": some authors tend to compress time, using many perfective past forms and moving quickly from cause to effect, while others dilate it, focusing on detailed descriptions and using imperfective past forms to create a static scene. Closely related is the structure of agentivity, where a chronic preference for certain voices becomes a personality marker: some individuals display low agentivity, frequently externalizing themselves from action through passivization, indicating an avoidant style, while others demonstrate excessive agentive control, characteristic of dominating or authoritarian thinking[6]. In addition, the way the author links sentences - cohesion and local coherence - completes the picture: fragmentary coherence with frequent logical jumps suggests an associative thinking style, whereas rigid, linear cohesion indicates systematic thinking. These traits are extremely difficult to synthesize artificially, whether by an algorithm or by a casual imitator.

In open-source investigations, extracting a psycholinguistic fingerprint must allow the construction of a reference profile (baseline profile) that serves as a standard for comparison. Once this profile is established on the basis of a text corpus - such as forum posts under a known identity - it can be overlaid onto other anonymous corpora to identify matches. Identity validation does not rely on the presence of a single keyword, but on the statistical convergence of multiple fingerprint dimensions: the same distribution of grammatical categories, the same preferences for phrasal structures, and, most importantly, the same psychological "voice". Therefore, the psycholinguistic fingerprint transforms text from a mere vehicle of information into forensic evidence, capable of supporting or refuting

[4] Coulthard, M., Johnson, A. (2007). *An Introduction to Forensic Linguistics: Language in Evidence*, Routledge.
[5] Juola, P. (2006). *Authorship Attribution. Foundations and Trends in Information Retrieval*, Now Publishers.
[6] Fast, D.C. et all. (2008) Personality as Manifested in Word Use: Correlations with Self-Report, Acquaintance Report, and Observer Report in *Journal of Personality and Social Psychology 94(2)*, American Psychological Association.

hypotheses about attribution of actions in cyberspace, thus offering a robust solution to the problem of anonymity in the digital age.

4. From signature to attribution: operationalizing psycholinguistic analysis in OSINT

Translating a psycholinguistic fingerprint into actionable attribution requires a disciplined workflow that combines linguistic inference with corroboration from other open-source signals. In practice, the goal is not to "name" an author from a single text, but to establish a defensible linkage between corpora: to show, with measurable confidence, that two or more bodies of writing are likely produced by the same cognitive system.

The operational starting point is corpus construction. Investigators should collect a representative baseline set of texts from a known identity (the *reference corpus*) and a set from the target, anonymous identity (the *questioned corpus*), while controlling for topic, genre, and platform constraints as much as possible. Preprocessing matters: preserving original punctuation, paragraphing, and revisions can be essential because these features often carry stable cues. When translation is unavoidable, analyses should be performed primarily on same-language samples, since translation can flatten stylistic variance and reduce the diagnostic value of syntactic markers.

Next comes feature extraction across multiple layers of language. At the surface level, analysts can quantify function-word patterns, preferred discourse connectors, pronoun ratios, and morphological choices. At the structural level, they can evaluate sentence-length distributions, clause embedding, agentivity preferences (active vs. passive), and coherence strategies (linear argumentation versus associative jumps). At the psychological level, they can track affective loading, certainty markers, threat proximity, and repetition under pressure. The strength of the method lies in convergence: a single indicator is rarely decisive, but a consistent cluster across layers is difficult to fabricate and harder to sustain over time.

For intelligence purposes, attribution should be treated as probabilistic and auditable. Analysts should document which markers were stable, which were context-dependent, and how strongly each marker discriminated between candidate authors. Where possible, apply cross-validation: test the baseline profile against unrelated texts by the same known author and against texts from plausible alternatives. This reduces false positives and helps identify when an apparent match is driven by topic rather than by cognitive style.

Finally, psycholinguistic evidence should be triangulated with complementary OSINT signals - posting schedules, platform affordances, interaction patterns, and recurrent situational details - without allowing any one channel to dominate. Ethical and legal constraints are central: psycholinguistic profiling can be intrusive and can amplify confirmation bias if used carelessly. A multidisciplinary review process, in which the analyst's technical assessment is paired with a psychologist's behavioral interpretation, is therefore not a nice-to-have, but a safeguard that improves both accuracy and accountability.

5. Conclusion

Finally, this paper shows that, both in the dynamic context of information-field security and within the cybersecurity framework, the open information ecosystem requires a reconfiguration of classical investigative methods. Through its exploratory approach, the study underscores the need to integrate and recalibrate the way open-source investigations are conducted and beyond. Exploring the concept of the "psycholinguistic signature" has highlighted its potential to serve as an identifying anchor in the volatile context of information security.

To move from the theoretical identification of the patterns mentioned above to their operational application, it is imperative to adopt a multidisciplinary approach that directly bridges information technology and the behavioral sciences. In this context, the need to develop, within the psychology paradigm, a new generation of specialists becomes critical.

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The Significance of the Allegorical and Symbolic Register, Including Their Polarity within Painting

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Abstract. Allegory and symbol are analyzed as fundamental instruments for communicating moral and spiritual concepts, marked by a structural interdependence throughout art history. While the symbol is defined as a unitary and transcendent revelation of the absolute - reaching its peak in Romantic mysticism - allegory takes shape as a narrative and material structure used to humanize abstract ideas. Although abstract modernism marginalized allegory in favor of symbolic purism and an escape from the mundane, postmodernism rehabilitates it through what Craig Owens terms the "allegorical impulse." This return transforms allegory into a critical tool for deconstruction, abandoning the illusion of aesthetic autonomy to re-engage visual discourse with the complexity of social and historical reality.
Keywords: *Allegory; context; significance (or meaning); symbol; structural.*

Introduction

The relationship between allegory and symbol represents one of the recurring themes in the theoretical reflection on the artistic image, as these two registers constitute essential means through which visual art conveys complex meanings of a moral, spiritual, or conceptual nature. Throughout the history of art, they have been examined both in opposition and in complementarity, generating an interpretative framework in which the image surpasses its simple representational function and becomes an instrument for articulating abstract ideas. Allegory operates through a discursive and narrative structure in which multiple visual elements construct an extended meaning, while the symbol tends to condense significance into a unitary form oriented toward the revelation of a transcendent dimension. At various historical moments, the status of these two concepts has undergone significant transformations, from the predominance of allegory within the figurative tradition to the valorization of the symbol in the aesthetics of Romanticism and modernity. Nevertheless, contemporary artistic discourse demonstrates a reactivation of the allegorical mechanism, reinterpreted as a critical instrument capable of interrogating cultural and social reality. In this context, the present study aims to analyze the structural interdependence between allegory and symbol, highlighting the manner in which these two registers participate in the configuration of meaning within the artistic image.

I. The Framework of Allegory in Historical Perspective

A colossal volume within the collective memory of humanity is comprised of storytelling - a milieu that portrays a framework of art incomparable in its mastery and serves as a determining element in the process of self-knowledge. Throughout history, mankind has embraced the act of storytelling, crafting this framework through a broad palette of forms: from the literary realm to the performing arts, through narration and musical contexts, to visual conception or distinctive non-oral methods.

It must be noted that Allegory is considered one of the most effective elements employed for the disclosure of a particular narrative or idea. The term originates from Latin, constituting a description of a 'hidden language.' In the same semantic vein, Allegory relates or indicates a certain presentation - usually a meticulously 'packaged' concept or moral - whose meaning is distinct from what is overtly displayed, requiring, at the same time, a pause for research and careful decoding.

In this context, specialized literature utilizes a far more extensive palette of sources compared to other arts, particularly invoking the spectrum of semantic figures of speech, such as epithets, similes, hyperboles, metaphors, and so forth. Within the visual arts - specifically on the path of painting - creators have opted for the allegorical range to convey plurivalent concepts, such as the existential plane, love, virtue, morality, ethics, or justice, through symbolic elements and metaphors of a plastic and aesthetic nature. Unequivocally, Allegory possesses the potential to be interpreted as a veiled meaning, intended to be deciphered by the 'reader' of the image.

Ultimately, Allegory manifests as a stance, a specific technique, a body of knowledge, or a process; in this context, it emerges whenever a text is seconded by another text at a different level. Furthermore, allegories can be presented as artistically framed figures of speech mediated through distinctive yet complementary expressive elements, which prompt a 'vertical' reading - paradigmatic 'filters' that establish new concordances on the horizontal segment, separate from common interpretations. Moreover, it could be considered that Allegory achieves a detachment into other classes or even subject matters, indicating that an allegorical elaboration is summative, capable of transcending even the boundaries of the aesthetic. It possesses the potential to encompass the emotional realm, capitalizing on flaws, affiliations, or partial information.[2]

"Allegory has been widely used throughout history not only in painting and sculpture but in all forms of art. Graphics (and especially printmaking) represented a plenary medium of expression through allegory. A major reason for this is its immense power to illustrate complex ideas and concepts in ways that are both easily decipherable and, at the same time, tangible for the viewers of each period" (Răzvan-Constantin Caratănase, *A History of Romanian Graphics: Notions, Concepts, and Principles*, 2025, p. 61). This citation highlights the role of printmaking as a primary, accessible medium for allegorical expression.

We began by specifying Allegory within the field of literature because it has been constituted, and continues to be, as a primordial or equally significant source for providing the accepted cases within the visual arts.

The sphere of visual arts is excellently suited for considering the allegorical segment, as an image allows for a focused narration of a story while remaining accessible to the person interacting with the work. Certainly, these allegorical images often incorporate elements, characters, or symbols that humanize various affective reactions, such as envy, greed, impetuosity, love, and so forth. Spiritual symbolism is frequently rendered in the form of a flower, a bird, or a ray of light.

From the inventory of allegorical subjects across various geographical meridians and eras, such works were commonly produced in painting from the Renaissance until the mid-19th century - a considerable interval during which Allegory reached its peak of fame. On the other hand, a substantial number of such creations have been perceived as having esoteric or imprecise content by contemporary audiences; this is because such compositions are conditioned by the viewer's ability to recognize them, an ability to decode that not everyone retains over time. Against this backdrop of interpretative subjectivity, their meanings often suggest a sequence of speculative elements and constant contradictions.

A prime example of this would be Sandro Botticelli's (1445-1510) famous work, 'Primavera,' which is revered by the general public even without specific cultural training; nonetheless, viewers possess the capacity to observe the staging of the characters, the rendered atmosphere, the harmony, and other aspects. Furthermore, it is worth noting that even his contemporary audience did not necessarily benefit

[2] Craig Owens, *The Allegorical Impulse: Toward a Theory of Postmodernism*, în „MIT Press Journal Article", vol. 12 (Spring, 1980), p. 67, online: https://www.jstor.org/stable/778575

from the formal training required to perceive the nature of the meanings embedded within this splendid allegory.

Following the aforementioned example, creators have continued to resort to allegory up to the present day, just as numerous precedents existed prior to the Renaissance. It is necessary, however, to point out that there are specialized voices capable of bringing the purpose of allegory to light, especially since there is an immeasurable volume of examples spanning several centuries.

The famous work 'Guernica' by the illustrious artist Pablo Picasso presents a series of symbols that are generally not deciphered by the public. These can only be decoded if the viewer possesses knowledge regarding the Spanish Civil War (1936-39), specifically the bombing of the town of Guernica in the Basque Country (April 26, 1937) - the very year the artist created this work as an overt manifesto. This creation incorporates symbols of prehistoric origin (from cave paintings, such as the bull, rendered in a Cubist manner through the 'distortion' of perspective) or symbols correlated with a subjective mythological framework, belonging to a personal lexical fund of signs that later became world-renowned alongside the international recognition of the artist's work. Thus, such symbols were absorbed into the compositional register, specifically within the 'galaxy' of allegories.

Craig Owens, one of the most reputable art critics, identified the foundation of the Postmodernist movement, decisively labeling it an 'allegorical impulse.' He maintained that restructuring and recoding establish a prominent effect in our contemporary era in relation to a new work. Furthermore, he argued that it is nearly impossible to realize an artistic creation that remains authentic as long as the traditional (classical) modes of expression remain unchanged. The emergence of such authentic creations might be possible - though certainly not in all circumstances - most likely within new media, aided by increasingly advanced technologies, potentially correlated with the framework of artificial intelligence; however, these directions lie beyond the scope of the present study.

To reiterate, the postmodernist operation with fragments (sections) exceeds the exploration of a complete ensemble (of a symbolic nature), just as the framework of seriality supersedes uniqueness (of the artistic creation), which was once regarded as an irrevocable, finalized form. This line of thought established the framework for the characteristic implementation of allegory in the visual arts, displacing it from its traditional sphere - namely, literature. In other words, the inclusion of the post-structuralist concept in accordance with this argumentative endeavor facilitated the innovative transposition of the concept of allegory into the realm of visual arts, operating a necessary distinction from its traditional literary content. The process consists in assuming the post-structuralist paradigm, according to which the act of receiving a text is not static; on the contrary, the interaction between the reader and the work generates polysemic meanings and distinct effects[3], conditioned by the variability of the temporal and subjective context.

Establishing a precise ontology of allegory imperatively requires relating it to the concept of the 'symbol' - a term with which it maintains a semantic proximity that is often a source of confusion. In contemporary theoretical discourse, the two notions are frequently correlated, with allegory not uncommonly perceived as an extension or as a specific mode of manifestation of the symbolic[4].

II. **The Context of the Symbol**

The analysis of the previously mentioned examples reveals a structural interdependence between the two registers: allegory often encapsulates the valences of the symbol, just as the latter can constitute the foundation or the catalyst of allegorical architecture.

Analogous to allegory, the nature of the symbol constitutes the object of vast exegesis. In the view of Ananda Coomaraswamy, symbolism represents the 'art of thinking in images' - a faculty that modern man seems to have lost over the last three centuries, a phenomenon that occurred, perhaps, as a consequence of the *'catastrophic theories of Descartes.'*[5]. However, research in the fields of

[3] Joel D. Black, *Allegory Unveiled*, în *Poetics Today*, nr. 4(1), 1983), p. 112
[4] Angus Fletcher, *Allegory: The Theory of a Symbolic Mode*, Ed. Princeton University, 2021
[5] Coomaraswamy shares the perspectives of Erich Fromm and Harold Bayley, authors who theorized these aspects in theoretical works with explicit titles such as *The Forgotten Language* and *The Lost Language of Symbolism*, respectively

anthropology and psychoanalysis demonstrates that this atrophy is confined solely to the conscious plane; the subconscious, as Juan Cirlot emphasizes, seems to have compensated for this centuries-old deficiency through an exuberant repression, becoming an overloaded repository of symbolic structures.[6].

In the visual plane, masterpieces such as Hieronymus Bosch's *The Garden of Earthly Delights* exhibit a remarkable symbolic density; however, their power derives from their integration into a compositional architecture that configures a consummate allegorical model. In contrast, in the case of contemporary visual replicas or citations - such as the re-reading of Bosch's work proposed by Lluís Barba - the symbolic detail migrates toward the foreground, acquiring an anecdotal valence. In this context, the compositional solutions (and, by extension, the allegorical mechanism) remain beholden to the matrix established by the Dutch master, allowing the symbol to function autonomously.

A distinct paradigm is offered by William Blake who, in the pure spirit of Romanticism, built a parallel mythology grounded in a personal hermeneutics. His creation, at once fascinating and hermetic, is intrinsically symbolic, rejecting the structured rigor of allegory.

Viewed through the lens of stylistic succession, the supremacy of the symbol was consecrated by the Romantic era. The thinkers of this movement postulated that the symbol represents the sole vehicle through which the artistic imagination achieves plenitude. From this perspective, allegory was demoted to the status of a mere artifice - a conventional mechanism that risked altering the purity of the work. Following this theoretical decline, allegory began to be perceived as a form lacking phenomenological authenticity, reduced to a repertoire of signs and technical procedures - a vision that has survived, with remarkable persistence, from the nineteenth century into contemporary discourse.[7]

"Among the characteristics of Romanticism, we include: the exaltation of nature, captured in the Kantian guises of the 'beautiful' and the 'sublime'; the exaltation of the artist as the supreme individual creator, whose creative spirit is more important than the strict adherence to formal rules and traditional procedures; the prevalence of emotion over reason and of the senses over the intellect; the revaluation of the self; the exploration of mental states; the preoccupation with genius, heroes, passions, and inner struggles." (op. cit., Aura Evelina Radu, *Analysis of Visual Art Elements*, Eurostampa Publishing House, Timișoara, 2024, p. 67)

The revaluation of William Blake's work in the 1930s exerted a catalytic influence on the Neo-Romantic group, represented by prominent figures such as Graham Sutherland, Paul Nash, John Piper, John Craxton, and Keith Vaughan. These artists assimilated Blake's mystical visions, transposing them into a visual language marked by a metaphysical sensitivity toward the landscape. Blake's famous axiom - the possibility of glimpsing an entire universe captive within a grain of sand - constituted the aesthetics of these creators, leading them to explore and cultivate the intrinsic poetic valences of the natural world, perceived as a repository of profound spiritual meanings[8].

III. **The Duality Between the Allegorical and Symbolic Registers**

The antithesis between symbol and allegory has been a subject of reflection since Antiquity, with Platonic dialogues providing a fundamental reference point in this regard, through which allegory was invested with the status of a superior artistic form.

From a structural perspective, allegory can be defined as an extended or sustained metaphor. While the symbol is distinguished by a unitary character and a vocation for transcendence, allegory takes shape as an open, predominantly narrative device. Within this mechanism, a plurality of images or emblems resonates with an external referent which, in turn, possesses a multiple nature and an intrinsic complexity.

In contrast to the polysemantic nature of allegory, the symbol functions as a unitary sign, establishing a one-to-one (biunique) metaphorical relationship with its referent. It is governed by the attributes of clarity and conciseness, being frequently associated with aesthetic grace or radiance by virtue of specific

[6] Juan Eduardo Cirlot, *A Dictionary of Symbols*, Ed. Routledge, 1962, London, p. 30
[7] Glenn Adamson, *Craft and the Allegorical Impulse*, articol în André Gali; Knut Astrup Bull, *Material Perceptions: Documents on Contemporary Crafts No. 5*, Ed. Arnoldsche, 2018, p. 15
[8] https://www.tate.org.uk/visit/tate-britain/display/ancients-and-moderns-legacies-william-blake

cultural conventions. In the economy of the symbol, the particular element is not a mere phantasmal projection or a 'shadow' of reality, but constitutes an immediate revelation of the general, providing access to an otherwise ineffable dimension of knowledge.[9]

Walter Benjamin stated that: *"allegory offers the dark background against which the bright world of the symbol might stand out. By its nature, the symbol is multivalent, uniting two or more meanings."* To also quote the literary theorist William Empson, *"the effect of allegory is to keep the two levels distinct in the mind, though they interpenetrate in numerous details."*.[10]

In alignment with the aforementioned accounts, W.B. Yeats stated that: "a symbol is the only expression of an invisible essence, a transparent lamp which reveals the spiritual flame; while allegory is one of many possible representations of an embodied thing, which belongs to fancy and not to imagination.[11]

The antithesis between allegory and symbol is accurately reflected in the dissonance between the figurative tradition - be it naturalistic or mimetic - and the modernist abstractionism of the twentieth century. Allegory remains intrinsically linked to the materiality of representation and to the status of the work as a finite, empirical object. For instance, in Jacques-Louis David's study, *Allegory of the French People Offering the Crown and Sceptre to the King*, the expressive potential of the paper support is exploited not merely as a simple receptacle, but as a constitutive element of the visual discourse.

Furthermore, allegory obstinately asserts its condition as an artifact; it emphasizes that the image is a product of the intellect, a construction that does not claim to belong to the objective world, but to the sphere of conscious representation. In contrast, symbolic art tends toward an elusion of the material component. In this case, the artistic will seeks to transcend the physical support, so that the work is no longer perceived as an object, but as an epiphany or a vehicle for a spiritual reality that transcends its own material presence.[12]

The divergence between the two paradigms is eloquently illustrated by the antithesis between the compositions of Jacques-Louis David - articulated through complex narratives and engaged in the socio-political issues of the era - and the visions of modernists such as Piet Mondrian or Mark Rothko. In the case of the latter, the image is governed by an organic unity and a depth that exclusively invokes the aesthetic and spiritual dimension. Allegory, by its very nature, refuses to offer what constitutes the essence of the aforementioned works: that self-referential and autonomous escape from the contingencies of the mundane.

While in Mondrian's *Composition with Red, Large Blue, Yellow and Black*, we witness an 'immaterial' and transcendent use of the symbol - where pure form becomes the vehicle of the absolute - the replica proposed by Lluís Barba recontextualizes this heritage in a postmodern key. Thus, a mutation occurs from the autarchic symbol to the 'social' allegory; the work no longer aspires to an atemporal reality but becomes a critical mechanism that interrogates art history and the structures of contemporary society.

The significance of allegory can be interpreted through the lens of a lateral movement, a semantic excursion that deviates from the vertical axis of univocal meaning. This discursive nature explains the marginalization of allegory within Modernism - a movement that privileged the verticality and purism of Abstract Expressionism - but equally grounds its rehabilitation within the paradigm of Postmodernism. In this new context, the allegorical subject is embraced as a tool for deconstruction, intended to negate the 'false promise' of the visual sign's autarchy. Thus, through the recourse to allegory, postmodern art refuses the illusion of the image's absolute dominance and opts for a re-engagement of the aesthetic act within the social sphere, re-establishing the connection between representation and the contingencies of reality.

Allegorical significance can be circumscribed within a lateral dynamic, constituting a hermeneutic excursion that refuses the point-like concentration of meaning in favor of a discursive expansion. This

[9] Goethe, apud. Susan Skinner, *Symbols of the Soul: Sacred Beasts,* Ed. Circle Books, 2012, p. 11
[10] Walter Benjamin și William Empson, apud. Glenn Adamson, ibid., pp. 15-18
[11] Bainard Cowan, *Walter Benjamin's Theory of Allegory*, în „New German Critique 22" (Winter, 1981), p. 111
[12] Termed, in his/her terminology, as Alois Riegl, *„kunstwollen".*

centrifugal nature explains the exclusion of allegory from the Modernist canon - a paradigm that privileged the autarchy and purism of Abstract Expressionism[13] - while simultaneously becoming fundamental to its recovery by Postmodernism. Within this new theoretical framework, the allegorical impulse is embraced as a deconstruction strategy, intended to denounce the 'false promise' of immanence and the absolute dominance of the visual sign. Through the recourse to allegory, postmodern art abandons the illusion of aesthetic autonomy and opts for a necessary re-engagement on the social plane, re-establishing a fertile dialogue between the image and the complexity of external contingencies.

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[13] Glenn Adamson, *Thinking Through Craft*, Ed. Bloomsbury Academic, 2007, p. 40

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The Concept of Taxation Efficiency Benchmarks and Considerations

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Abstract. Taxation is the primary mechanism through which governments generate revenue to fund public services and maintain economic stability. Traditional concepts of fiscal efficiency focus on maximizing revenue while minimizing economic distortions and administrative costs. However, an exclusive emphasis on revenue, as illustrated by the Laffer Curve, may neglect the distributional consequences of tax policy. This study integrates a revenue-oriented perspective with measures of income inequality, using Lorenz curves and Gini coefficients to analyze Romania's income distribution from 2020 to 2024. The analysis highlights the trade-offs between revenue maximization and social equity, showing that improvements in tax collection efficiency do not automatically translate into equitable outcomes. Findings indicate that while targeted fiscal policies can optimize revenue, attention to income distribution is critical for achieving overall economic efficiency and fairness. The combined approach underscores the importance of designing tax systems that balance instrumental efficiency with equity considerations, providing a framework for policymakers to assess both fiscal and social outcomes.
Keywords: *tax efficiency, Laffer Curve, public revenue, fiscal pressure.*

Introduction

The concept of taxation efficiency is often interpreted in terms of the state's capacity to collect budget revenues and ensure taxpayer compliance. This instrumental approach treats taxation exclusively as a mechanism for maximizing public revenues. This paper analyzes the limitations of this perspective, discusses the role of the Laffer Curve in fiscal theory, and examines Romania's position relative to European Union member states through a comparative analysis of tax revenues as a percentage of GDP. The study highlights that fiscal efficiency must be assessed within a broader framework that includes budgetary sustainability, social equity, and the state's ability to finance essential public goods.

Taxation represents the primary mechanism through which governments secure the resources necessary for their functioning and provision of public services. In traditional economic theory, fiscal

efficiency is often defined by a system's ability to collect sufficient revenues with minimal economic distortions and low administrative costs.

This perspective attributes an exclusively instrumental value to taxation, where its main function is revenue generation. Within this context, the Laffer Curve becomes a central theoretical tool, proposing a relationship between tax rates and total tax revenues.

However, modern fiscal policy realities extend beyond this strictly technical framework, as taxation also influences income distribution, investments, social cohesion, and long-term economic stability.

The concept of efficiency in taxation often assumes a purely instrumental role of taxes, focusing on their capacity to generate government revenue rather than broader economic or social objectives. In this perspective, taxation is treated primarily as a mechanism for maximizing budgetary income and ensuring the strict fulfillment of fiscal obligations (Musgrave & Musgrave, 1989; Tanzi, 1992).

The Laffer Curve, introduced by Laffer (1974), exemplifies this approach by illustrating the relationship between tax rates and revenue, emphasizing only the first of these objectives—revenue maximization—without explicitly addressing considerations of economic efficiency or distributional equity. According to this framework, there exists a tax rate beyond which increasing rates actually reduce revenue, highlighting the instrumental nature of taxation as a tool for revenue optimization rather than a broader policy instrument for efficiency or welfare.

While the Laffer Curve emphasizes the revenue-maximizing aspect of taxation, it does not address the distributional consequences of tax policies. To evaluate the broader economic impact of taxation, it is essential to consider how revenue-raising instruments affect income distribution across different segments of the population. In this context, Lorenz curves provide a visual representation of cumulative income shares, illustrating how taxation and other fiscal policies influence inequality. The associated Gini coefficient quantifies the deviation from perfect equality, allowing policymakers to assess not only the revenue implications but also the social and economic efficiency of tax systems (Lorenz, 1905; Clementi, Gallegati, & Kaniadakis, 2016). By combining the revenue-focused perspective of the Laffer Curve with Lorenz-based measures of inequality, analysts can better understand the trade-offs between maximizing fiscal income and promoting a more equitable distribution of wealth. This integrated approach highlights that an exclusive focus on revenue can inadvertently exacerbate disparities, underscoring the importance of designing tax policies that balance instrumental efficiency with social equity.

1.1. Fiscal Efficiency as an Instrumental Value

In its classical interpretation, fiscal efficiency pursues two main objectives: maximizing budget revenues and ensuring effective tax compliance. A system is considered efficient if it generates large revenues with minimal administrative costs and high compliance levels.

However, this perspective neglects the redistributive and social effects of taxation. A tax system can be technically efficient yet exacerbate inequalities or underfund essential public services. Therefore, collection efficiency does not always equate to overall social welfare.

Formulated in the 1970s, the Laffer Curve suggests that there exists an optimal tax rate that maximizes tax revenues. At a 0% tax rate, revenues are zero, and at an extreme 100% rate, economic activity is discouraged, leading again to low revenues.

The model highlights that excessively high rates may reduce the tax base by discouraging work, investment, and compliance. However, the theory focuses solely on revenue dimensions and does not consider how revenues are used or their impact on development.

The concept of tax efficiency often focuses on the instrumental purpose of taxation, treating taxes primarily as a mechanism to generate government revenue while ensuring compliance with fiscal obligations (Musgrave & Musgrave, 1989; Tanzi, 1992). In this perspective, taxation is viewed less as a tool for promoting social welfare and more as an instrument for maximizing budgetary income.

The *Laffer Curve* (Laffer, 1974) exemplifies this revenue-centered approach. It illustrates that tax revenue initially rises as tax rates increase, but beyond a certain threshold—denoted t∗t^*t∗—further increases in the tax rate actually reduce total revenue. This phenomenon occurs because excessively high tax rates diminish the taxable base through behavioral responses, such as reduced labor supply or investment.

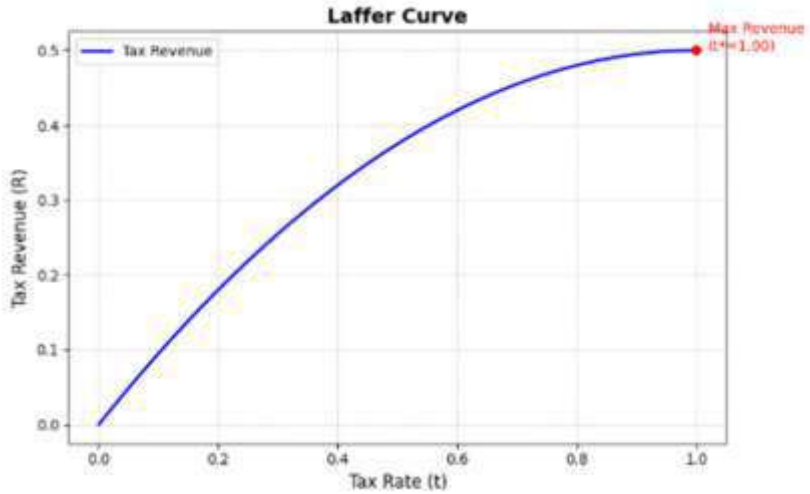
Mathematical Representation
A simple representation of the Laffer Curve is:

$$R(t) = t \cdot B(t)$$

Where:

- R(t)R(t)R(t) = total tax revenue as a function of the tax rate ttt
- ttt = statutory tax rate ($0 \leq t \leq 1$)
- B(t)B(t)B(t) = tax base (which depends on ttt; typically decreasing as ttt increases due to behavioral responses)

The revenue-maximizing tax rate t∗t^*t∗ is defined by the condition:



- Axă X: Tax Rate ttt (0–100%)
- Axă Y: Tax Revenue R(t)R(t)R(t)
- Curba albastră arată cum venitul fiscal crește, atinge un maxim (t∗t^*t∗) și apoi scade.
- Punctul roșu marchează Max Revenue cu t∗t^*t∗ (reprezentând rata de impozitare care maximizează veniturile).

While the Laffer framework emphasizes revenue maximization, it does not consider the distributional effects of taxation. To capture these effects, Lorenz curves and the Gini coefficient are widely used in economic analysis. Lorenz curves visualize the cumulative income share held by different segments of the population, while the Gini coefficient quantifies the degree of inequality (Lorenz, 1905; Clementi, Gallegati, & Kaniadakis, 2016). Integrating the revenue-focused perspective of the Laffer Curve with Lorenz-based measures allows analysts to evaluate both the instrumental efficiency and the equity impact of tax policies.

This approach underscores the trade-off between maximizing government revenue and promoting a more equitable income distribution, highlighting the importance of designing tax systems that balance fiscal, economic, and social objectives.

1.2. Empirical Interpretation of Lorenz Curve Patterns

Although detailed raw income distribution data (e.g., by decile) are not provided here, summary statistics and related interpretations allow us to reconstruct an approximate narrative of how the Lorenz curve would differ year by year:

In 2020–2021, with Gini values near 34, the Lorenz curve would have exhibited larger deviations from equality, with the bottom deciles receiving a relatively smaller share of total income.

By 2023, with the Gini subsequently reduced to around 31, the curve suggests greater income dispersion narrowing, whereby lower percentiles gained a slightly larger share relative to higher percentiles.

In 2024, with the Gini estimated near 28—the lowest in over a decade—the Lorenz curve likely shows the smallest gap from the line of equality within the 2020–2024 period, implying more equitable distribution than earlier in the decade.

In practical terms, these shifts reflect that the share of total income earned by the poorest segments of the population has increased modestly, while the richest segments accounted for a smaller share than in previous years. This trend is consistent with analyses noting growth in the middle class and reduced polarization between upper and lower income groups.

1.3. Discussions and results

Fiscal Revenue Collection in the European Union

A commonly used indicator to analyze fiscal pressure is the ratio of tax and social contribution revenues to GDP. Recent Eurostat data indicate that the average tax-to-GDP ratio in the EU was approximately 40.4% in 2024.

However, significant disparities exist among member states. Nordic and Western European countries exceed 45% of GDP, reflecting social models based on extensive public services, whereas Central and Eastern European states, including Romania, fall below the EU average

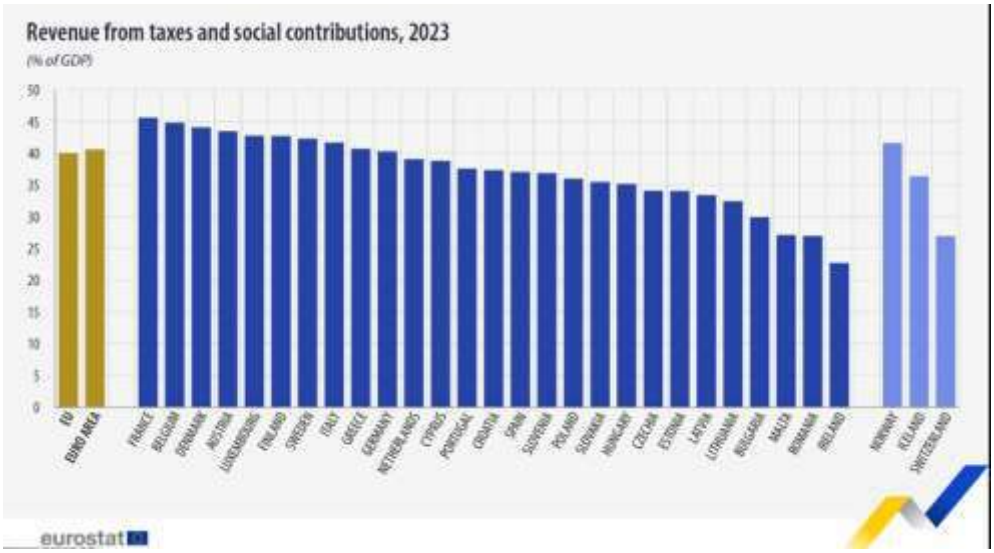
Romania recorded a tax revenue ratio of approximately 28.8% of GDP in 2024, placing it among the lowest in the EU and more than 11 percentage points below the European average

Country	**% of GDP**
Denmark	45.8
France	45.3
Belgium	45.1
Germany	41.9
Italy	41.7
Spain	39.0
Poland	34.0
Hungary	35.0
Bulgaria	31.5
Malta	29.3
Romania	**28.8**
Ireland	22.4
EU average	**40.4**

Date agregate Eurostat: în 2024, media UE pentru taxele și contribuțiile sociale ca procent din PIB a fost de 40.4%. România rămâne sub această medie și printre cele mai scăzute ponderi din UE

These differences reflect not only varying tax levels but also collection efficiency, the size of the informal economy, and tax structure. Romania relies more heavily on indirect taxes, which can have regressive effects on lower-income populations.

Figure 1. Comparison of Tax Revenue as a Percentage of GDP in EU Member States



Source: Eurostat Graph comparing tax revenue ratios across EU countries

The chart above illustrates the comparison between EU countries in terms of the share of tax revenues in GDP for 2024 — from the highest values (e.g. Denmark, France, Belgium) to the lowest (Ireland, Romania)

Conclusions

The Lorenz curve, together with the Gini coefficient and related indicators, offers a comprehensive framework for examining income distribution trends in Romania over the 2020–2024 period. Evidence from these years indicates a gradual reduction in inequality, reflected in the Lorenz curve's movement toward the line of perfect equality and in the decline of the Gini coefficient to some of its lowest values in recent years by 2024. Nevertheless, income and wealth remain strongly concentrated among high-income groups. Further research based on detailed household datasets, such as EU-SILC or national income surveys, would enhance future assessments of regional and socio-economic disparities across Romania.

Studies on inequality measurement show that fluctuations in the Gini coefficient mirror adjustments in the shape of the Lorenz curve, signaling redistribution among income groups. Clementi and colleagues emphasize that Lorenz dominance analysis is particularly valuable because identical Gini values may conceal important differences in distribution patterns, making scalar measures alone insufficient for comprehensive evaluation.

The situation observed in the Campania region illustrates a systemic form of environmental crime, conducted by organized networks that exploit regulatory weaknesses or corruption. Although Italian criminal legislation, supported by European regulatory frameworks, provides instruments to combat such offenses, their practical success depends on effective enforcement, strong cooperation among institutions, and improved investigative and prosecutorial capacity in environmental crime cases. Empirical research on Romania similarly indicates that wage income plays a decisive role in shaping inequality trends. Decomposition analyses conducted by Andrei and collaborators demonstrate that changes in labor income distribution exert a significant influence on overall inequality dynamics, consequently affecting the configuration of the Lorenz curve.

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Quality of life in Romania: a current analysis in a European and global context

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Abstract: This article examines the quality of life in Romania, based on current indicators such as life expectancy, cost of living, access to healthcare and education, and the country's position in international rankings. While Romania has made progress in areas such as personal safety and civil liberties, significant challenges remain, particularly in healthcare, pollution, and regional inequalities. The analysis highlights the need for strategic investments to improve social well-being, amid global stagnation observed in 2024-2025. The article provides a balanced perspective, emphasizing both positive aspects and areas requiring urgent interventions.
Keywords: *quality of life, Romania, life expectancy, social progress index, cost of living, healthcare, education.*

Introduction.

The quality of life in Romania is a complex indicator reflecting the population's satisfaction with economic, social, and environmental conditions. According to recent studies, the quality of life is significantly influenced by disposable income, access to public services, healthcare and educational infrastructure, as well as perceptions of safety and social stability (Eurostat, 2024). Although Romania has recorded considerable economic progress in recent decades, disparities between urban and rural areas continue to affect social equity and equal development opportunities (Romanian National Institute of Statistics, 2023).

Beyond economic factors, the subjective component of quality of life—related to psychological well-being, job satisfaction, and social relationships—has become increasingly significant in recent evaluations (OECD, How's Life?, 2023). The COVID-19 pandemic, external migration, and demographic changes have exacerbated vulnerabilities in the social system, leading to a temporary decline in feelings of safety and trust in state institutions (World Bank, Romania Country Economic Memorandum, 2022). However, current trends in administrative modernization and digitalization provide a foundation for improving quality of life in the coming years, particularly in large urban areas (Romanian Ministry of Development, 2023).

Quality of life is a multidimensional concept encompassing health, education, income, the environment, and personal safety. In Romania, the evolution of this indicator reflects the post-communist transition, European integration, and recent challenges such as the COVID-19 pandemic, inflation, and climate change. According to the 2024 Social Progress Index (SPI), Romania achieved a score of 74.61, ranking 45th globally, a slight improvement from the previous year (Deloitte, 2025) However, the country lags behind the EU average, where scores often exceed 85 points. This article analyzes key indicators, highlighting progress and shortcomings to provide a realistic picture of the current state and future prospects.

1. Main Indicators in Quality of Life.

The quality of life in Romania can be assessed through various international indices that combine economic, social, and environmental data.

The Social Progress Index, calculated by the Social Progress Imperative with Deloitte's support, measures three dimensions: basic needs, well-being, and opportunities. In 2024, Romania ranked 45th

out of 170 countries with a score of 74.61, a slight increase from 2023 (Deloitte, 2025). The country performs above the global average (64.02) but below countries like Poland (ranked 36th) or Hungary (40th) (SPI 2024). Strengths include personal freedom (37th) and access to information (42nd), while weaknesses persist in healthcare (83rd) and basic education (80th). (Deloitte, 2025)

Numbeo Quality of Life Index. According to the Numbeo platform, Romania has a quality of life index of 142.2 out of 240 in 2025, placing it 44th globally (Quality of Life Index by Country, 2025). The country excels in safety (index of 71.9 in Bucharest, surpassing Paris or London) but struggles with pollution and heavy traffic. Cities like Timișoara (167) (Safety Index by City, 2025) and Cluj-Napoca (163.7) outperform Bucharest (131.1) in local rankings.

Indicator	Romania Score (2024-2025)	EU/Global Position
SPI General	74.61	45/170 (last in EU)
Numbeo QoL	142.2	44/88
Life Expectancy	75.1 years	3rd lowest in EU (Alpha Bank, 2025)
Safety (Numbeo)	71.9	Top 10 in Europe (Safety Index by City, 2025)

For the city of Craiova, the Quality of Life Index is 153.09—high, surpassing the national average (142.2) and comparable to Dublin (155.91 in recent comparisons). Limited data suggests comfortable urban living.

Economic Indicators. A country's economy forms the objective foundation of quality of life, as income determines access to goods, services, and personal development opportunities (Eurostat 2024). In Romania, GDP growth in recent years has positively impacted living standards, but regional and urban-rural disparities remain significant (Romanian National Institute of Statistics 2023). Average net income and purchasing power are key indicators used to assess economic well-being.

Employment stability directly influences economic security and life satisfaction. Unemployment rates, job quality, and professional security are often correlated with education levels and digital skills (Employment Outlook, 2023). While Romania's overall unemployment rate is relatively low, generational disparities exist, with young people and those over 55 facing reintegration challenges in the labor market. (Romanian National Institute of Statistics, 2023)

Poverty and social inequality, measured by indicators like the poverty risk rate and the Gini coefficient, are also relevant (World Bank, 2023). Although relative poverty has steadily declined, territorial disparities, particularly in the Northeast and Southwest regions, remain pronounced, affecting not only material conditions but also social cohesion and trust among citizens (Romanian National Institute of Statistics, 2023)

Social indicators reflect access to education, healthcare, and social services, which are essential for a dignified and productive life. In Romania, the quality of the education system directly impacts employment opportunities and social mobility. Investments in education remain below the EU average, and early school dropout rates are still high (Eurostat, 2023). Education also influences social capital and civic participation.(Simon & Schuster, 2000)

In healthcare, key indicators include life expectancy, infant mortality, and access to medical services (World Health Statistics, 2023). Despite some progress, Romania lags behind the EU average in most of these metrics (Romanian National Institute of Statistics, 2023). Shortages of medical personnel, inadequate infrastructure, and the exodus of specialists continue to affect healthcare quality and public perception of the system (Romanian Ministry of Health, Annual Report, 2024).

On a social level, quality of life is influenced by community cohesion, social support, and opportunities for cultural participation. Societies with high levels of solidarity and civic engagement tend to report greater life satisfaction. In Romania, community initiatives and social inclusion projects are gradually strengthening social capital and reducing exclusion (UNODC, 2023)

Environmental and Housing Indicators**.** The quality of the natural environment is a critical factor in quality of life, directly impacting public health and overall well-being (European Environment Agency, 2023) In Romania, air pollution, inefficient waste management, and shrinking urban green spaces remain persistent challenges (Romanian Ministry of Environment, 2023). While European green transition policies have spurred programs to reduce emissions and energy consumption, gaps between developed and rural regions persist. Housing conditions reflect another fundamental aspect of quality of life, correlating with health, safety, and psychological comfort. A significant portion of Romania's population lives in overcrowded or poorly equipped homes, particularly in rural areas (Romanian National Institute of Statistics, 2023). The quality of housing infrastructure, access to modern utilities (water, sewage, gas, internet), and housing maintenance are commonly used to assess living standards (OECD, 2023). The built environment also contributes to community identity and social cohesion. Areas with balance urban planning, accessible green spaces, and sustainable infrastructure promote social integration and reduce daily stress (WHO Europe, 2023). In recent years, sustainable urban development and the regeneration of degraded neighborhoods have become strategic priorities for Romania's major cities.(Romanian Ministry of Development, 2024). Safety and Governance Indicators**.** Perceptions of public safety and institutional stability are defining elements of quality of life, directly influencing trust and psychological balance (Eurofound 2023). In Romania, overall crime rates have significantly decreased over the past decade, but cybercrime and economic-financial offenses have risen steadily (Romanian Ministry of Internal Affairs 2023). Perceived safety depends not only on crime rates but also on the quality of public services and authorities' responsiveness (UNODC, 2023).

Effective governance requires a transparent, participatory, and citizen-oriented institutional system (World Bank 2023). Progress in public administration digitalization and bureaucracy reduction is strengthening public trust, though perceptions of corruption remain a challenge (Transparency International, 2023). Corruption perception, press freedom, and civic participation are key indicators for assessing governance quality. (OECD, 2023). Active citizen participation in democratic processes and community involvement are also expressions of social quality of life. Societies with high civic engagement exhibit greater satisfaction and social resilience (Norris, 2011). In Romania, increasing civic education and decision-making transparency can strengthen the state-citizen relationship (Romanian Ministry of Justice, 2024).

Subjective Well-Being Indicators**.** Beyond objective measurements, quality of life includes subjective dimensions such as overall life satisfaction, emotional balance, and perceived happiness. These reflect how individuals interpret and value their daily experiences. Eurostat studies show that Romanians report an average satisfaction level of 6.5/10, an increase from recent years but still below the EU average (Eurostat, 2024). Work-life balance is another critical indicator, impacting mental health and social relationships (Diener, 2009). Overwork, emotional instability, and lack of leisure time can reduce perceived happiness (Kahneman, 2011). In Romania, policies supporting work-life balance, such as flexible work arrangements and parental leave, are being strengthened (Eurostat, 2024).

Interpersonal relationships and a sense of community belonging are major emotional resources for well-being (Ryff, 2018). A strong social network based on trust and empathy enhances resilience to stress and increases life satisfaction (Seligma, 2011). In Romania, local communities and informal support networks remain key pillars of social cohesion and psychological balance (UNICEF 2024).

3. Statistical Insights on Romania

Life expectancy in Romania increased by 2 years between 2007 and 2022, reaching 75.1 years, but it remains the third lowest in the EU (Alpha Bank, 2025). Healthy life expectancy is only 59 years, the lowest in the region, affected by chronic diseases and limited healthcare access. Men live an average of 72 years, women 79, but only 58-61 of those are healthy years (Eurostat, 2023-2025). In the 2025 CEOWORLD ranking, Romania holds a modest position, influenced by high rates of cardiovascular diseases and unhealthy lifestyles (CEOWORLD, 2025).

Living standards have doubled in the past 10 years but remain low compared to Western Europe. A family of four spends €2,070 (10,364 RON) monthly for a normal lifestyle, excluding rent, while a

single person spends 5,980 RON (Deloitte, 2025). The cost of living index is 34, three times lower than Switzerland's (98.4). Local purchasing power is higher in Timișoara than in Bucharest, and food prices are lower in Constanța (Numbeo, 2025). However, regional inequalities persist, with rural areas at a disadvantage.

Basic education remains a weakness (80th in SPI), with unequal access between urban and rural areas (Deloitte, 2025). The environment is affected by pollution: no Romanian city ranks in the top 200 of the 2025 London Institute for Quality of Life, unlike Budapest (110th). Safety is a strength, with a high index compared to other European capitals. Overall life satisfaction is 7.7/10, equal to Austria and above the EU average (7.3). Key challenges include the digital divide, gender inequality in caregiving, and the impact of climate change on health. Prospects are optimistic through PNRR investments, but education and healthcare require focus (OECD, 2024). Experts estimate that reducing pollution could increase life expectancy in Bucharest by 4 years.

4. Conclusions on Quality of Life in Romania

Quality of life in Romania is a multidimensional phenomenon at the intersection of economic progress, social equity, and individual well-being. While the country has seen significant economic growth in recent decades, benefits have not been evenly distributed across regions and social groups. Territorial disparities, urban-rural gaps, and income inequalities remain obstacles to achieving a balanced and sustainable standard of living. Thus, quality of life cannot be assessed solely through economic indicators but must consider the interplay between material development and human well-being.

Essential Dimensions of Well-Being**.** Social, environmental, safety, and subjective indicators show that life satisfaction increasingly depends on non-material factors such as health, a clean environment, social relationships, and a sense of security. In Romania, these dimensions are undergoing gradual transformation, influenced by public service modernization, administrative digitalization, and growing awareness of emotional balance. Sustainable development is no longer seen merely as an issue of infrastructure or economy but as an integrated strategy involving education, health, culture, and civic engagement.

Directions for Improvement**.** Improving quality of life in Romania requires a strategic and integrated approach focused on investing in human capital, strengthening institutions, and reducing social vulnerabilities. Public policies must aim to reduce inequalities, increase access to quality services, and protect the environment. Fostering a culture of cooperation and solidarity is also essential to restore trust between the state and citizens. Such a vision would transform economic development into a human-centered process, where every individual finds dignity, balance, and hope for a better future.

Romania's quality of life shows signs of improvement, with progress in safety and access to information, but it remains hindered by deficiencies in healthcare and the environment. Its 45th ranking in the SPI highlights untapped economic potential. To advance, Romania must prioritize equitable investments, reduce regional disparities, and improve public services. Only then can the country translate its economic potential into real well-being for its citizens.

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Special functions of the embassy in contemporary diplomatic practice

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Abstract. The 1961 Vienna Convention on Diplomatic Relations, in Article 3, outlines the primary functions of diplomatic missions (embassies). However, this enumeration is not exhaustive. Diplomatic practice has revealed additional functions—considered minor or special in relation to the Convention text—which may be of particular interest to certain states in specific situations.
Keywords: *diplomatic mission, embassy, Vienna Convention, special functions*

1. Introduction

The Vienna Convention on Diplomatic Relations, adopted in 1961, represents the cornerstone of modern diplomatic law. Article 3 of the Convention establishes the fundamental functions of diplomatic missions: representing the sending state, protecting its interests and those of its nationals, negotiating with the government of the receiving state, ascertaining conditions and developments in the receiving state by lawful means, and promoting friendly relations and developing economic, cultural, and scientific relations between the two states.[1]

Diplomatic practice over the past six decades has demonstrated that embassies perform additional functions beyond those explicitly enumerated in the Convention. These functions, while considered "special" or "minor" in relation to the Convention text, often carry significant importance in particular bilateral contexts or situations. They reflect the evolving nature of diplomatic relations and the diverse needs that arise in contemporary international affairs[2].

The special functions of embassies can be broadly categorized into six main areas: (a) lodging protests; (b) monitoring the interests of national minorities, particularly persons of the sending state's ethnicity; (c) protecting foreign interests on a permanent or provisional basis; (d) performing notarial functions; (e) executing acts of criminal procedure; and (f) specific functions of the apostolic nunciature (the diplomatic mission of the Roman Catholic Church).[3]

Understanding these special functions is essential for grasping the full scope of diplomatic activity in the modern international system. While the core functions outlined in the Vienna Convention remain central to diplomatic work, these additional responsibilities reflect the complex realities states face when maintaining representation abroad. Each function addresses specific practical needs that arise in the conduct of international relations, from protecting minority rights to facilitating legal processes across borders.

[1] Vienna Convention on Diplomatic Relations, Article 3 (1961).
[2] Ion M. Anghe, *Drept diplomatic şi consular* (Bucharest: Lumina Lex, 2002), p.202.
[3] Ibid., 203.

This article examines each of these special functions, analyzing their legal basis, practical application, and significance in contemporary diplomatic practice. By exploring these dimensions of embassy work, we gain a fuller understanding of how diplomatic missions serve as multifunctional instruments of state policy, adapting to diverse challenges while maintaining their core representational role.

2. The Function of Lodging Protests

In the practice of international politics and diplomatic relations, situations frequently arise in which one state's government experiences serious dissatisfaction with the attitude, declaration, or action of another state's government, or with that state's diplomatic agent. In such situations, the aggrieved government may perceive that its sovereignty and dignity have been offended, and that the offending state has violated its legitimate rights and interests. Under these circumstances, the state expresses its disapproval through a formal *protest*.[4]

A protest constitutes a form of diplomatic démarche that draws the attention of the state responsible for the offensive declaration or action to its political and diplomatic responsibility for such an act or fact. As a diplomatic instrument, a protest may take written form or be expressed verbally, with the receiving state being the party considered culpable. The protesting government may, depending on the author of the political-diplomatic incident, address itself even to an international organization (which, in the sense of public international law, means an intergovernmental organization).

The diplomatic démarche constituted by a protest may request certain clarifications or explanations from the government responsible for the incident regarding the declaration, act, attitude, or action considered offensive by the government of the state subjected to the incident. The state issuing the démarche expresses in polite form its concern, unease, or worry regarding news or information concerning the intentions of the state that caused the incident.

The legal literature identifies three essential aspects of a protest: (a) a reasoned expression of disagreement, supported by arguments; (b) a requirement for material or moral reparation, as appropriate, of the prejudice considered to have been caused, or satisfaction of another nature; and (c) a certain threat, which sometimes results implicitly from the very manner in which the protest is drafted.[5]

The function of lodging protests reflects the embassy's role as the primary channel through which states communicate formal objections and maintain their positions on matters of principle. While protests are ultimately expressions of state will, embassies serve as the institutional mechanism through which such communications are delivered, recorded, and sometimes negotiated. In contemporary practice, protests may address a wide range of issues, from alleged violations of international law to concerns about the treatment of nationals or the conduct of diplomatic personnel.

The effectiveness of protests as a diplomatic tool depends significantly on the broader relationship between the states involved, the gravity of the alleged offense, and the willingness of both parties to engage in dialogue. While protests rarely resolve disputes immediately, they serve important functions in establishing a state's legal position, creating a diplomatic record, and signaling the seriousness with which particular issues are viewed.

3. Monitoring the Interests of National Minorities

Although the nineteenth century was dominated by the principle of nationalities, neither that century nor the twentieth succeeded in creating purely national state units. The geography of populations proved more indifferent to political geography than political leaders anticipated. The formation and proclamation of national states in Europe after World War II, and the manner in which borders were drawn for African and Asian states following the long colonial period, failed to achieve the utopia of the purely national state.[6]

[4] Ibid., p.203-204
[5] *Dicționar diplomatic* (Bucharest: Editura Politică, 1979), p.712.
[6] Anghe, Drept diplomatic și consular, 204

Even states declared through contemporary constitutions as *national states* (for example, Hungary, Bulgaria, the Russian Federation, Poland, Italy, Turkey, Greece, Spain, etc.) contain within their territories populations belonging to other minority and ethnic or linguistic groups, despite the express declaration through constitutions of a single official language. The increasingly rapid and intense process of globalization in today's world implies intense population movements and an intensification of migration from poor, less-developed states toward wealthy states. On the territory of many of the world's states, alongside *historical minorities*, *immigrant minorities* are appearing and developing.[7]

Consequently, one of the tasks and functions of the diplomatic mission/embassy, as well as of the diplomatic agent, consists of carefully monitoring the conditions and treatment accorded to minorities in the receiving state. This function, which is relatively new in the history of diplomatic functions, differs from the function of *protecting power* that one state exercises over the interests, property, and nationals of a sending state on the territory of a receiving state. The function of monitoring national minority interests concerns persons who are in fact citizens of the receiving state.

This function reflects a new concern and, simultaneously, a stage in the development of public international law, through various international treaties and bilateral and multilateral conventions that recognize states' right to observe and monitor the condition and treatment to which citizens of a state are subjected when living in that state's territory yet representing a national minority or ethnic group distinct from the state's majority population. This is particularly relevant when part of the majority population of one national state coexists historically on the territory of another neighboring national state, especially in the case of new national states formed after World War I through the dissolution of the former Austro-Hungarian Empire (for example, Romania, Hungary, Serbia, Slovakia, etc.).

The treatment of members of national minorities or ethnic groups is determined by the legislation of the state of residence, in accordance with its right of sovereignty. Nevertheless, whenever a state has violated any of the rights of a national minority, other states have protested by virtue of international treaties, pacts, and declarations. Under universal legislation, any state is entitled to take a position in cases of persecution of minorities by the state on whose territory the respective minority lives.[8]

Although such a function of the diplomatic mission does not appear in Article 3 of the 1961 Vienna Convention, the protection of national minorities and linguistic minorities has been the focus of United Nations documents and has been developed in the practice of European states through measures agreed within the Organization for Security and Co-operation in Europe (OSCE) Framework Convention. Nevertheless, few receiving states readily admit to diplomatic missions the pretext of protecting a minority, as this is considered to fall within their own jurisdiction.[9]

The contemporary significance of this function has increased in the context of European integration and the development of human rights norms. While states remain sensitive about external monitoring of their treatment of minorities, international human rights frameworks and regional organizations have created space for diplomatic observation and engagement on minority issues. Embassies increasingly serve as channels for gathering information about minority communities, facilitating cultural connections, and, when necessary, raising concerns about discriminatory treatment or policies.

4. Protection of Foreign Interests on a Permanent or Provisional Basis

This diplomatic function does not arise from an extraordinary event (such as the breaking of diplomatic relations following a war), but rather results from a legal agreement established between a protecting power state and a state that, prior to such delegated protection, had no diplomatic mission in the receiving/host state. It is an agreement between the requesting state and the protecting state, strictly limited to the protection of the interests of the requesting state.[10]

[7] Ibid., p.204-205.
[8] Ibid., p.205.
[9] Ibid., p.205; OSCE Framework Convention for the Protection of National Minorities (1995).
[10] Anghe, *Drept diplomatic şi consular*, p.205.

In European diplomacy, a notable example is Switzerland, which serves as a protecting state for the small principality of Liechtenstein in all states where Liechtenstein lacks diplomatic representation. These missions also represent the interests of Liechtenstein (in fact, the only state in which Liechtenstein maintains a diplomatic mission is Switzerland, in that country's capital, Bern).[11]

The institution of protecting powers has historical roots in situations where diplomatic relations were severed, often due to armed conflict. During such periods, a third state—acceptable to both the sending and receiving states—would assume responsibility for protecting the interests of the sending state's nationals and property. This arrangement allowed for the continuation of certain consular and protective functions even in the absence of formal diplomatic relations.[12]

In contemporary practice, permanent arrangements for protecting interests (as in the Liechtenstein-Switzerland case) represent cost-effective solutions for small states that cannot maintain extensive diplomatic networks. The protecting state's embassy performs certain consular functions for nationals of the protected state, facilitates communications, and represents the protected state's interests in routine matters. Such arrangements require clear legal foundations, typically established through bilateral agreements that specify the scope and limitations of the protective functions.[13]

Provisional arrangements for protecting interests have been employed in various conflict situations throughout the twentieth and twenty-first centuries. The United States, for example, has frequently relied on Switzerland or other neutral states to protect American interests in countries with which it had severed relations. Similarly, during the Iran hostage crisis (1979-1981), Switzerland represented U.S. interests in Iran. These arrangements demonstrate the flexibility of diplomatic practice and the continued relevance of this special function in exceptional circumstances.

5. The Notarial Function

Citizens of the sending state may find themselves temporarily or permanently residing on the territory of the receiving state and in need of concluding legal acts of a notarial nature, such as: registration of marriage, birth, or death; maintenance of citizen records; authentication of documents; issuance of passports, visas, etc. Generally, such notarial acts represent a function of the consulate. However, where no consulate of the sending state operates on the territory of the receiving state, such functions fall to the embassy of the sending state.

The notarial function reflects the embassy's role in providing essential civil services to nationals abroad. In many cases, particularly in countries where the sending state maintains limited representation, the embassy serves as the sole point of contact for nationals requiring official documentation or legal authentication. This function has become increasingly important as international mobility has grown and individuals more frequently need documentation that is recognized both in their country of citizenship and in their country of residence.[14]

Common notarial acts performed by embassies include: authenticating signatures on legal documents, certifying copies of official documents, taking sworn statements and affidavits, registering births and deaths of nationals abroad, and facilitating marriage documentation. These services ensure that nationals can conduct legal affairs even when physically distant from their home country, and they maintain the integrity of civil registration systems across borders.

The legal authority for embassies to perform notarial functions typically derives from the sending state's domestic legislation, which extends certain powers of civil registration and authentication to diplomatic and consular officers abroad. While the receiving state generally accepts documents authenticated by foreign embassies (particularly when legalized through apostille procedures under the 1961 Hague Convention), the specific recognition and legal effect of such documents depends on bilateral agreements and the receiving state's domestic law.

[11] Ibid., p.205-206.
[12] Vienna Convention on Diplomatic Relations, Articles on protecting powers, 1961
[13] Anghe, *Drept diplomatic și consular*, p.206.
[14] Vienna Convention on Consular Relations, Article 5 (1963).

6. Execution of Acts of Criminal Procedure

In the event that, in the sending state, the perpetrator of a criminal act is discovered and, in order to evade investigation, prosecution and criminal trial, or execution of a criminal sentence, the accused or offender flees from the territory of the state under whose jurisdiction they fall to the territory of the receiving state, and provided that an extradition convention in force exists between the sending state and the receiving state, it falls to the embassy to undertake all appropriate measures, together with the relevant public authority in the host country, to obtain and execute the extradition of the guilty or criminally convicted person.[15]

This function reflects the embassy's role in facilitating international criminal justice cooperation. Extradition represents one of the most sensitive areas of diplomatic work, as it involves balancing competing legal systems, human rights considerations, and political relationships. While extradition is fundamentally a legal process governed by treaties and domestic law, diplomatic missions play a crucial role in initiating requests, facilitating communications between justice authorities, and resolving procedural or political obstacles that may arise.[16]

The legal framework for extradition typically consists of bilateral extradition treaties that specify the offenses for which extradition may be granted, the procedures to be followed, the documentation required, and the grounds on which extradition may be refused. Common grounds for refusal include political offenses, the risk of torture or inhumane treatment, insufficient evidence, or the expiration of statutory limitations. Diplomatic missions must navigate these complex legal requirements while ensuring that requests are properly formulated and transmitted through appropriate channels.

Beyond extradition, embassies may assist in other forms of international criminal cooperation, including: transmitting requests for mutual legal assistance in criminal matters, facilitating service of judicial documents, supporting witness testimony across borders, and coordinating investigations involving multiple jurisdictions. These functions have grown in importance as transnational crime has increased and as international legal cooperation mechanisms have become more sophisticated.

The embassy's role in criminal procedure extends to protecting the rights of its nationals who face criminal charges in the receiving state. While embassies cannot interfere with the receiving state's judicial processes, they can monitor proceedings, ensure access to legal representation, and intervene diplomatically if there are concerns about fair trial rights or consular access under the Vienna Convention on Consular Relations.

7. Specific Functions of the Apostolic Nunciature

The Roman Catholic Church, being one of the confessions with a universal character, has exercised throughout European and subsequently world history a distinctive religious and political role, especially after its organization as a state under Mussolini's regime, based on three treaties concluded at the Lateran (papal cathedral) in 1929. Following these, the Vatican—the seat of papal residence—became a state (although at 1.2 km² in area, it is the smallest independent state in the world). Given the universality (apostolicity) of the Pope as Bishop of Rome, being the head of the Roman Catholic Church, and given his traditional political influence and financial and media power, the Vatican is recognized as a subject of international law, enjoys legal personality on the international plane as a state, and maintains diplomatic relations with other states, operating 160 diplomatic missions.[17]

The Vatican's embassy is called a *nunciature/apostolic nunciature*, and the head of the Vatican's diplomatic mission bears the title of *nuncio/papal nuncio*, equivalent in diplomatic rank to *ambassador*. The functions of the nunciature are not contained in Article 3 of the 1961 Vienna Convention; nevertheless, the activity of the nunciature and its functions are subject to legal rules, namely the canon

[15] Anghe, *Drept diplomatic şi consular*, 206
[16] Council of Europe. European Convention on Extradition. Paris, December 13, 1957. European Treaty Series No. 24
[17] Geamănu, Grigore. Dreptul diplomatic și consular [Diplomatic and Consular Law]. Bucharest: Editura Didactică și Pedagogică, 1962, p. 25.

law of the Roman Catholic Church, contained in the *Code of Canon Law*. According to this Code, the functions of the nunciature are of a dual nature: ecclesiastical on one hand, and pertaining to public international law on the other. Both sets of functions derive from the personal authority granted by the Pope, as head of the Roman Catholic Church, to his legates/nuncios (the theory of personalization of diplomatic functions).[18]

Canon 362 of the Code reveals the bipolarity of the function of papal legates/nuncios, as well as the Code's provision, in this matter, for the preeminence of conventional law (treaty law) in relation to the Code itself. The canon states: "The Roman Pontiff (the Pope—our note) has the innate and independent right to appoint and send his own Legates either to particular Churches in various nations or regions, or to states and public authorities, as well as the right to transfer and recall them, observing however the norms of international law concerning the sending and recall of Legates accredited to states."[19]

Accredited to states or other public authorities (in the sense of international law, this can be interpreted), papal nuncios/legates are appointed directly by the Pope as his absolute personal representatives (the medieval theory dating to the sixteenth century) and have as special functions, in this capacity of representation to states, those of *representation*, *negotiation*, *information and observation*, and *protection of the interests of the Catholic Church* both as a whole and specifically as regards dioceses and religious orders on the territory of the receiving state.[20]

The dual nature of the nuncio's role—as both a religious representative and a diplomatic agent—creates a unique position in diplomatic practice. In states with significant Catholic populations, the nuncio often enjoys particular prestige and access to government officials, facilitating both ecclesiastical administration and diplomatic dialogue. The nunciature serves as a channel for Vatican perspectives on issues ranging from religious freedom and human rights to international peace and social justice.[21]

In numerous states, particularly those characterized by a Catholic majority or shaped by the historical norms of European diplomacy, the apostolic nuncio is traditionally accorded the status of *doyen* (dean) of the diplomatic corps. This prerogative is granted *ex officio*, by virtue of the nuncio's ecclesiastical dignity as the representative of the Holy See, rather than on the basis of seniority determined by the duration of diplomatic service in the receiving state. The origins of this protocol privilege can be traced to the prominent role played by the Holy See in the development of early modern European diplomacy, where papal representatives frequently acted as mediators and arbiters in inter-state relations. Although contemporary diplomatic law—codified, inter alia, in the Vienna Convention on Diplomatic Relations—does not mandate such precedence, it permits states to maintain customary practices. Consequently, the recognition of the nuncio as dean persists in a number of jurisdictions, reflecting continuity with historical tradition, albeit with notable variation across different geopolitical and cultural contexts.

In the contemporary international system, the functions of the apostolic nunciature have evolved considerably, extending well beyond the conventional scope of diplomatic representation. While the nuncio continues to perform classical diplomatic tasks—such as maintaining bilateral relations, facilitating dialogue with governmental authorities, and representing the interests of the Holy See—the role also encompasses a distinct ecclesiastical dimension. Specifically, the nuncio is entrusted with coordinating relations between the Holy See and the local Catholic hierarchy, including the transmission of communications, the assessment of ecclesial conditions, and the provision of confidential reports to the Vatican. A particularly significant responsibility involves participation in the process of episcopal appointments, whereby the nuncio gathers information, consults relevant stakeholders, and submits recommendations to the Roman Curia.

Furthermore, the apostolic nunciature plays an active role in monitoring the state of religious freedom and human rights within the host country, often engaging with governmental institutions, non-

[18] Vatican City. Codex iuris canonici [Code of Canon Law]. Canon 362. Official text and Romanian translation. Monitorul Oficial al României, Part I, No. 798 bis, November 27, 2008.
[19] Codex iuris canonici, Canon 362.
[20] Geamănu, Grigore. Dreptul diplomatic și consular, pp. 25-26.
[21] Holy See. Lateran Treaties. February 11, 1929. Acta Apostolicae Sedis 21 (1929): 209-294.

governmental organizations, and representatives of various religious communities. This engagement reflects the broader diplomatic and moral mission of the Holy See, which seeks to promote peace, social justice, and interreligious dialogue at the international level. The dual character of the nuncio's mandate—simultaneously diplomatic and ecclesiastical—constitutes a defining feature that distinguishes the apostolic nunciature from other diplomatic missions. As both an ambassador accredited to the state and a liaison to the local Church, the nuncio operates at the intersection of international law, canon law, and transnational religious governance, thereby embodying a unique institutional synthesis within the framework of contemporary diplomacy.

8. Conclusions

The special functions of embassies examined in this article underscore the increasingly multifaceted and dynamic character of diplomatic missions within the framework of contemporary international relations. While the Vienna Convention on Diplomatic Relations codifies the fundamental functions common to all diplomatic missions—such as representation, negotiation, information gathering, and the protection of national interests—these core responsibilities represent only the foundational layer of diplomatic activity. In practice, the evolution of global governance, economic interdependence, and transnational challenges has led to a significant expansion in both the scope and complexity of embassy functions.

Modern diplomatic missions are now required to operate within a highly interconnected and rapidly changing international environment, where traditional state-to-state interaction is complemented by engagement with a wide array of non-state actors, including international organizations, civil society, multinational corporations, and transnational advocacy networks. Consequently, embassies have assumed additional roles in areas such as public diplomacy, economic promotion, cultural exchange, crisis management, and the facilitation of international cooperation in fields ranging from security to environmental protection.

This functional diversification reflects broader transformations in the nature of diplomacy itself, which has shifted from a predominantly bilateral and protocol-driven activity to a more flexible, multidimensional practice. Embassies are increasingly expected to act as strategic platforms for advancing national interests across multiple domains, requiring a high degree of institutional adaptability and professional specialization. In this context, the classical legal framework provided by the Vienna Convention remains essential, yet it is continuously complemented and, in certain respects, transcended by evolving diplomatic practices that respond to the complexities of globalization and the demands of contemporary statecraft.

These special functions—lodging protests, monitoring minority interests, protecting foreign interests, performing notarial acts, facilitating criminal procedure, and the unique role of the apostolic nunciature—reveal how embassies serve as flexible instruments of state policy, adapting to diverse challenges while maintaining their fundamental representational character. Each function addresses specific practical needs that arise in the conduct of international relations, from protecting the rights of nationals abroad to facilitating cross-border legal processes.

The evolution of these functions reflects broader trends in international relations: the increasing importance of human rights and minority protection, the growing need for international legal cooperation in criminal matters, the persistence of religious diplomacy alongside secular state practice, and the continued relevance of traditional diplomatic instruments such as formal protests in maintaining international norms and state sovereignty.

Looking forward, the special functions of embassies are likely to continue evolving in response to new challenges. Globalization, digital technology, transnational crime, migration, and the increasing complexity of international legal regimes all suggest that diplomatic missions will face growing demands for services and representation that extend beyond the Vienna Convention's enumerated functions. Understanding these special functions is therefore essential not only for comprehending current diplomatic practice but also for anticipating how embassies will continue to adapt to serve the interests of their sending states in an increasingly interconnected world.

Ultimately, the special functions examined here underscore a fundamental truth about diplomatic practice: while international law provides frameworks and guidelines, effective diplomacy requires flexibility, creativity, and responsiveness to the unique circumstances and needs that arise in bilateral relations. The embassy, as an institution, must balance adherence to established legal norms with the practical necessity of addressing diverse challenges, serving multiple constituencies, and maintaining productive relationships even in the face of disagreements or conflicts. The special functions discussed in this article represent concrete expressions of this balancing act, demonstrating how diplomatic missions continue to serve as indispensable instruments of international engagement.

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Communication as a Strategic Orientation: Effects on Trust, Sensemaking, and Decision-Making

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Abstract
Organizations increasingly operate in environments marked by uncertainty, rapid change, and heightened interpretive demands. This study examines how communication orientation shapes key organizational processes under such conditions. Rather than treating communication as a set of messages or responses, the study conceptualizes **strategic** and **reactive** communication as distinct organizational orientations with different implications for coherence, trust, sensemaking, and decision effectiveness.
Using survey data from 200 organizational members, the study employs correlation analysis, ordinary least squares regression, and bootstrapped mediation and moderation models. The results show that a strategic communication orientation is consistently associated with higher organizational coherence, stronger trust in leadership, clearer collective sensemaking, and greater perceived decision effectiveness. In contrast, a reactive communication orientation is linked to lower trust and fragmented sensemaking. Organizational coherence and trust in leadership partially mediate the relationship between strategic communication and decision effectiveness, indicating that communication influences decisions primarily through relational and interpretive mechanisms. The moderating role of environmental turbulence was not statistically supported.
The findings position communication orientation as a structural dimension of leadership and governance, demonstrating that decision effectiveness depends less on responsiveness and more on communicative clarity, consistency, and explanatory capacity.
Keywords: *communication orientation, strategic communication, reactive communication, sensemaking, trust in leadership, decision effectiveness*

Introduction

Contemporary organizations operate in contexts characterized by volatility, ambiguity, and increasing pressure from both internal and external stakeholders. Accelerated economic, technological, and social changes intensify uncertainty and heighten organizational reliance on processes through which meaning is constructed, negotiated, and stabilized (Christianson et al., 2020). In this environment, communication can no longer be understood as an auxiliary or purely instrumental function, but rather as a structural leadership mechanism through which direction, legitimacy, and the coordination of collective action are articulated (Zerfass et al., 2018; Falkheimer, 2017).

Despite this, many organizations continue to function predominantly through a reactive communication logic, responding to events, crises, or external pressures as they arise. This orientation is often justified by the need for speed and adaptability; however, recent research suggests that

continuous reaction, when not embedded within a strategic framework, tends to become institutionalized as a dominant pattern (Jong, 2024). Over the medium and long term, such patterns are associated with message fragmentation, loss of coherence, and erosion of trust in leadership, ultimately undermining an organization's capacity to make and implement effective decisions (Coombs, 2022; van Zoonen et al., 2022).

In contrast, strategic communication is increasingly conceptualized as an intentional, goal-oriented organizational capability that supports governance, sensemaking, and decision-making processes (Heide et al., 2018; Zerfass et al., 2018). This perspective extends beyond the crafting of well-formulated messages and involves aligning communication with organizational objectives, systematically explaining the rationale behind decisions, and anticipating how messages will be interpreted by organizational members. Through these mechanisms, strategic communication contributes to the stabilization of meaning and the reduction of ambiguity, particularly in contexts of change or crisis (Andersson, 2023).

Although the literature has addressed strategic communication, crisis communication, organizational sensemaking, and trust in leadership as distinct domains, relatively few empirical studies have examined comparatively the effects of reactive versus strategic communication on these processes. Moreover, the relationships among communicative orientation, organizational coherence, trust in leadership, and decision-making effectiveness remain insufficiently integrated into a unified explanatory framework capable of capturing the mechanisms through which communication influences organizational functioning.

Against this backdrop, the present article aims to analyze communication orientation as an explanatory mechanism of organizational functioning. The purpose of the study is to examine how reactive and strategic communication influence organizational coherence, the quality of collective sensemaking, trust in leadership, and perceived decision-making effectiveness, as well as to test the role of environmental turbulence within these relationships.

By integrating perspectives from strategic communication, leadership, and sensemaking research, this study contributes to a more nuanced understanding of communication as a central organizational process. The article offers both conceptual clarification and empirical evidence relevant to scholars and practitioners interested in how communication shapes organizational direction, coherence, and decision-making capacity under conditions of uncertainty.

2. Theoretical Foundations and Recent Contributions

2.1 Strategic Communication as an Organizational Capability

The literature of the past decade highlights a significant paradigm shift in the understanding of strategic communication. Rather than being viewed exclusively as a set of techniques, tools, or messages, strategic communication is increasingly conceptualized as an *organizational capability* embedded in governance, leadership, and decision-making processes (Zerfass et al., 2018). This reconceptualization aligns with broader developments in organizational theory that emphasize capabilities, processes, and interpretive infrastructures over isolated actions.

Heide et al. (2018) argue that strategic communication must be analyzed in relation to organizational complexity, decision-making dynamics, and long-term value creation. From this perspective, communication becomes strategic when it is intentionally aligned with organizational purpose and contributes to the stabilization of interpretations over time. By providing consistent explanatory frames, strategic communication enables organizational members to understand not only what decisions are made, but also why they are made and how they relate to overarching goals.

Contemporary communication scholarship further emphasizes the constitutive role of communication in organizing. Cornelissen (2020) conceptualizes strategic communication as a managerial capability that shapes meaning, coordinates action, and supports organizational legitimacy across multiple stakeholder groups. Rather than merely transmitting strategy, communication actively enacts strategy by structuring sensemaking processes and guiding collective action. When

communication is coherent, future-oriented, and explanatory, it functions as a form of organizational infrastructure that supports coherence, trust, and coordinated decision-making over time.

2.2 Sensemaking and the Role of Communication in Leadership

Sensemaking refers to the process through which organizational members interpret ambiguous situations, assign meaning to events, and construct a shared understanding of organizational reality. This process becomes particularly salient in contexts characterized by uncertainty, change, or crisis, when existing interpretive frameworks are disrupted or rendered insufficient. Contemporary research emphasizes that sensemaking is not an individual cognitive activity, but a fundamentally social and communicative process shaped by interaction, narratives, and shared frames of reference (Christianson et al., 2020). Within this context, leadership communication plays a decisive role in structuring collective interpretations. Leaders influence sensemaking not merely by transmitting information, but by providing cognitive and normative cues that guide how events are understood and integrated into coherent narratives. Through communication, leaders help define what is happening, why it is happening, and what is likely to follow, thereby reducing ambiguity and enabling coordinated action.

Empirical studies demonstrate that inconsistent, fragmented, or contradictory messages amplify anxiety, confusion, and interpretive fragmentation, undermining organizational adaptation and coordination (van Zoonen et al., 2022). Conversely, coherent and explanatory communication facilitates convergence of interpretations and supports collective sensemaking. In this way, communication functions not only as an input to sensemaking processes, but as a central leadership mechanism through which interpretive quality and organizational action are shaped during periods of change and uncertainty.

2.3 Reactive Communication in Crisis Contexts

The crisis communication literature increasingly highlights the limitations of strictly reactive communication responses, particularly in complex and prolonged crisis situations. While rapid response has traditionally been emphasized as a key principle of effective crisis communication, recent theoretical developments suggest that speed alone is insufficient when responses are not embedded within a coherent strategic frame. Updates to Situational Crisis Communication Theory indicate that messages misaligned with stakeholder perceptions, expectations, and situational dynamics may exacerbate the loss of trust and organizational legitimacy rather than mitigate it (Coombs, 2022).

Reactive communication is typically triggered by external events, media pressure, or stakeholder demands, and is characterized by short-term orientation and a focus on damage control. Although such responses may be necessary in the early stages of a crisis, research suggests that when reactivity becomes the dominant communication logic, organizations tend to produce fragmented, defensive, and inconsistent messages. These patterns increase ambiguity, weaken credibility, and undermine stakeholders' ability to interpret organizational intent and direction over time. Jong (2024) argues that many communication failures in crises do not stem from inaccurate messages, but from the absence of a strategic communication orientation capable of anticipating the trajectory and escalation of crisis situations. Without such orientation, organizations remain locked in a cycle of response, continually adapting to emerging pressures rather than shaping stakeholder interpretations proactively. As a result, reactive communication may inadvertently intensify uncertainty and erode relational capital, highlighting the need to distinguish between short-term responsiveness and sustained strategic communication capacity in crisis contexts.

3. Conceptual Framework and Definition of Constructs

This study proposes a conceptual framework that differentiates organizations' communicative orientations and explains how these orientations influence relational and cognitive processes essential to organizational functioning. The analyzed constructs are derived from the relevant literature and operationalized at a perceptual level in order to capture employees' lived experiences of leadership communication practices.

Reactive communication refers to communicative practices triggered primarily by external stimuli, unforeseen events, or immediate pressures that require a rapid organizational or leadership response. This form of communication is characterized by a short temporal horizon, a strong focus on managing effects, and a high dependence on situational context (Coombs, 2022; Jong, 2024).

Within crisis communication research, rapid response is often considered necessary to prevent escalation. However, recent studies indicate that when reactive communication becomes an institutionalized pattern, it tends to generate fragmented, defensive messages that are weakly integrated into a coherent organizational narrative (van Zoonen et al., 2022). Such communication makes it difficult to identify a clear direction and undermines leadership predictability.

Although reactive communication may serve a functional role in the short term, its use as a dominant mode of communication is associated with loss of coherence and erosion of trust, particularly in contexts characterized by uncertainty and heightened pressure (Jong, 2024).

From a practitioner-oriented perspective developed in the author's recent work, reactive communication can be understood as communication shaped by urgency rather than intention. Under time pressure, messages tend to address immediate effects while neglecting continuity of meaning. Over time, this produces episodic communication that weakens interpretive stability, increases cognitive load for organizational members, and makes leadership behavior appear inconsistent, even when decisions themselves are rational or well intended.

Descriptive items (perceptual indicators of reactive communication):

- Communication primarily occurs in response to problems or emerging events.
- Leaders' messages are formulated under urgency and time pressure.
- Official positions change frequently depending on immediate context.
- Explanations focus on short-term effects rather than overall direction.

3.2 Strategic Communication (SC)

Strategic communication is defined as an intentional, goal-oriented form of communication through which organizations and their leaders align interpretations, coordinate action, and support medium- and long-term direction (Zerfass et al., 2018; Heide et al., 2018). Unlike reactive communication, it is not primarily triggered by events, but by shared objectives, values, and decision criteria.

Recent literature emphasizes that strategic communication should be understood as an organizational capability integrated into governance and leadership, rather than as a collection of isolated techniques or messages (Falkheimer, 2017). It manifests through the deliberate design of messages, the systematic explanation of decisions, and the anticipation of how these messages will be interpreted by different internal audiences.

A core element of strategic communication is its explanatory dimension. By providing cognitive and normative reference points, leaders structure future behavior and reduce ambiguity, thereby contributing to the stabilization of meaning within the organization (Andersson, 2023). Strategic communication also implies an extended temporal horizon, with messages formulated in consideration of their cumulative effects on organizational culture, trust, and coherence.

Strategic communication can be understood as an infrastructure of meaning rather than as a sequence of isolated messages. Its defining feature is not rhetorical sophistication, but intentionality, namely the capacity to connect individual decisions to a coherent narrative of organizational purpose. By consistently articulating the logic underlying decisions and situating them within a broader direction, strategic communication enables organizational members to anticipate future actions and align their behavior accordingly. Over time, this continuity transforms communication into a stabilizing mechanism that supports trust, coherence, and coordinated action, particularly in contexts of uncertainty and change.

Descriptive items (perceptual indicators of strategic communication):

- Communication is guided by clear and explicitly assumed objectives.
- Messages are designed to be consistent across channels and organizational levels.
- Communication explains not only what decisions are made, but why they are made.

- Leaders anticipate reactions before communicating major decisions.
- Communication contributes to clarifying the organization's overall direction.

3.3 Organizational Coherence (CO)

Organizational coherence refers to the perceived alignment between communication, decision-making, and action within an organization. It enables organizational members to accurately interpret the meaning of communicated messages and to anticipate leadership behavior over time (Heide et al., 2018). Importantly, coherence does not imply stability or the absence of change, but rather the consistency of the underlying logic through which change is justified, communicated, and enacted.

From a process perspective, coherence functions as an interpretive anchor that allows organizational members to connect past decisions, present actions, and future intentions into a meaningful whole. When communication provides stable explanatory frames and decisions follow articulated principles, employees are better able to understand how individual actions fit within broader organizational direction. In this sense, coherence supports predictability without rigidity and flexibility without arbitrariness.

Empirically, organizational coherence becomes visible when employees perceive congruence between what leaders communicate and what they subsequently do, and when decisions remain consistent with previously stated priorities and values. Conversely, the absence of coherence manifests through contradictory messages, frequent shifts in justification, or decisions that appear disconnected from prior communication. Such misalignment generates perceptions of arbitrariness, instability, and loss of direction, which in turn foster cynicism, reduce trust, and increase internal resistance (Andersson, 2023).

Thus, organizational coherence emerges as a relational and communicative property rather than a structural one, shaped cumulatively through repeated interactions between leadership communication and organizational action. As such, coherence represents a critical mechanism linking communication orientation to trust, sensemaking, and effective collective action.

Descriptive items (perceptual indicators of coherence):

- There is consistency between what leadership communicates and what it does.
- Decisions are aligned with previous messages.
- Contradictions between official messages are rare.
- Communication supports a unified direction.

3.4 Organizational Sensemaking (SM)

Sensemaking represents the process through which organizational members interpret events, reduce ambiguity, and construct a shared understanding of organizational reality (Christianson et al., 2020). This process is inherently social and communicative, emerging through interaction, shared narratives, and the explanatory frames provided by leadership. Sensemaking does not occur in isolation at the individual level, but is continuously shaped by how situations are framed, discussed, and legitimized within the organization.

In conditions of uncertainty or change, sensemaking becomes particularly salient. When clear interpretive reference points are absent, organizational members tend to rely on fragmented cues, informal conversations, and personal assumptions, leading to divergent interpretations and, in some cases, polarization. In such contexts, leadership communication plays a critical role in shaping the quality of collective sensemaking by offering structure, context, and direction.

Strategic communication supports sensemaking by articulating coherent narratives that link events to organizational purpose, values, and longer-term direction. By clarifying why changes occur and how they fit into a broader logic, strategic communication reduces interpretive ambiguity and facilitates convergence of meaning. In contrast, reactive communication, focused primarily on immediate events and short-term effects, tends to amplify uncertainty and fragment collective interpretations. When messages are episodic, inconsistent, or weakly connected to a broader narrative, sensemaking processes become unstable and less effective (van Zoonen et al., 2022).

Consequently, sensemaking emerges as a key cognitive mechanism through which communication orientation influences coordination, trust, and organizational action.

Descriptive items (perceptual indicators of sensemaking):

- Employees understand what is happening in the organization during periods of change.
- Communication helps interpret uncertain situations.
- There is a shared understanding of major organizational issues.
- Leaders' messages help clarify the overall context.

3.5 Environmental Turbulence (ET)

Environmental turbulence refers to the degree of instability, unpredictability, and rapid change in the external and internal environments in which an organization operates (Jong, 2024). Such turbulence may arise from economic volatility, technological disruption, regulatory change, competitive pressure, or internal restructuring, all of which increase uncertainty and reduce the reliability of established routines and expectations.

The literature indicates that under conditions of heightened turbulence, organizational members become more dependent on leadership communication as a primary source of interpretive guidance (Coombs, 2022). When environmental cues are ambiguous or conflicting, employees rely more heavily on messages from leaders to understand what is happening, how threats and opportunities should be interpreted, and what actions are appropriate. As a result, communication assumes a heightened sensemaking and coordinating function in turbulent contexts.

At the same time, environmental turbulence increases the costs of communicative inconsistency. Shifts in messaging, unclear rationales, or contradictory explanations are more likely to be interpreted as signals of uncertainty, loss of control, or strategic confusion. Research in crisis and change communication suggests that in such contexts, reactive and event-driven communication may unintentionally amplify ambiguity and anxiety, whereas consistent and explanatory communication can function as a stabilizing force (Jong, 2024; Coombs, 2022).

Thus, environmental turbulence does not merely intensify communication demands but alters the conditions under which communication influences trust, sensemaking, and coordinated action. It represents a critical contextual variable in examining how different communication orientations affect organizational functioning.

Descriptive items (perceptual indicators of turbulence):

- The organization operates in an unpredictable environment.
- Unexpected changes occur frequently.
- External pressures influence internal decisions.

3.6 Trust in Leadership (TR)

Trust in leadership reflects organizational members' evaluations of leaders' competence, integrity, and predictability, and is built cumulatively through the perceived congruence between communication and action (van Zoonen et al., 2022). Unlike momentary interpersonal trust, trust in leadership represents a systemic and relational judgment that develops over time, shaped by repeated interactions, communicated decisions, and their consistent implementation.

A central component of trust is behavioral predictability. Employees do not merely evaluate leadership based on outcomes, but on their ability to understand the logic underlying decisions, the criteria applied, and the principles guiding action. When leaders consistently articulate the reasoning behind decisions and apply similar logics across situations, their behavior becomes more predictable, even in complex or controversial contexts. Importantly, predictability does not imply rigidity; rather, it reflects transparency and coherence in decision-making processes.

Communication plays a critical role in the construction and maintenance of trust. Explanatory communication that provides context, rationale, and normative reference points reduces uncertainty and enhances perceptions of competence and fairness. When leaders explain not only what decisions are made but also why they are made, employees are better able to interpret intentions and anticipate future

actions. In contrast, incongruence between communicated messages and enacted decisions quickly undermines trust, even when decisions are technically sound. Shifting justifications, vague explanations, or unfulfilled commitments are often interpreted as signs of arbitrariness or lack of integrity.

Trust in leadership becomes particularly salient under conditions of uncertainty and change. When external cues are unstable or ambiguous, employees rely more heavily on leadership communication to make sense of organizational direction and to assess whether risks are being managed responsibly. In such contexts, trust functions as a relational mechanism that reduces internal resistance, facilitates cooperation, and enables coordinated action. Consequently, trust should be understood not as a static attribute of leaders, but as an emergent outcome of consistent, transparent, and explanatory communication practices that align words and actions over time.

Descriptive items (perceptual indicators of trust):

- Employees trust leaders' judgment.
- Leaders' messages inspire a sense of security.
- Leaders are perceived as consistent.
- Leadership behaviors are predictable.

3.7 Decision Effectiveness (DE)

Decision-making occupies a central place in organizational functioning, traditionally being evaluated through the lens of decision quality. From this perspective, a decision is considered sound when it is analytically robust, based on accurate information, rational evaluation of alternatives, and alignment with strategic objectives. Such an approach emphasizes optimal choice under given constraints and is often associated with normative and economic models of decision-making.

However, high analytical quality does not necessarily translate into effective organizational outcomes. A decision may be technically well designed yet fail to produce coordinated action, timely implementation, or acceptance among organizational members. This distinction has led scholars to differentiate between **decision quality** and **decision effectiveness**, the latter focusing on what decisions actually achieve within organizational contexts.

Decision effectiveness refers to the extent to which decisions generate clarity, coordination, and coherent action across the organization. It encompasses not only the analytical merits of a decision, but also how decisions are communicated, understood, accepted, and enacted (Andersson, 2023). From this perspective, effectiveness is a relational and processual outcome, emerging through interaction rather than residing solely in the decision itself.

Communication plays a decisive role in bridging the gap between quality and effectiveness. Decisions embedded within a coherent narrative, where rationale, direction, and implications are clearly articulated, are more likely to be accepted and implemented than decisions communicated in a fragmented or purely instrumental manner. When organizational members understand why a decision was taken, how it relates to prior actions, and what is expected of them, resistance is reduced and coordination is enhanced.

Accordingly, decision effectiveness should be understood as a communicative accomplishment, dependent on the alignment between decision logic, leadership communication, and collective sensemaking. In this view, communication functions not as a post hoc transmission channel, but as an integral component of decision-making itself, shaping whether decisions translate into coherent organizational action.

Descriptive items (perceptual indicators of effectiveness):

- Decisions are well explained.
- The rationale behind decisions is clear for implementation.
- Decisions are internally accepted.
- Implementation occurs with a low level of resistance.

4. Communication Orientation as an Explanatory Mechanism: Hypothesis Development

This section develops the study's hypotheses based on the assumption that communication orientation reactive versus strategic, operates as a core explanatory mechanism of organizational functioning. Rather than treating communication as a peripheral managerial activity, this perspective aligns with process-oriented views of organizations, which emphasize that meaning, coordination, and action emerge through ongoing communicative practices (Weick, 1995; Tsoukas & Chia, 2002).

Strategic communication is increasingly understood as a deliberate organizational capability that supports stability of meaning and coordinated action across time (Mintzberg, 2009; Cornelissen, 2020). In contrast, reactive communication, while often necessary in acute situations, reflects a short-term, event-driven logic that may undermine coherence when it becomes institutionalized (March, 1994). Framing communication orientation as a structural property allows for a systematic examination of how organizations differ in their ability to construct coherence, trust, sensemaking, and decision effectiveness.

4.1 Communication Orientation and Organizational Coherence

Organizational coherence refers to the organization's capacity to maintain a perceptible alignment between communication, decision-making, and action over time. From a systems-theoretical perspective, coherence functions as a mechanism for reducing complexity, enabling organizational members to recognize a stable internal logic even under conditions of change (Luhmann, 1995). When coherence is present, employees can connect individual decisions to broader organizational direction and anticipate leadership behavior, thereby reducing uncertainty and interpretive effort.

Communication orientation plays a central role in the construction or erosion of such coherence. Strategic communication contributes to coherence by intentionally integrating messages into a continuous narrative anchored in organizational purpose, values, and decision criteria (Zerfass et al., 2018). Through consistency of messaging and explicit explanation of decision rationales, strategic communication reinforces the perception of a unified organizational logic and limits interpretive discontinuities (Andersson, 2023). In this sense, communication does not merely reflect coherence, but actively produces it by stabilizing meaning across time and situations.

In contrast, reactive communication privileges immediacy and responsiveness to events over narrative integration. While potentially effective in addressing short-term disruptions, an event-driven communication logic increases the likelihood of fragmented messages, shifting justifications, and perceived inconsistency between discourse and action (March, 1994; Jong, 2024). Over time, these discontinuities undermine the perception of organizational coherence, particularly during periods of strategic change, when employees rely more heavily on communication to infer direction and intent.

Accordingly, communication orientation represents a key explanatory mechanism through which coherence emerges or deteriorates. Organizations that rely predominantly on strategic communication are better positioned to sustain coherent interpretations and coordinated action, whereas organizations dominated by reactive communication face greater risks of fragmentation and loss of alignment.

H1: *Organizations characterized by a predominantly strategic communication orientation exhibit higher levels of organizational coherence than organizations dominated by reactive communication.*

4.2 Communication Orientation and Trust in Leadership

Trust in leadership represents a complex relational evaluation through which organizational members assess leaders' competence, integrity, and predictability. Organizational research consistently shows that trust is essential for cooperation, commitment, and the acceptance of decisions, functioning as a mechanism that reduces coordination costs and internal resistance (Mayer et al., 1995; Dirks & Ferrin, 2002). Unlike momentary interpersonal trust, trust in leadership develops cumulatively over time, based on repeated interactions and the perceived consistency between communicated intentions and enacted decisions.

Communication orientation plays a decisive role in shaping these trust evaluations. Strategic communication supports trust by providing clarity of intent, consistency of messaging, and explicit

explanation of decision rationales. When leaders systematically articulate why decisions are made and how they relate to organizational values and priorities, employees are better able to understand the logic guiding leadership behavior and to anticipate future actions. This communicative predictability signals competence and integrity, even in situations involving uncertainty or unpopular decisions (Simons, 2002; Andersson, 2023).

In contrast, reactive communication, characterized by urgency and contextual pressure, tends to generate fragmented, defensive, or shifting messages. Even when decisions are technically sound, the absence of a stable explanatory frame can be interpreted as improvisation or lack of control. Over time, such communication patterns erode perceptions of predictability and integrity, undermining trust in leadership and increasing skepticism toward managerial intentions (Coombs, 2022; Jong, 2024).

Accordingly, communication orientation functions as a central mechanism through which trust in leadership is either constructed or weakened. Strategic communication fosters trust by stabilizing expectations and making leadership behavior intelligible, whereas reactive communication introduces relational vulnerability, particularly in contexts of heightened uncertainty.

H2: *Strategic communication orientation is positively associated with employee trust in leadership, whereas reactive communication orientation is negatively associated with trust.*

4.3 Communication Orientation and Sensemaking Quality

Sensemaking refers to the process through which organizational members interpret events, reduce ambiguity, and construct shared understandings of organizational reality. Sensemaking is particularly salient in situations of uncertainty, change, or disruption, when established routines and interpretive frameworks are challenged. Prior research emphasizes that sensemaking is not an individual cognitive activity, but a fundamentally social and communicative process, shaped by interaction, language, and leadership framing (Weick, 1995; Christianson et al., 2020).

Communication orientation plays a critical role in determining the quality of collective sensemaking. Strategic communication facilitates sensemaking by providing stable interpretive frames that connect events to organizational purpose, values, and longer-term direction. Through coherent narratives, contextual explanations, and explicit prioritization, strategic communication reduces ambiguity and supports convergence of interpretations across organizational members. By articulating not only what is happening but also why it is happening and what it means for future action, leaders enable employees to integrate new information into a coherent understanding of organizational reality (Gioia & Chittipeddi, 1991).

In contrast, reactive communication tends to undermine sensemaking quality. When communication is driven primarily by immediate events and external pressures, messages are often episodic, incomplete, or weakly connected to a broader narrative. Such communication patterns leave interpretive gaps that employees attempt to fill through informal sensemaking processes, increasing the likelihood of divergent interpretations, rumor formation, and polarization (Maitlis & Sonenshein, 2010). Rather than reducing ambiguity, reactive communication may unintentionally amplify it by continually shifting frames and justifications.

Over time, these differences in communication orientation shape the organization's capacity for collective sensemaking. Strategic communication supports interpretive stability and coordinated understanding, whereas reactive communication fragments meaning and increases cognitive dispersion, particularly in periods of sustained uncertainty.

H3: Strategic communication orientation positively influences the quality of collective sensemaking in contexts of uncertainty, compared to reactive communication orientation.

4.4 Communication Orientation and Decision Effectiveness: The Mediating Role of Coherence and Trust

Decision effectiveness refers to the extent to which decisions generate clarity, coordination, and coherent action within the organization. While traditional decision research has emphasized analytical quality such as information accuracy, rational evaluation of alternatives, and optimal choice scholars

increasingly distinguish between **decision quality** and **decision effectiveness**, noting that analytically sound decisions may still fail if they are not understood, accepted, or implemented (March, 1994). From this perspective, effectiveness is not inherent in the decision itself but emerges through organizational processes surrounding it.

Communication orientation is expected to influence decision effectiveness primarily through indirect mechanisms. Strategic communication contributes to decision effectiveness by creating conditions that enable decisions to translate into coordinated action. Specifically, strategic communication fosters organizational coherence by aligning messages, decisions, and actions over time, and it builds trust in leadership by making decision logic transparent and predictable. When employees perceive both coherence and trust, they are more likely to interpret decisions as legitimate, to reduce resistance, and to align their behavior with organizational intent (Mayer et al., 1995; Edmondson, 1999).

In contrast, reactive communication undermines these mediating conditions. Event-driven and fragmented messaging weakens perceived coherence and erodes trust, increasing the likelihood that decisions will be reinterpreted negatively or contested internally. Even technically justified decisions may be perceived as arbitrary when they are not embedded within a stable communicative framework, leading to implementation difficulties and coordination failures.

Accordingly, decision effectiveness should be understood as a relational and communicative outcome, shaped by how decisions are explained, contextualized, and integrated into an ongoing organizational narrative. Strategic communication enhances decision effectiveness not by improving decision content per se, but by strengthening the relational and interpretive infrastructures that support collective action.

H4: *The relationship between strategic communication orientation and decision effectiveness is mediated by organizational coherence and trust in leadership.*

4.5 The Moderating Role of Environmental Turbulence

Environmental turbulence refers to the degree of instability, unpredictability, and rapid change in the internal and external environment in which organizations operate. Research in strategic management and organizational change suggests that turbulence intensifies uncertainty, weakens established routines, and increases the cognitive demands placed on organizational members (Ansoff, 1980; Eisenhardt, 1989). Under such conditions, employees rely more heavily on leadership communication to interpret events, assess risks, and calibrate their responses.

From a communication perspective, environmental turbulence alters the conditions under which different communication orientations exert their effects. In relatively stable environments, inconsistencies or gaps in communication may be temporarily absorbed through routines, informal coordination, or shared experience. In contrast, in highly turbulent environments, the margin for interpretive error narrows. Ambiguous or shifting messages are more likely to be interpreted as signals of strategic confusion, loss of control, or lack of direction, thereby amplifying their negative relational and cognitive consequences.

Reactive communication is particularly vulnerable under conditions of high turbulence. Because it is driven by immediate events and short-term pressures, reactive communication tends to produce episodic and rapidly changing frames. In turbulent contexts, such patterns can exacerbate ambiguity, accelerate the erosion of trust in leadership, and fragment collective sensemaking, as employees struggle to integrate continuously changing cues into a coherent understanding. By contrast, strategic communication is expected to function as a stabilizing mechanism, providing continuity of meaning and interpretive anchors even when external conditions are volatile.

Accordingly, environmental turbulence is theorized to moderate the relationship between communication orientation and key organizational outcomes. As turbulence increases, the negative effects of reactive communication on trust and sensemaking are expected to become more pronounced, while the relative value of strategic communication for maintaining interpretive stability and relational confidence increases.

H5: *The negative effects of reactive communication on trust in leadership and collective sensemaking are amplified under conditions of high environmental turbulence.*

5. Data Analysis and Empirical Results

5.1 Descriptive Analysis and Data Preparation

Survey data were analyzed using standard statistical procedures for quantitative research based on Likert-type scales. The final sample consisted of 200 respondents, with no missing values. All variables were measured on 7-point Likert scales, and construct scores were computed as the mean of the corresponding items (Likert, 1932; DeVellis, 2017).

Preliminary distributional analyses indicated acceptable values of skewness and kurtosis, within the recommended thresholds for the application of parametric methods. This supported the use of correlation analyses and ordinary least squares (OLS) regression models (Kline, 2015). Internal consistency was assessed using Cronbach's α, with all scales demonstrating satisfactory reliability ($\alpha > .79$), supporting the reliability of the measurement instruments (Cronbach, 1951; Nunnally & Bernstein, 1994).

5.2 Correlation Analysis

To explore relationships among the variables included in the model, a Pearson correlation matrix was computed using the aggregated construct scores (Pearson, 1895). The results reveal a pattern consistent with the proposed theoretical framework.

Strategic communication (SC) is positively and significantly correlated with organizational coherence ($r \approx .60$, $p < .001$), trust in leadership ($r \approx .65$, $p < .001$), sensemaking quality ($r \approx .55$, $p < .001$), and perceived decision effectiveness ($r \approx .62$, $p < .001$). These associations suggest that a strategic communication orientation co-varies with higher perceptions of clarity, alignment, and organizational effectiveness.

In contrast, reactive communication (RC) shows significant negative correlations with trust in leadership ($r \approx -.40$, $p < .001$) and sensemaking ($r \approx -.35$, $p < .001$), indicating that a reactive orientation is associated with erosion of trust and difficulties in constructing shared understandings of organizational reality.

A moderate negative correlation is observed between strategic and reactive communication ($r \approx -.30$, $p < .001$), supporting the conceptualization of the two orientations as distinct constructs rather than opposite ends of a single continuum.

Environmental turbulence (ET) is moderately positively correlated with reactive communication ($r \approx .30$, $p < .001$) and negatively correlated with relational and cognitive variables such as trust ($r \approx -.25$, $p < .001$) and sensemaking ($r \approx -.22$, $p < .01$). This pattern suggests a context in which the risks associated with predominantly reactive communication become more salient.

Table 1. Pearson Correlation Matrix

Variable	1	2	3	4	5	6	7
1. RC	—						
2. SC	−.30***	—					
3. CO	−.25***	.60***	—				
4. TR	−.40***	.65***	.58***	—			
5. SM	−.35***	.55***	.52***	.60***	—		
6. DE	−.20**	.62***	.63***	.59***	.55***	—	
7. ET	.30***	−.15*	−.20**	−.25***	−.22**	−.18*	—

*p < .05, **p < .01, ***p < .001

Summary interpretation. The correlation analysis provides preliminary support for the proposed hypotheses. Strategic communication orientation is consistently associated with positive organizational

outcomes, whereas reactive communication orientation is negatively associated with critical relational and cognitive variables. These results justify further testing of the proposed directional relationships through regression and mediation/moderation analyses.

5.3 Regression Analyses and Hypothesis Testing (H1–H5)

For hypothesis testing, construct scores were standardized (z-scores), allowing regression coefficients to be interpreted as standardized β values. Hypotheses H1–H3 were tested using OLS regression, while H4 was tested through mediation analysis with bootstrapping, a recommended approach for estimating indirect effects (Hayes, 2018; Preacher & Hayes, 2008).

H1: Communication Orientation and Organizational Coherence (CO)

Model (OLS): CO = f(SC, RC)

$R^2 = 0.274$

SC → CO: $\beta = 0.455$, $p < .001$

RC → CO: $\beta = -0.164$, $p = .010$

Interpretation: Strategic communication is a strong positive predictor of organizational coherence, while reactive communication has a smaller but significant negative effect.

H1: confirmed

H2: Communication Orientation and Trust in Leadership (TR)

Model (OLS): TR = f(SC, RC)

$R^2 = 0.402$

SC → TR: $\beta = 0.498$, $p < .001$

RC → TR: $\beta = -0.282$, $p < .001$

Interpretation: Strategic communication is associated with increased trust in leadership, whereas reactive communication is associated with decreased trust.

H2: confirmed

H3: Communication Orientation and Sensemaking Quality (SM)

Model (OLS): SM = f(SC, RC)

$R^2 = 0.298$

SC → SM: $\beta = 0.381$, $p < .001$

RC → SM: $\beta = -0.302$, $p < .001$

Interpretation: Strategic communication supports clarity and convergence of interpretations, while reactive communication undermines them.

H3: confirmed

H4: Mediation, Strategic Communication → Decision Effectiveness (DE) via CO and TR

(1) Total effect

Model: DE = f(SC, RC, ET)

$R^2 = 0.380$

SC → DE (total effect): $\beta = 0.589$; 95% bootstrap CI [0.482, 0.694]

(2) Mediated model

Model: DE = f(SC, CO, TR, RC, ET)

$R^2 = 0.540$

CO → DE: $\beta = 0.394$, $p < .001$

TR → DE: $\beta = 0.212$, $p = .001$

SC → DE (direct effect, c'): $\beta = 0.304$, $p < .001$

RC → DE: $\beta = 0.036$, $p = .512$ (n.s.)

ET → DE: $\beta = -0.024$, $p = .636$ (n.s.)

(3) Indirect effects (5,000 bootstrap samples)

SC → CO → DE: indirect = 0.178; 95% CI [0.109, 0.256]

SC → TR → DE: indirect = 0.105; 95% CI [0.049, 0.169]
Total indirect effect: 0.283; 95% CI [0.194, 0.378]

Interpretation: Organizational coherence and trust in leadership significantly mediate the relationship between strategic communication and decision effectiveness. The direct effect of strategic communication remains significant, indicating partial mediation.

H4: confirmed (partial mediation via CO and TR).

H5: Moderating Role of Environmental Turbulence (ET) on the Effects of Reactive Communication

H5a: Trust in leadership (TR) as dependent variable
Model: TR = f(SC, RC, ET, RC × ET)
$R^2 = 0.411$
RC × ET → TR: $\beta = -0.092$, $p = .100$ (n.s.)

H5b: Sensemaking (SM) as dependent variable
Model: SM = f(SC, RC, ET, RC × ET)
$R^2 = 0.309$
RC × ET → SM: $\beta = -0.092$, $p = .130$ (n.s.)

Interpretation: Although the direction of the interaction effects is negative and consistent with theoretical expectations, the moderating effect of environmental turbulence does not reach statistical significance in this sample. Main effects remain robust: reactive communication reduces trust and sensemaking, while strategic communication enhances them.

H5: Not confirmed

5.4 Synthesized Results Conclusion

Hypotheses H1, H2, and H3 are confirmed: strategic communication orientation is positively associated with organizational coherence, trust in leadership, and sensemaking quality, whereas reactive communication orientation is negatively associated with trust and sensemaking. Hypothesis H4 is confirmed, as the relationship between strategic communication and perceived decision effectiveness is significantly mediated by organizational coherence and trust in leadership (partial mediation). Hypothesis H5 is not confirmed in this sample; environmental turbulence does not significantly amplify the negative effects of reactive communication on trust and sensemaking, although the direction of the interactions is theoretically consistent.

6. Academic and Practical Implications

The findings of this study support the view that communication orientation constitutes a central organizational mechanism with direct implications for how organizations build coherence, trust, and decision-making capacity. From an academic standpoint, the study contributes first by sharpening the conceptual distinction between **reactive communication** and **strategic communication**, treating them as **distinct orientations with differentiated effects**, rather than as variations in intensity of a single construct. The moderate negative correlation between the two orientations, alongside their opposing relationships with relational and cognitive variables, suggests the presence of two different communication logics operating within organizations.

Second, the study extends the organizational sensemaking literature by indicating that a **strategic communication orientation functions as a cognitive infrastructure** that stabilizes collective interpretations, while a **reactive orientation amplifies ambiguity**. Communication therefore emerges not merely as information transmission, but as an active mechanism through which organizational reality is structured and coordinated under uncertainty.

A third theoretical contribution concerns the relationship between communication, trust in leadership, and decision effectiveness. Results indicate that the effects of strategic communication on perceived decision effectiveness are **partially mediated by organizational coherence and trust in leadership**, supporting process-based perspectives on decision-making. This shifts emphasis from the

purely technical quality of decisions to the communicative and relational conditions that enable decision acceptance and implementation.

Regarding contextual conditions, the hypothesized moderating role of environmental turbulence was not statistically supported. Although interaction effects pointed in the expected direction, the results suggest that the impact of communication orientation is robust even without contextual amplification, inviting future research to test alternative moderators (e.g., organizational structure, role ambiguity, psychological safety, or the severity and duration of change).

From a practical perspective, the implications are straightforward. Improving organizational communication is not primarily a matter of style, rhetorical skill, or response speed, but of **changing the underlying communication orientation** and integrating communication into leadership and decision processes. Strategic communication, characterized by clarity, consistency, and explicit rationale-giving, directly supports coherence and trust, thereby facilitating decision acceptance and implementation.

By contrast, the institutionalization of reactive communication generates cumulative costs through message fragmentation, erosion of trust, and weakening of collective sensemaking. Even under pressure and uncertainty, investing in strategic communication operates as a mechanism of interpretive stability. Managerially, this implies treating communication as part of the organization's **decision architecture and governance**, rather than as a secondary instrument for reacting to events.

Final Conclusion

This study examined communication orientation as an explanatory mechanism of organizational functioning, highlighting systematic differences between reactive and strategic communication and their effects on organizational coherence, trust in leadership, sensemaking quality, and perceived decision effectiveness. The findings provide consistent empirical support for the claim that how communication is designed and practiced is a central determinant of perceived organizational effectiveness, beyond the immediate content of messages or individual leader skills.

Analyses indicate that a strategic communication orientation is positively associated with organizational coherence, trust in leadership, and the clarity of collective sensemaking processes. Strategic communication, defined by intentionality, consistency, and rationale-giving, contributes to stabilizing interpretations and aligning action across the organization. In contrast, reactive communication orientation is negatively associated with trust and collective sensemaking capacity, suggesting that continuous event-driven responsiveness, in the absence of a coherent explanatory frame, produces cumulative organizational costs.

A key contribution of the study is the identification of a mediation mechanism through which strategic communication influences decision effectiveness. Organizational coherence and trust in leadership account for a significant portion of this relationship, indicating that decisions become effective not only through analytical quality but through how they are understood, accepted, and implemented. Communication thus functions as a relational and cognitive infrastructure of decision-making.

Although the moderating hypothesis regarding environmental turbulence was not statistically supported, the observed direction of effects suggests contextual relevance and the need for more nuanced future investigations. Overall, the study supports a reconceptualization of communication as a strategic dimension of leadership and organizational governance. Investment in communicative clarity, consistency, and explanatory capacity is not a secondary managerial concern, but a foundational condition for coherence, trust, and decision effectiveness in contemporary organizations.

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Reconfiguring the Sketch in the Digital Environment of Visual Arts: Compositional Structures Between Tradition and Technology

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Abstract. This article examines the transformations of compositional structures within the digital environment of visual arts, with particular emphasis on the reconfiguration of the sketch from traditional techniques to contemporary media arts. Starting from the function of the sketch as an instrument of visual thinking and as a preliminary stage in the analog creative process, the study highlights how digitalization reshapes the logic of image construction without altering the conceptual essence of artistic practice. The reversibility of operations, layering, modularity, and the iterative possibility of adjustment transform digital composition into an open system subject to continuous recalibration.
The analysis proposes a perspective of continuity between traditional and digital practices, arguing that contemporary technology operates as a cognitive and operational extension of the artist rather than as a substitute for creativity. In this context, the digital sketch no longer represents merely a transitional phase, but becomes a structural matrix and a space for conceptual experimentation. The article supports the idea of a hybrid practice in which the dialogue between manual gesture and digital processing reinforces compositional coherence. Consequently, structure precedes technology, while digital media amplifies the possibilities of articulating the contemporary image.
Keywords: *digital sketch, compositional structure, visual thinking, digital media art, hybrid artistic practice, modularity and reversibility*

Introduction

In the process of conceiving an artistic project, one of the fundamental stages is the use of the sketch as a primary means of articulating visual intention. In most traditional practices, the sketch precedes the realization of the final work, functioning as an intermediary space between idea and materialization. It does

not represent merely a technical step, but rather a territory of visual thinking in which compositional structures are tested, adjusted, and reorganized.

The artist perceives reality through a personal filter, where sensory data intersect with imagination, affective memory, and subjective experience. The result of this process is a vision that does not simply reproduce the world, but reconfigures it. The essential question that arises in this context is: through what mechanisms are these visions organized? How are they structured so as to acquire compositional coherence and expressive consistency?

The Sketch as Infrastructure of Visual Thinking

The sketch emerges as a response to this need for organization. Often regarded as merely a preliminary step or a "scribble" lacking aesthetic autonomy, it in fact represents a space of internal ordering. Through the coordination between cerebral activity and the gesture of the hand, which becomes an instrument of thought, the artist externalizes mental structures. Line, mark, rhythm, tension, and the distribution of visual masses thus become forms of thought translated into visual terms.

In contemporary practice, this process undergoes a significant transformation generated by the digitalization of working environments. Technology does not intervene merely as an auxiliary instrument; rather, it alters the very structure through which elements are organized, layered, and reconfigured. Digital applications enable rapid, reversible, and iterative manipulation of composition, introducing new paradigms of visual construction.

The path from intention to the completed artistic object requires not only the articulation of a visual structure but also the configuration of a coherent concept and intelligible content. In this regard, Răzvan-Constantin Caratănase emphasizes that "The path from idea to a finished work certainly requires a concept, regardless of what the artist understands by it, but also content, which, if not universal, must at least exist outside the artist and address potential viewers. Content may consist of the subject itself, a narrative, or a visual sign, whether an icon or a motif."[2]

This observation is essential for understanding the status of the sketch within the digital environment. If the sketch constitutes the structural infrastructure of the artwork, concept and content are what provide it with direction and meaning. Technology, whether analog or digital, does not intervene in the conceptual essence of the work, but in the formal articulation of that essence. Consequently, the choice of medium does not compromise the integrity of the idea; it merely influences the mode through which visual language is configured.

Thus, the digital sketch can function as a space of conceptual organization just as legitimately as the traditional sketch, as long as the relationship between concept, structure, and content remains coherent.

Within this framework, digital tools, algorithms, graphical interfaces, automated functions, and even artificial intelligence systems, can be understood not as substitutes for human creativity, but as extensions of the cognitive process. They do not replace thought; rather, they amplify and reorganize it. If in traditional practice the coordination between brain and hand constituted the fundamental mechanism of image structuring, in the digital environment this relationship is mediated by the interface, yet not nullified.

This mediation through the interface introduces a shift not only in technique, but in the epistemology of visual creation itself. The sketch becomes a site where cognition, perception, and technological mediation intersect. Rather than being confined to the immediacy of gesture, visual thinking expands into a dialogic process between intention and system, between intuition and programmable structure. The screen does not

[2]R.-C. Caratănase, (2025). *O istorie a graficii românești, Noțiuni, concepte și principii*. Sfântu Gheorghe: Art Printer, p.23

merely display the emerging composition; it becomes an active field of negotiation in which decisions are constantly evaluated, modified, and recontextualized.

In this expanded framework, the sketch functions simultaneously as draft, laboratory, and analytical model. It allows the artist to visualize structural hypotheses, to simulate compositional tensions, and to anticipate relational dynamics between elements before they are definitively stabilized. The possibility of zooming, isolating fragments, or restructuring spatial hierarchies enhances the reflective dimension of the act of drawing. Consequently, the sketch evolves from a spontaneous notation of ideas into a strategic instrument of compositional research.

Moreover, the digital sketch introduces a form of layered intentionality. Because elements can coexist on separate strata without immediate fusion, the artist gains the ability to think composition in parallel registers. Foreground, background, and intermediary planes no longer depend solely on optical illusion or material superposition; they become adjustable structural variables. This reinforces the analytical awareness of spatial construction and deepens the understanding of compositional balance.

At the same time, the cognitive extension offered by digital tools does not eliminate the necessity of critical judgment. On the contrary, the abundance of options requires heightened discernment. The sketch remains the site where selection, hierarchy, and synthesis occur. Technology expands the field of possibilities, but it is the artist who establishes coherence.

Thus, the sketch, whether analog or digital, continues to operate as the foundational infrastructure of visual thinking. What changes is not its essential role, but the conditions under which it unfolds. In the digital environment, it becomes an expanded cognitive space in which structure, concept, and experimentation converge.

Technology as Cognitive Extension. Historical Continuities

The algorithm becomes a form of procedural delegation, while digital tools function as mechanisms for accelerating and refining visual decisions. The possibility of intervening in intermediate stages, adjusting proportions, recalibrating chromatic relationships, reorganizing compositional layers, introduces a new dynamic into image construction. The correction of gesture no longer implies erasure or material reworking, but structural reconfiguration.

In this sense, the translation or adjustment carried out in the digital environment can be considered as legitimate as direct intervention upon a traditional support. Authenticity does not reside in the material nature of the instrument, but in the coherence of the compositional system and in artistic intentionality. The choice of representational style, whether analog or digital, does not compromise the integrity of the work; rather, it contributes to diversifying the modes through which vision is articulated.

Thus, the digital environment does not eliminate the sketch; instead, it transforms its status: from a preliminary gesture, it becomes an open structure subject to continuous recalibration.

It is necessary to acknowledge that each artistic epoch has constructed its own technological instruments, which artists have employed in order to achieve aesthetic objectives. Technology has never been external to artistic creation; rather, it has functioned as a structural partner. From rudimentary drawing tools to the sophisticated mechanisms of contemporary representation, technological evolution has consistently influenced the organization of the image.

In this context, the education of the contemporary artist cannot ignore the digital dimension. Even a minimal understanding of digitalization processes, interface functionality, and algorithmic logic becomes essential for comprehending contemporary visual language. This is not a matter of replacing tradition, but of expanding structural competencies. Technological developments in recent decades have profoundly transformed the infrastructure of artistic production. The manufacture and large-scale distribution of personal computers, video cameras, and other digital devices have made these instruments accessible to artists interested in experimentation. As Boris Magrini observes, “the manufacture and retail of personal

computers, video cameras and other digital devices made this technology available and affordable for artists who wanted to experiment with them, facilitating the establishment of a unique artistic field at the threshold of art and technology"[3]

This observation confirms that the digital environment should not be understood as a mere technical extension, but as a distinct artistic field situated at the intersection of art and technology. Within this framework, the digital sketch does not represent a degradation of the traditional process, but rather an adaptation to the new material and cultural conditions of visual production.

From a retrospective perspective, the technique of using the grid during the Renaissance, by which an image was proportionally transferred onto another support, constituted a strategy of compositional control and spatial fidelity. Artists such as Leonardo da Vinci and Albrecht Dürer employed measuring systems and optical devices in order to rigorously organize representation.

The transfer method through gridding, the use of the camera obscura, and perspective devices were, in their time, advanced technological forms. By comparison, the use of the digital grid, layers, and automatic alignment functions in contemporary applications represents a continuation of the same structural principle.

The underlying concept remains constant: the organization of proportions, the control of spatial relationships, and the establishment of a coherent compositional architecture. The difference lies in the nature of the instrument, not in artistic intention. Thus, digital assemblage carried out through grids or modular systems can be interpreted as a natural evolution of structuring strategies employed in previous epochs.

Therefore, rather than witnessing an ontological rupture between traditional and digital practices, we observe a transformation in the operational medium of the same compositional thinking.

Compositional Structure in the Digital Environment

In comparison to the inherent limitations of sketches executed through traditional means, where the materiality of the instrument (pencil, ink, charcoal, engraving needle) directly determines expressivity and the possibilities of intervention, the digital environment offers a significant expansion of visual configuration options. In the analog realm, intervention often involves erasure, material superimposition, or the complete reworking of a compositional fragment; in digital space, however, the structure of the image can be reorganized without the loss of previous stages.

Layer-based workflows, selective cropping, opacity adjustments, controlled deformation of forms, the application of filters, and morpho-structural integration effects introduce a new paradigm of visual construction. Compositional elements become independent entities, manipulable and reversibly reconfigurable. This digital stratification enables the artist to operate upon spatial and structural relationships with a degree of flexibility that is difficult to achieve within a physical medium.

These technological horizons open an expanded field of plastic expression, propelling imagination beyond the constraints imposed by material resistance or the irreversibility of gesture. Digital language does not replace the artistic idea; rather, it facilitates its articulation and integration within a coherent system. When employed consciously and critically, the digital environment becomes an accelerator of the compositional process.

Nevertheless, this operational expansion does not entail the elimination of traditional stages. On the contrary, the transition between analog and digital may constitute a complementary process. The sketch need not be generated exclusively within the virtual environment; it may originate in direct drawing, through manual gesture, and subsequently be transferred, reinterpreted, or further developed digitally.

[3] B. Magrini, (2017). *Confronting the Machine: An Enquiry into the Subversive Drives of Computer-Generated Art*. Berlin: De Gruyter, p.53

Hybrid Practice and the Ontological Status of the Digital Sketch

Practical experience demonstrates that the act of direct drawing activates an organic relationship between hand and thought, facilitating an embodied understanding of forms and spatial tensions. Manual gesture implies sensory involvement and continuity of movement, reinforcing compositional unity. Analogous to the difference between handwriting and typing, the manual process appears to encourage a more natural sedimentation of ideas.

Therefore, the digital environment should not be understood as a substitute for tradition, but as its extension. The dialogue between the two working spaces, analog and digital, can generate a hybrid practice in which compositional structure is constructed through a continuous process of translation and reinterpretation.

A defining feature of the digital environment is its iterative character. While in traditional practice intervention upon the image entails a certain degree of irreversibility, erasure leaves traces, superimposition permanently alters underlying layers, and reworking often requires reconstructing the support, in digital space the process becomes reversible and potentially infinite. The "undo" function, the ability to save multiple versions, and the possibility of returning to previous stages transform compositional construction into an open system.

This reversibility does not diminish the complexity of the artistic act; rather, it reconfigures the very logic of visual decision-making. The artist is no longer constrained by the definitive character of each intervention, but gains the possibility of exploring multiple structural variants, testing alternative rhythms, and comparing compositional solutions without compromising earlier stages of the process. Consequently, creation acquires the dimension of progressive exploration, and the sketch loses its status as a fixed preliminary phase, transforming into a permanently reconfigurable device.

Within this framework, the digital environment introduces a new form of artistic temporality. Composition is no longer the result of a linear and irreversible sequence of interventions, but the expression of a dynamic system of branching, returning, and successive adjustments. The creative process thus becomes non-linear, open, and potentially unlimited.

This characteristic is also emphasized in the specialized literature. Aura Evelina Radu notes that "The most important characteristics of digital collage are that all operations are reversible and that the possibilities for working and derivation are unlimited. What should be emphasized is that changes in textures or dimensions are both possible and easily achieved, as are automated processes, multiplications, and so on"[4].

In this context, the digital image can no longer be understood as a static object, but as a dynamic system of relationships in which the modification of textures, dimensions, or structural proportions can be carried out rapidly, controllably, and reiteratively.

Therefore, the digital sketch acquires an ontological status distinct from that of the traditional sketch: it does not merely anticipate the artwork, but coexists with it within a continuous process of derivation and adjustment.

Another essential aspect is the modular character of the digital image. Elements are no longer inseparable from their support, but can be treated as independent units reorganizable within a system. The digital grid, automatic alignment functions, and proportional distribution tools reactivate, within a new technological framework, the classical principles of spatial ordering.

This modularity encourages an architectural mode of compositional thinking. The image is constructed as an ensemble of interdependent structures, where each component can be adjusted without destabilizing the whole. Paradoxically, technological flexibility may lead to increased structural rigor, as relationships

[4] A.-E. Radu, (2024). *Analiza elementelor de artă vizuală*. Timișoara: Eurostampa, p.15

can be measured and calibrated with precision. Thus, the digital environment does not dilute compositional discipline; rather, it provides additional instruments for articulating it.

The theorist Lev Manovich, in *The Language of New Media*, identifies among the fundamental principles of new media the notions of variability and modularity. The digital image is not a fixed object, but a set of data susceptible to multiple configurations[5].

This characteristic supports the idea that digital compositional structure is not a closed final result, but a temporary configuration within a field of possibilities.

When related to the sketch, this perspective redefines its ontological status. The sketch no longer represents merely an anticipation of the artwork, but a structural matrix subject to successive transformations. It becomes an interactive medium of visual thinking.

In contemporary artistic practice, the interaction between analog and digital generates a hybrid process. A manually executed sketch may constitute the structural nucleus of a composition, subsequently transferred and reinterpreted within the digital environment. This trajectory preserves the tactile and gestural dimension of drawing while simultaneously harnessing technological flexibility.

The direct experience of drawing, bodily involvement, pressure of the instrument, rhythm of movement, contributes to an organic understanding of space and formal tensions. Subsequently, the digital environment facilitates the reorganization and refinement of these structures without negating their gestural origin. A continuous circuit is thus created between intuition and analysis, between corporeality and algorithm.

Conclusions

The analysis of compositional structures within the digital environment of visual arts demonstrates that technological transformations have not produced a radical rupture in the logic of image construction, but rather a reconfiguration of the means through which it is articulated. The sketch, traditionally understood as a preliminary stage of the creative process, does not disappear in the context of digitalization; instead, it undergoes a functional and ontological transformation. From a transitional instrument, it becomes an open space of continuous experimentation.

If in analog practice the relationship between brain and hand generated a direct externalization of visual thinking, in the digital environment this relationship is mediated by interface and algorithm without losing its conceptual essence. The reversibility of operations, the iterative possibility of adjustment, and structural modularity do not diminish the authenticity of the artistic act; rather, they expand its field of operation. Digital composition should therefore not be interpreted as mere automation, but as a flexible architecture of visual decision-making.

Contemporary technology, now accessible and integrated into artistic practice, has contributed to the configuration of a domain situated at the intersection of art and technology. Within this framework, compositional structure is no longer constrained by the limits of material support, but becomes a system of dynamic relationships subject to continuous recalibration. Functions such as layering, multiplication, controlled deformation, and modular reorganization transform the image into a set of reconfigurable visual data.

Nevertheless, the analysis demonstrates that digitalization does not negate the necessity of traditional foundations. Concept and content remain the core of any visual work, regardless of the medium employed. The choice of instrument does not substitute artistic intention, but offers a different mode of formal articulation. Hybrid practice, based on the alternation and interaction between analog sketching and digital processing, thus emerges as a coherent solution for the contemporary artist.

[5] L. Manovich, (2001). *The Language of New Media*. Cambridge, MA: MIT Press, pp.15-26

The digital sketch can function as a structural matrix, as a space of extended visual thinking, and as a territory of conceptual experimentation. It enables intuition and analysis, gesture and calculation, spontaneity and control to coexist. In this sense, the transformation of the medium does not compromise the integrity of the artwork, but amplifies the possibilities of compositional organization.

Therefore, structure precedes technology, and technology amplifies structure. The relationship between analog and digital should not be understood in terms of opposition, but of complementarity. In media arts, the sketch is not a vestige of tradition, but an active principle of construction, adapted to the new material and cultural conditions of the contemporary image.

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Assessing urban-rural inequality based on European Social Survey (ESS)

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Abstract. This paper examines the urban–rural inequality across European countries using data from the European Social Survey (ESS). Urban–rural disparities manifest across socio-economic, well-being, and attitudinal domains and have significant implications for social policy and territorial cohesion. Using cross-national comparative ESS data, this study analyzes empirical patterns in subjective well-being, socio-economic conditions, and social perceptions to highlight persistent spatial inequalities. Findings suggest that rural areas continue to lag behind urban counterparts in multiple dimensions, though the magnitude and direction of disparities vary across regions and outcome variables. Understanding these patterns is crucial for targeted policy interventions that aim to strengthen social inclusion and reduce territorial inequalitiesc.
Keywords: *income inequality, European Social Survey, socio-economic inequality.*

Introduction

Income The European Social Survey (ESS) is a biennial, academically driven survey that collects high-quality comparative data on attitudes, socio-demographic characteristics, and behavior patterns across European populations. It has been widely used to study social stratification, inequalities, health outcomes, and political attitudes. The ESS data are rigorously sampled using multi-stage probability methods, ensuring national representativity and cross-national comparability.

Urban–rural inequality refers to systematic disparities in living conditions, economic opportunities, well-being, access to services, and social outcomes between populations residing in urban versus rural areas. These inequalities reflect deep structural variations in infrastructure, labor markets, educational access, and social capital. Within the European context, urban areas often display higher levels of economic activity, service access, and educational attainment, while rural areas may face depopulation, limited employment prospects, and distinct social dynamics. Understanding urban–rural divisions contributes to territorial cohesion debates central to European social policy.

1.1. Literature Review: Efficiency in Taxation and Revenue Maximization

The The efficiency of taxation has been a central focus of public finance research, with many early analyses emphasizing revenue maximization as a primary objective. Musgrave and Musgrave (1989) argue that policies concentrating exclusively on maximizing government revenue often fail to account for broader economic efficiency and social welfare. Similarly, Tanzi (1992) shows that in developing economies, structural factors such as informality, regional disparities, and economic volatility can limit the effectiveness of revenue-driven taxation strategies. These studies highlight that an instrumental approach to tax policy, focused narrowly on revenue outcomes, may produce distortions that compromise both economic performance and equitable resource allocation.

From a theoretical perspective, optimal tax system design balances revenue objectives with efficiency considerations. Slemrod (1990) emphasizes that focusing solely on revenue can ignore behavioral responses, such as labor supply and investment adjustments, which may undermine the intended outcomes. Auerbach and Hines (2002) extend this analysis, demonstrating that well-designed tax structures can achieve revenue goals while minimizing efficiency losses, provided that policymakers carefully select instruments and consider their interaction effects. Fullerton and Metcalf (2002) further underscore the importance of tax incidence analysis, showing that the distributional burden of taxes can significantly influence the overall efficiency and social acceptability of fiscal policy.

Beyond single-instrument approaches, models of tax competition and instrument choice reveal additional constraints on revenue maximization. Bucovetsky and Wilson (1991) show that interjurisdictional competition between regions limits the capacity of governments to rely on a single tax instrument, requiring a diversified approach. Cremer and Gahvari (1993) illustrate that nonlinear taxation can be employed to target social objectives effectively without sacrificing efficiency, highlighting the interplay between equity and revenue objectives. Additionally, scholars such as Stiglitz (1982) and Kotlikoff (1989) stress that ignoring distributional considerations in pursuit of revenue maximization may exacerbate inequality, further underscoring the need for a balanced approach that integrates efficiency, equity, and revenue goals.

1.2. Conceptual Framework and Methodology

The ESS collects individual-level data, including respondents' place of residence (classified into urban and rural categories), socio-economic characteristics (such as income, education, occupation), subjective well-being measures, and perceptions of social conditions. When researchers operationalize urban–rural analyses in ESS data, they typically use residence classification combined with outcome variables reflecting socio-economic or attitudinal inequalities.

Subjective well-being, for example, is a multi-dimensional construct captured by ESS items on life satisfaction, happiness, and financial stability. This allows comparisons across rural and urban populations while controlling for socio-demographic factors. Institutional trust, satisfaction with democracy, and perceptions of social support are other attitudinal indicators available in ESS that help illustrate urban–rural divides in socio-political dimensions (as analyzed in recent urban–rural political studies).

1.3. Discussions and results

Subjective Well-Being and Territorial Differences

Studies leveraging ESS data have shown variations in subjective well-being metrics between rural and urban residents. For instance, a comparative analysis of data from ESS Rounds 4 (2008) and 9 (2018) across Central European countries (Austria, Croatia, Czech Republic, Germany, Hungary, Poland, Slovenia, and Slovakia) found that urban areas generally reported higher subjective well-being scores than rural areas in 2008, though rural well-being improved in some contexts by 2018.

The authors construct a composite subjective well-being index that includes happiness, life satisfaction, and financial stability. They report not only persistent spatial differences but also evidence that rural conditions can change over time, suggesting dynamic socio-territorial processes rather than static disparities.

The analysis of urban-rural inequalities is a central direction in European social research, as these differences influence social cohesion, economic mobility and trust in institutions. The European Social Survey (ESS) is one of the most important comparative data sources for assessing these disparities, providing standardised information on living conditions, social perceptions, civic participation and subjective well-being in over thirty European countries (ESS ERIC, 2022).

The results of the ESS analyses show that urban-rural differences manifest themselves simultaneously at the economic, educational and institutional levels. The urban population generally benefits from better employment opportunities and higher incomes, increased access to education and healthcare, and a more developed digital infrastructure. These conditions favour higher levels of life satisfaction and a higher degree of social and political participation (Ballas, Dorling & Hennig, 2017).

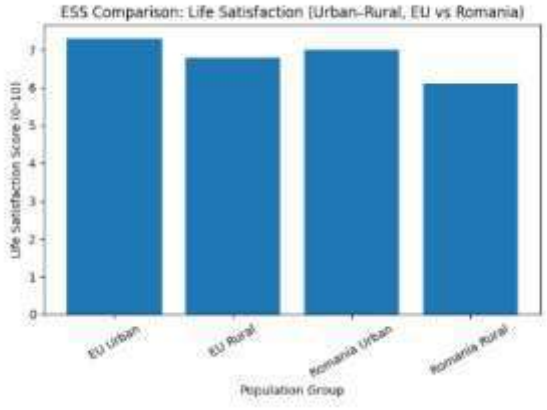
In contrast, rural areas are often characterized by limited economic opportunities, greater dependence on traditional sectors, and lower access to essential public services. The ESS also indicates a higher perception of economic insecurity and a lower level of trust in public institutions among the rural population, especially in Central and Eastern European countries (Cörvers & Mayhew, 2021).

For Romania, the ESS data reveal a more pronounced urban–rural gap than the European Union average in terms of household income, access to public services, and perception of social mobility. Rural areas have higher rates of at-risk-of-poverty and lower levels of satisfaction with public services, which contributes to internal migration to urban centers and external labor migration (European Commission, 2023).

These results suggest that reducing territorial disparities does not depend exclusively on economic growth, but also on investments in social infrastructure, education and digitalisation, as well as on regional development policies geared towards social inclusion. The ESS thus provides an essential empirical framework for assessing the impact of policies. Assessing urban-rural inequality using the European Social Survey (ESS). The European Social Survey (ESS) is one of the most important comparative databases used to analyse social and economic disparities in Europe, including urban-rural disparities. The ESS regularly collects data on living conditions, social perceptions, civic participation, institutional trust and well-being of the population in over 30 European countries.

Analysis of the ESS data highlights that urban-rural disparities manifest themselves on several dimensions. The urban population generally has better access to education, healthcare, digital infrastructure and employment opportunities, which leads to higher incomes and a higher level of life satisfaction. In contrast, rural areas frequently face problems such as an ageing population, limited economic opportunities and reduced access to public services. Therefore, the ESS is an essential tool for evaluating public policies aimed at reducing territorial disparities, and the urban-rural analysis provides important clues for designing regional development and social inclusion strategies.

Figure 1.: Difficulty living on income (urban-rural, EU vs Romania)



Source. Our recherché from Eurostat data

Highlights the difference between the urban and rural population regarding financial pressure, with a pronounced contrast in the case of Romania.

Figure 2.: Trust in institutions (urban–rural, EU vs Romania)

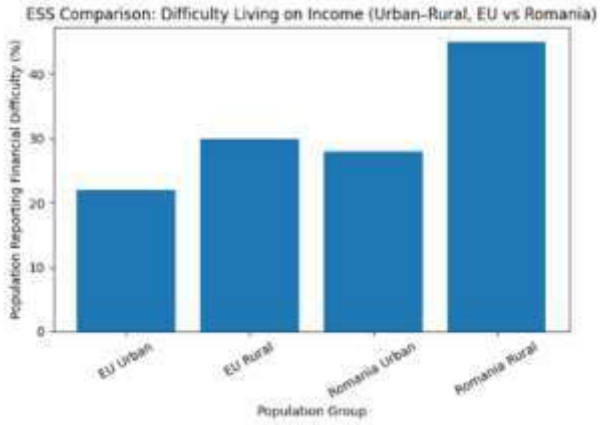
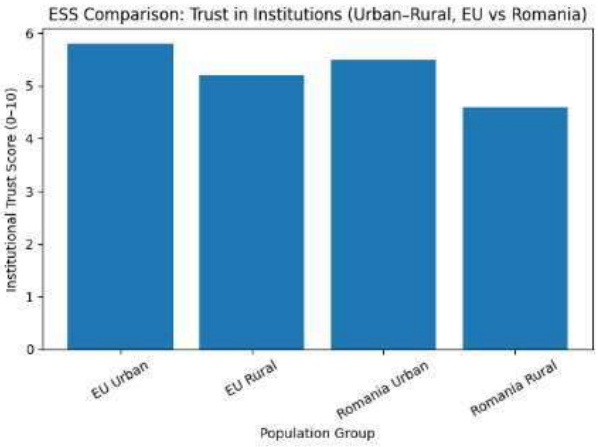


Figure 3. Households' difficulty in living on income – urban–rural ESS comparison



Shows the differences in institutional trust between urban and rural environments, as well as the gap between Romania and the EU average. The graph highlights the proportion of the population reporting financial difficulties, the difference being much more pronounced in rural Romania than in the EU average.

At the same time, the ESS shows that perceptions of inequality and social mobility opportunities differ significantly between urban and rural areas. Rural residents tend to express lower levels of trust in institutions and a higher perception of economic inequalities, especially in Central and Eastern European countries.

In the case of Romania, comparative data indicate a more pronounced difference than the European average between urban and rural living conditions, reflected in income, access to public services, infrastructure and educational opportunities. This situation contributes to internal and external migration and accentuates regional imbalances.

Urban-rural inequality is not limited to a single dimension; rather, it permeates economic conditions, subjective well-being, and political attitudes. ESS data provide rich comparative evidence that spatial residence is associated with differentiated lived experiences across Europe.

Policy discussions often focus on economic disparities, such as access to employment and infrastructure. Eurofound reports confirm that rural residents often have poorer access to public services and higher perceptions of institutional disregard than urban residents, reinforcing a social and spatial

divide. When combined with ESS evidence on subjective well-being and political attitudes, these findings point towards multi-layered inequality patterns.

Notably, ESS data and analyzes show that while urban advantage persists, rural improvement is possible, and the degree of inequality varies by context and over time. This temporal and spatial variation underlines the importance of regionally tailored policy interventions.

Conclusions

The This paper illustrates how ESS data can be used to evaluate urban–rural inequalities across Europe. The evidence suggests that *urban–rural disparities are significant and multi-dimensional,* affecting well-being, socio-economic opportunities, and political perceptions. However, the magnitude and direction of these inequalities can vary across countries, outcome variables, and over time. For policymakers, these patterns highlight the need for nuanced, place-based strategies that address both urban disadvantages (e.g., housing affordability pressures) and rural vulnerabilities (e.g., limited service access and economic opportunities). Finally, the importance of considering inequality and redistribution alongside revenue objectives has been emphasized in several studies. Stiglitz (1982) and Kotlikoff (1989) argue that an exclusive focus on revenue maximization may exacerbate disparities and reduce the overall welfare of the population. These perspectives suggest that efficient tax policy requires a *balanced approach*—one that integrates revenue, efficiency, and equity considerations rather than relying solely on instrumental maximization.

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Intimate partner violence against women in European states. A concentration analysis approach

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Abstract. Although the level of education, the standard of living and last but not least the attention paid to the female population are increasing in European countries intimate partner violence against women continues to be a negative phenomenon with implications not only for women but also for future generations. Among the main types of violence encountered in European countries are psychological, physical, sexual violence, as well as threats, with psychological consequences in the medium and long term and, much more seriously, with consequences which women life is in danger. In this context, the paper analyses the similarities and differences between European countries regarding shares of ever-partnered women who have experienced violence by an intimate partner, by type of violence and by main consequences.
Keywords: *intimate partner violence, violence against women, type of violences, consequences of violence, concentration analysis, Lorenz curve, Gini coefficient*
JEL Classification: C19, D19, J12, K36

Introduction

Violence against women is a violation of women's fundamental rights, affecting one in three women in the world, at all stages of their lives (Manasi, 2022), but which, although particularly important, cannot be easily prevented. Within this, intimate partner violence against women is a scourge that manifests itself in various aspects: physical, psychological, sexual or social with multiple consequences on women's health (Meseguer-Santamaría et al., 2021) and with direct consequences on national social and economic systems (Benocci, 2025).

Psychological and emotional violence is a form of violence that most women suffer within families, manifested most often through insults, shouting and threats (Darina, 2016). Also, psychological and emotional forms of violence often represent an important risk factor for other forms of intimate partner violence (Lausi et al., 2021). On the other hand, starting from the observation that although intimate partner violence against women is a complex and ubiquitous global phenomenon, Crapolicchio et al. (2023) considered that there was a relative lack of investigations on the negative consequences of psychological violence, highlighting that the association between psychological violence and depressive symptoms is moderated by perceived levels of positivity.

Another form of intimate partner violence against women, sometimes particularly serious, is physical violence. Several studies have highlighted the existence of a correlation between it and lower levels of education (Mosiño, 2025), poor economic situation, low income (Zaida et al., 2018; Amare et al., 2024). On the other hand, in a study on the dependence between the economic cycle and physical violence against women, Bhalota et al. (2018) highlighted that a one percent increase in the unemployment rate

among men increases the incidence of physical violence against women by 0.50 percentage points, while a one percent increase in the unemployment rate among women, conditioned by unemployment rates among men, causes a decrease in the probability of victimization by 0.52 percentage points.

In addition to physical violence, sexual violence is the most common type of violence (Selda, 2016), with a strong impact on women and the social climate, its reduction and eradication implying reconsideration of the hierarchical relationship between men and women and the effective assurance of gender equality, in countries with greater gender equality its incidence being lower (Belén et al., 2018).

Intimate partner violence against women has serious consequences on women's psychological and physical health, some of the most common involving mood disorders and stress with long-term side effects, such as impaired decision-making and cognitive function (Lausi et al., 2023). These are joined by consequences which women's life was in danger, among which the seriousness of the consequences of sexual violence (unbearable feeling of secrecy, threat and humiliation, constant fear and insecurity, physical and mental health problems, suicidal tendencies) must be highlighted, extremely negative in the long term due to the interconnection between body, mind and soul (Sigurdardottir & Halldorsdottir, 2021).

Taking these aspects into account, the paper analyses the similarities and disparities between EU Member States regarding the intensity and consequences of intimate partner violence against women (IPVAW) through the prism of shares of ever-partnered women who have experienced violence by an intimate partner, by type of violence and by main consequences.

1. Research methodology

In order to achieve the research objective, highlighting the similarities and disparities between EU Member States regarding IPVAW, we started from the analysis of the data series results from the EU survey on gender-based violence against women available in the Eurostat Database (EUDB, 2026), respectively: Ever-partnered women who have experienced violence by an intimate partner, by type of violence (IPVTV, 2025) and Ever-partnered women who have experienced violence by an intimate partner and consequences of violence (IPVCC, 2025). The identifiers and meanings of the variables included in the analyses are presented in table 1.

Table 1. The identifiers and meanings of the variables used in the analysis

Variable	Signification	Units
SWHEV	share of ever-partnered women who have experienced violence by an intimate partner	%
SWPHLV	share of ever-partnered women who have experienced psychological violence by an intimate partner	%
SWPHYV	share of ever-partnered women who have experienced physical violence by an intimate partner	%
SWSXV	share of ever-partnered women who have experienced sexual violence by an intimate partner	%
SWTHRV	share of ever-partnered women who were victims of treats by an intimate partner	%
SWHIPC	share of ever-partnered women who have experienced physical injury or psychological consequences by an intimate partner	%
SWHLDC	share of ever-partnered women who have experienced consequences which her life was in danger	%

To highlight and analyses the disparities and similarities between EU member states, as well as to determine their concentration in terms of IVPAW through the seven indicators, both descriptive methods and graphical procedures (Lorenz Curve) and numerical evaluations (Jaba, 2002) were used.

The Lorenz Curve was obtained starting from vectors of the form $W = [w_i]_{i=\overline{1,27}}$ sorted in ascending order ($w_i \leq w_{i+1}$), by generating the points cloud $(x_i, y_i)_{i=\overline{0,27}}$ (Zaharia & Gogonea, 2019):

$$(x_i, y_i) = \begin{cases} (x = 0, y = 0),\ i = 0 \\ \left(x_i = \frac{i}{27}, y_i = \frac{S_i}{S_n}\right),\ S_i = \sum_{j=1}^{i} w_j,\ i = \overline{1,27} \end{cases} \quad (1)$$

For the numerical evaluation of the degrees of concentration, the Gini Coefficient (G), Shannon Entropy (S) and Normalized Entropy (S_0) were used:

$$G = \sqrt{\sum_{i=1}^{n} g_i^2}\ ,\ \ g_i = \frac{x_i}{\sum_{i=1}^{n} x_i}\ ,\ G \in \left[\sqrt{\frac{1}{n}}\ , 1\right] \quad (2)$$

$$S = \sum_{i=1}^{n} g_i \cdot ln\frac{1}{g_i},\ S = [1\ , lnn];\quad S_0 = \frac{S}{lnn}\ ,\ S_0 \in [0, 1] \quad (3)$$

In conditions where n=27, $G \in [0{,}1924,\ 1]$, $S \in [1,\ 3{,}2958]$. The more the values of the indicators G, and S tend towards 1, and S0 towards 0, the higher the concentration degree.

2. Results and Discussion

The analyses carried out on the similarities and disparities between EU Member States regarding intimate partner violence against women focused on three aspects: (1) an overall analysis of the share of women who experienced violence by intimate partner, (2) particularities of the share of women who experienced violence by intimate partner by types of violence, (3) consequences of intimate partner violence against women.

2.1. The share of women who have experienced violence by an intimate partner

According to the data available in the Eurostat Database, the share of ever-partnered women who have experienced violence by an intimate partner (SWHEV), at the base year level, recorded values between 19.6%, the value recorded in Poland, and 54.6%, the value recorded in Hungary. Taking as a reference the estimated EU-average of SWHEV (31.8%), values higher than this were recorded in 15 countries (Figure 1), and lower values in only 12 countries.

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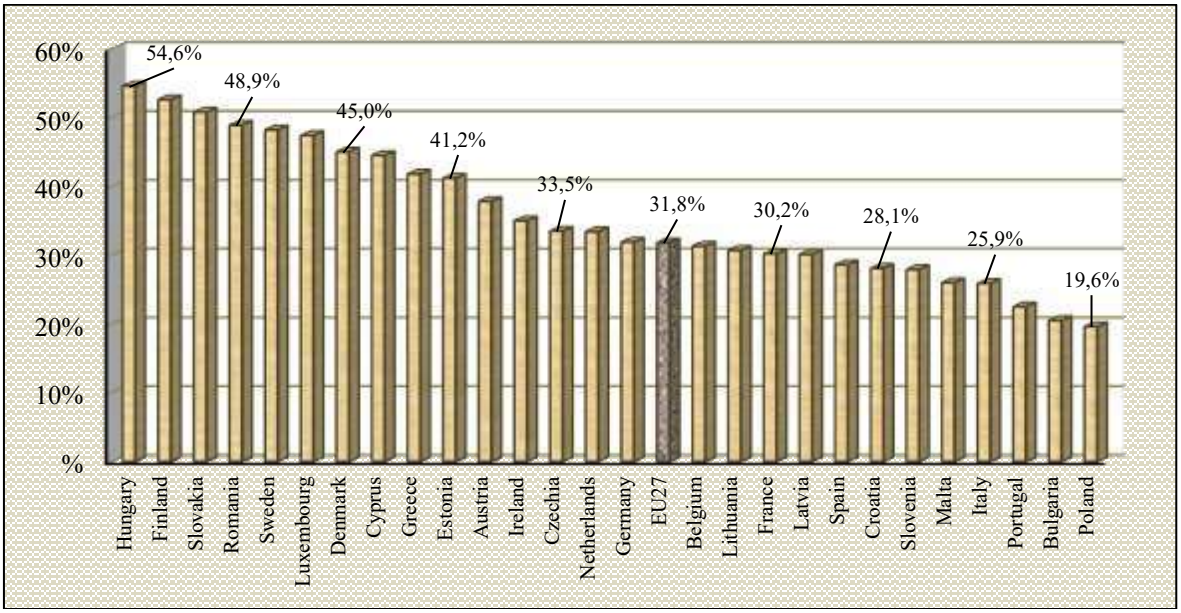

Figure 1. Ranking of EU member states according to SWHEV values. Source: prepared by the author

Given that the amplitude of the value interval is very large (35.0 percentage points), the values of the concentration coefficients Gini Coefficient (G=0.1999), Shannon Entropy (S=3.2958) and Normalized Entropy (S_0=0.9881) were determined. Both their values and the Lorenz curve (Figure 2) do not highlight a high degree of concentration.

To verify this finding, as well as for an image of the geographical distribution of SWHEV values (Figure 3), starting from the extreme values of SWHEV, five intervals of equal amplitudes (7 percentage points) were determined, entitled Minimal (between 19.6% and 26.6%), Low (between 26.6% and 33.6%), Middle (between 33.6% and 40.6%), High (between 40.6% and 47.6%) and Maximal (between 47.6% and 54.6%).

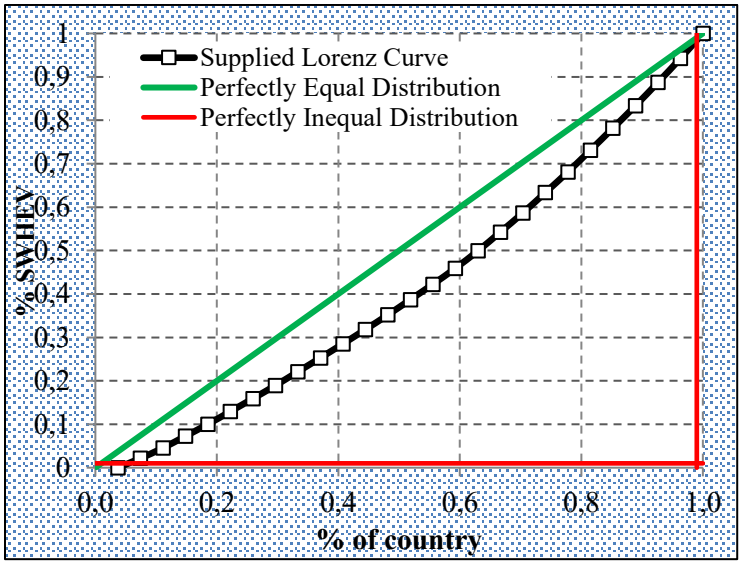

Figure 2 Lorenz curve of SWHEV Source: prepared by the author

The Minimal range (19.6% - 26.6%) includes five countries (Poland, Bulgaria, Portugal, Italy and Malta), with the lowest SWHEV value (19.6%) recorded in Poland and the highest (20.0%) in Malta.

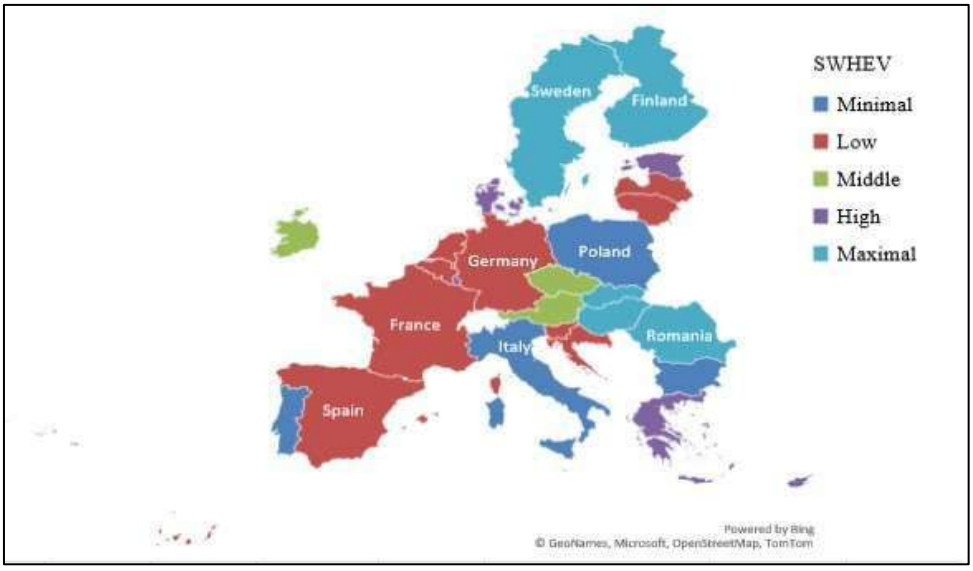

Figure 3 Geographic distribution of SWHEV value ranges.
Source: prepared by the author and powered by Bing

The Low range (26.6% - 33.6%) includes nine countries (Slovenia, Croatia, Spain, Latvia, France, Lithuania, Belgium, Germany and the Netherlands), with the lowest value (27.9%) recorded in Slovenia and the highest (33.4%) in the Netherlands.

The Middle range (33.6% - 40.6%) includes three countries (Czechia, Ireland and Austria), with the lowest value (35.6%) recorded in Czechia and the highest (37.8%) in Austria.

The High range (40.6% - 47.6%) includes five countries (Estonia, Greece, Cyprus, Denmark and Luxembourg), with the lowest value (41.2%) recorded in Estonia and the highest (47.4%) in Luxembourg.

Finally, the Maximal range (47.6% - 54.6%) also includes five countries (Sweden, Romania, Slovakia, Finland and Hungary), the lowest value (48.2%) being recorded in Sweden and the highest (54.6%) in Hungary.

Considering that, of the five equidistant ranges, three (Minimal, High and Maximal) include five countries each, respectively 18.52% of the 27 EU countries, and the Middle range included only 3 countries (11.11% of the total), while the Low range includes 9 countries (33.33% of the total), it results that there is a concentration of SWHEV values in this range.

2.2. Specifications by types of violence

According to Law no. 217/2003 art. 4 (LPCVD, 2020), domestic violence, implicitly violence against women, manifests itself in a wide range of forms, including verbal, psychological, physical, sexual, economic, social, spiritual and, last but not least, cyber violence. Of these, based on the data series Ever-partnered women who have experienced violence by an intimate partner, by type of violence (IPVTV, 2025) the structure of the European Union countries was analysed in terms of the share of women victims of psychological violence (SWPHLV), of physical violence (SWPHYV), of sexual violence (SWSXV) and victims of treats (SWTHRV).

In terms of the share of ever-partnered women who have experienced psychological violence by intimate partner (SWPHLV), the highest value of 52.1% was recorded in Hungary (Figure 4) and the lowest, 19.1%, in Poland.

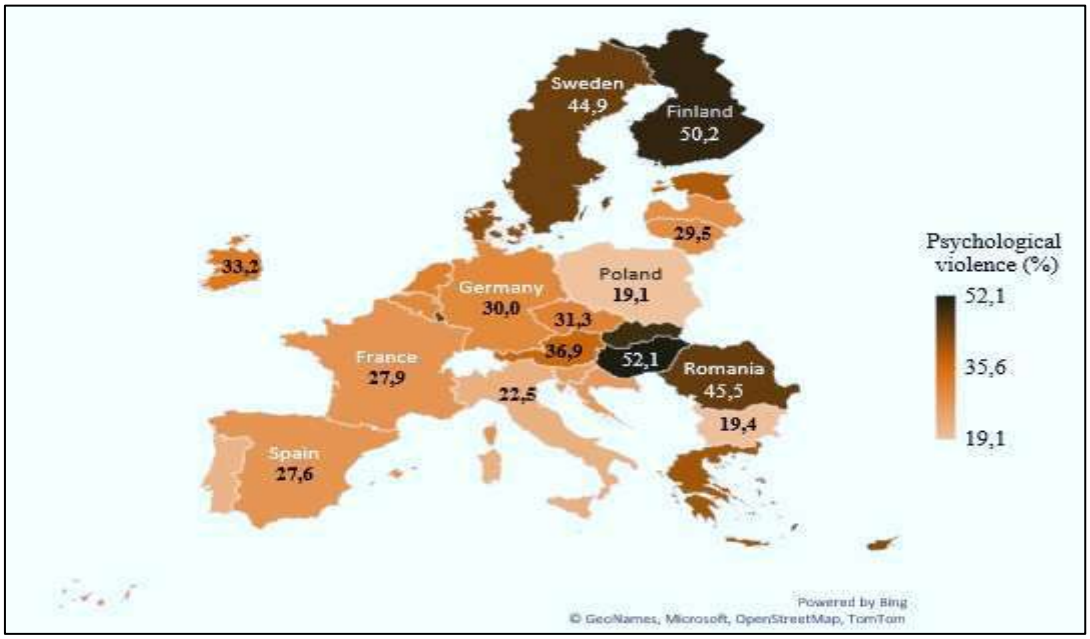

Figure 4. SWPHLV values in EU member states
Source: prepared by the author and powered by Bing

The Lorenz curve (Figure 5), as well as the values of the concentration coefficients Gini Coefficient (G=0.2000), Shannon Entropy (S=3.2561) and Normalized Entropy (S0=0.9879), do not highlight a very high degree of concentration in the case of SWPHLV either, being similar to that encountered in the case of SWHEV.

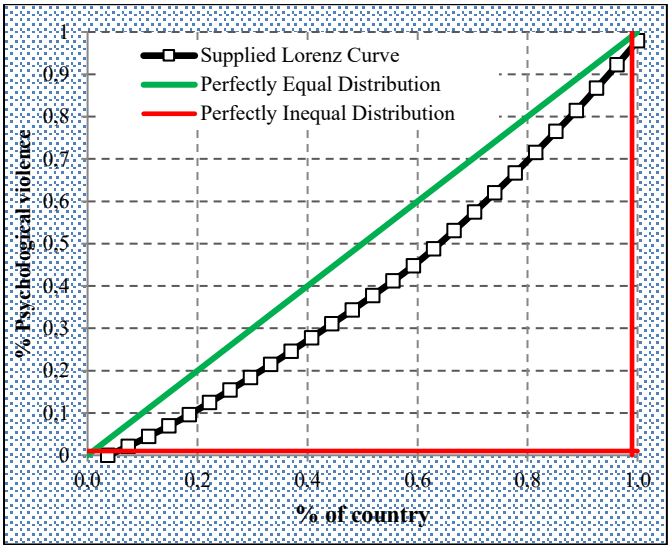

Figure 5. Lorenz curve of SWPHLV Source: prepared by the author

Some differences are highlighted by interval groups, both in terms of SWPHLV values and the number of countries included in them (Figure 6). Thus, in the case of SWPHLV, ten countries are included in the Low interval (25.7% - 32.3%), compared to nine in the case of SWHEV, by Czechia moving from the Middle interval to Low, in the case of SWPHLV the Middle interval (32.3% - 38.9%) including only two countries (Ireland and Austria). There were also changes in the High and Maximal intervals. In the case of SWPHLV, seven countries are included in the High interval (38.9% - 45.5%), compared to five countries in the case of SWHEV, by Sweden and Romania moving from the Maximal interval to High, the Maximal interval (45.5% - 52.1%) including in the case of SWPHLV only three countries (Slovakia, Finland and Hungary). On the other hand, the Minimal range (19.1% - 25.7%) includes the same five countries and in the same order as in the case of SWHEV.

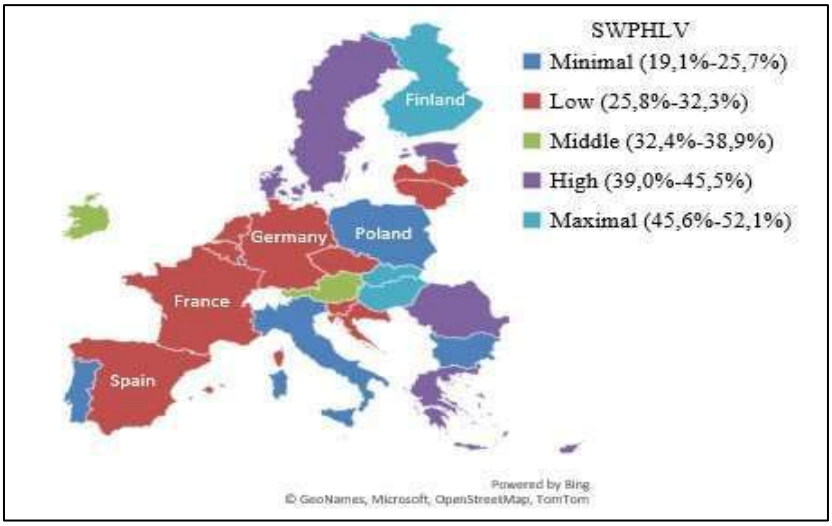

Figure 6. Geographical distribution of SWPHLV by value intervals
Source: prepared by the author and powered by Bing

Taking into account the fact that, in the case of SWPHLV, the Low interval includes 37.04% of EU countries, and that the Minimal and Low intervals include 55.56% of EU countries, it can be concluded that there is a significant concentration of them in the area of low SWPHLV values, with countries with Maximal values representing only 11.11% of the total.

In terms of the shares of women who have experienced physical, threats or sexual violence, by an intimate partner, taken as a whole, the distribution of EU member states is relatively similar (Figure 7) in the sense that the highest values are recorded in Hungary (41.1%) and Romania (37.0%), and the lowest in Bulgaria (9.3%), Portugal (10.3%) and Poland (11.2%).

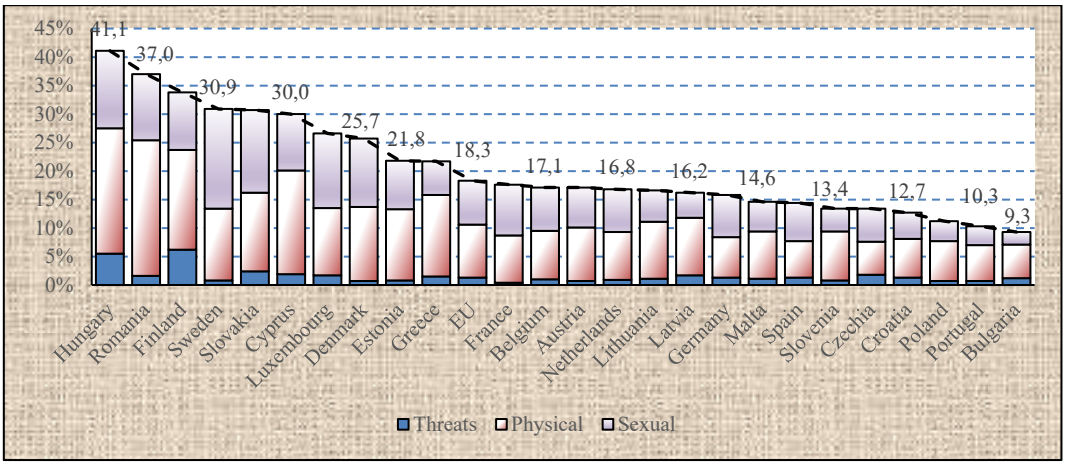

Figure 7. Ranking of EU states by shares of physical, threats or sexual violence
Source: prepared by the author

However, when analysed separately, the shares of the three types of violence included here, namely physical violence (SWPHYV), sexual violence (SWSEX) and treats (SWTHRV), lead to significantly different rankings of countries. The analyses do not include Italy, for which no data were available on the shares of each of the three types of violence.

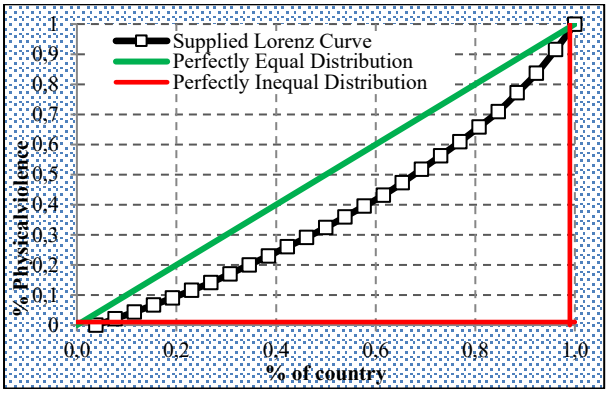

Figure 8. Lorenz curve of SWPHYV Source: prepared by the author

Thus, in terms of the share of women who have experienced physical violence by an intimate partner (SWPHYV), Romania (23.8%) is in first place, with 14.5 percentage points above the EU average, followed by Hungary (22.0%) and Cyprus (18.2%), with 12.7 and 8.9 percentage points above the EU average, while, at the opposite pole, the lowest values were recorded in Czechia (5.8%) and Bulgaria (5.9%), with 3.5 and 3.4 percentage points below the EU average. PWPHYV values around the EU level (9.3%) were recorded in Ireland (9.8%), Austria (9.4%), Slovenia (8.6%), Belgium (8.5%), the Netherlands (8.4%), as well as France and Malta, with 8.3% each.

In the case of SWHPYV the degree of concentration is higher than in the case of SWPHLV, a fact highlighted by the Lorenz curve (Figure 8) and by the values of the concentration coefficients Gini Coefficient (G=0.2137), Shannon Entropy (S=3.1731) Normalized Entropy (S_0=0.9739).

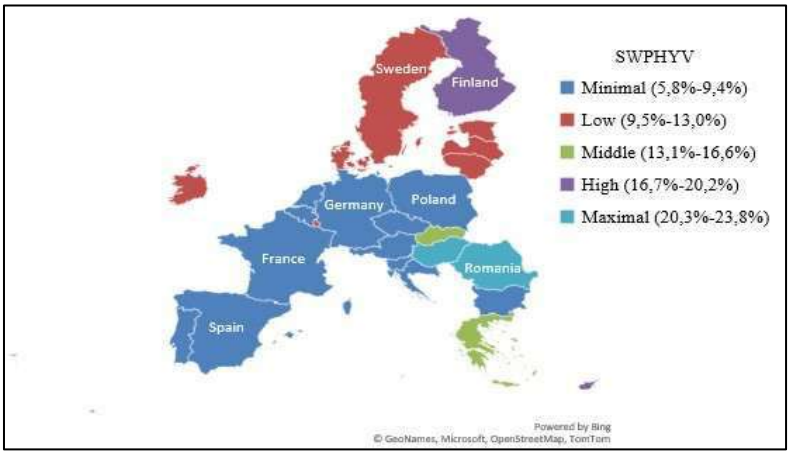

Figure 9. Geographic distribution of SWPHYV values
Source: prepared by the author and powered by Bing

This fact is also underlined by the geographical distribution of the twenty-six countries in the five value ranges (Figure 9). From this point of view, the Minimal range is differentiated, which includes 13 countries (50.0% of the total), while the Middle, High and Maximal ranges include only two countries each, respectively Slovakia and Greece, in the Middle range, Finland and Cyprus, in the High range, and Hungary and Romania, in the Maximal range. In terms of the share of women who have experienced sexual violence by an intimate partner (SWSXV), Sweden was in first place with a share of 17.5% (9.8 percentage points above the EU average), followed by Slovakia with a share of 14.5% (6.8 percentage points above the EU average). The lowest SWSXV values were recorded in Bulgaria (2.2%) and Portugal (3.3%) with 5.5 and 4.4 percentage points below the EU average. SWSXV values around the EU level (7.7%) were recorded in Estonia (8.5%), Austria (9.4%), Belgium (7.6%), the Netherlands (7.5%), Germany (7.4%) and Austria (7.0%).

Although the geographical distribution of SWSXV values (Figure 10) differs from that of SWPHYV values, the degree of concentration is also higher. Thus, while in the case of SWPHYV, the Gini Coefficient was G_{SWPHYV}=0.2137, in the case of SWSXV it is G_{SWSXV}=0.2168. The differences between the two consist in the fact that in the case of SWSXV most countries are included in the Low range, compared to the Minimal range in the case of SWPHYV.

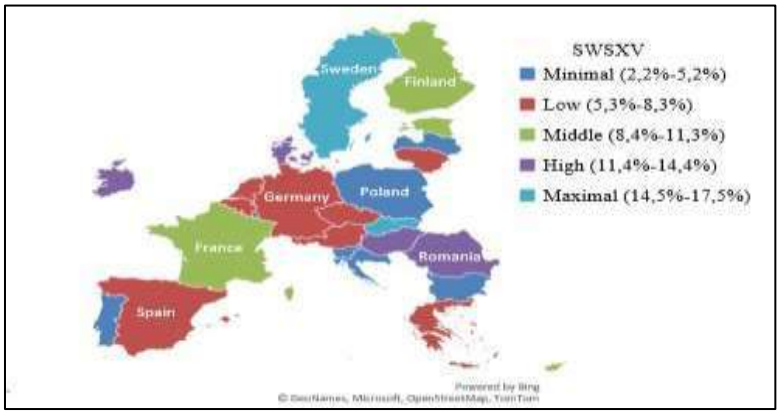

Figure 10. Geographic distribution of SWSXV values
Source: prepared by the author and powered by Bing

Regarding the share of women who were victims of threats by an intimate partner (SWTHRV), the values are much lower than in the cases of physical violence and sexual violence. The highest values of SWTHRV were recorded in Finland, of 6.2% (4.9 percentage points above the EU average) and Hungary, of 5.5% (4.2 percentage points above the EU average), and around the SWTHRV value at EU level (1.3%) were Romania (1.6%), Greece (1.5%), as well as Germany, Spain and Croatia with shares of 1.3% each. It is worth noting that, in the case of SWTHRV, in ten countries (Netherlands, Estonia, Sweden, Denmark, Austria, Poland, Portugal, France, Ireland and Slovenia) values below 1% were recorded.

2.3. Consequences of intimate partner violence against women

Depending on the available data, two categories of consequences of violence suffered by women who have experienced violence by an intimate partner were analysed: physical injury or psychological consequences (SWHIPC) and consequences which women life was in danger (SWHLDC).

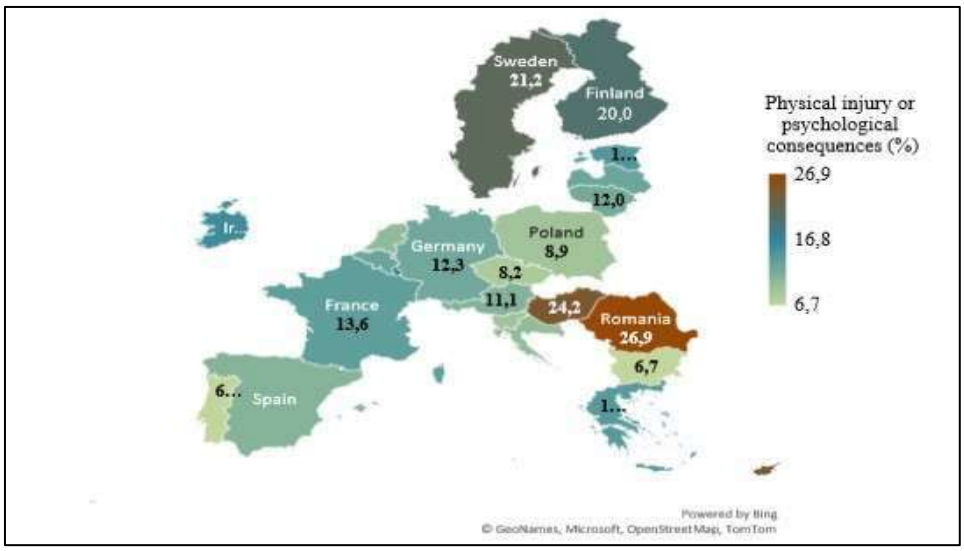

Figure 11. Geographic distribution of SWHIPC values.
Source: prepared by the author and powered by Bing

Given that, out of the twenty-seven EU countries, only twenty-four were included in the analysis, with no data available for Denmark, Italy and Slovakia, only three value ranges Low, Middle and High were used to analyses the concentration of SWHIPC and SWHLDC values.

In terms of the shares of women who have experienced physical injury or psychological consequences by an intimate partner (SWHIPC), the differences between the values recorded at the country level are significant, covering a range of values between 6.7%, a value recorded in Bulgaria, and 26.9%, a value recorded in Romania (Figure 11).

The group of countries with high SWHIPC values (High) included four countries (Figure 12), with SWHIPC values between 21.2%, a value recorded in Sweden, and 26.9%, a value recorded in Romania. Compared to estimated EU-averages (13.0%), in the case of the countries in this group, the SWHIPC values are higher than this with values ranging between 8.2 percentage points in Sweden and 13.9 percentage points in Romania.

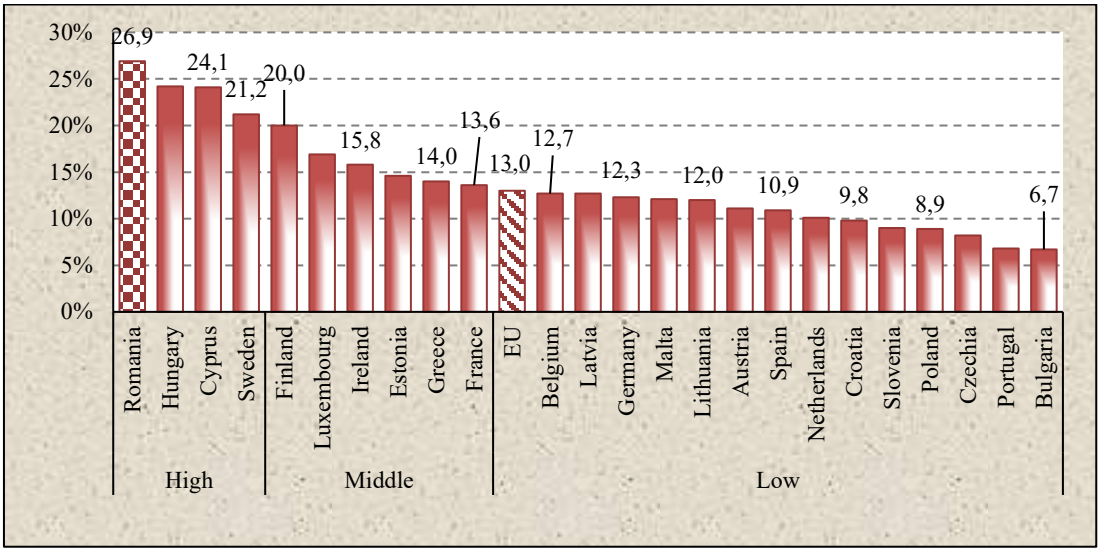

Figure 12. Ranking of countries according to SWHIPC values. Source: prepared by the author

The group of countries with middle values of SWHIPC (Middle) included six countries, with the highest SWHIPC values recorded in Finland (20.0%) and Luxembourg (16.9%), and the lowest in Greece (14.0%) and France (13.6%). In contrast to the countries in the High group, although five of the Middle group have values above the estimated EU-averages, the differences from them are much smaller, 3.9 and 2.8 percentage points in Luxembourg and Ireland, and below 2 percentage points in Estonia, Greece and France.

The third group (Low) included fourteen countries, with the highest SWHIPC values recorded in Belgium and Latvia (12.7%), as well as in Germany (12.3%) and Malta (12.1%), and the lowest in Bulgaria (6.7%) and Portugal (6.8%). This group is also characterized by the fact that it includes only countries with SWHIPC values lower than estimated EU-averages, ranging from -0.3 percentage points in Belgium and Latvia to -6.3 percentage points in Bulgaria.

In terms of concentration, the values of the Gini Coefficient (G=0.2195), Shannon Entropy (S=3.1048), and the Lorenz curve (Figure 13) highlight a situation similar to SWPHYV.

In the case of SWHIPC, the interval that includes the largest number of countries is Low, the fourteen countries included in it representing 58.33% of the countries included in the analysis, while the High interval includes only four countries (16.67%).

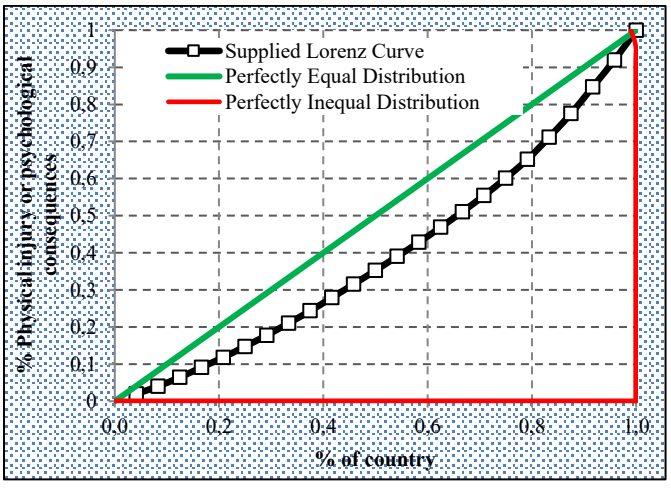

Figure 13. Lorenz curve of SWHIPC Source: prepared by the author

The second category of consequences is those in which women's life was in danger (SWHLDC). From this point of view, among the twenty-four countries included in the analysis, the lowest value of SWHLDC, of 2.4%, was recorded in Bulgaria, and the highest, of 16.1%, was recorded in Romania (Figure 14).

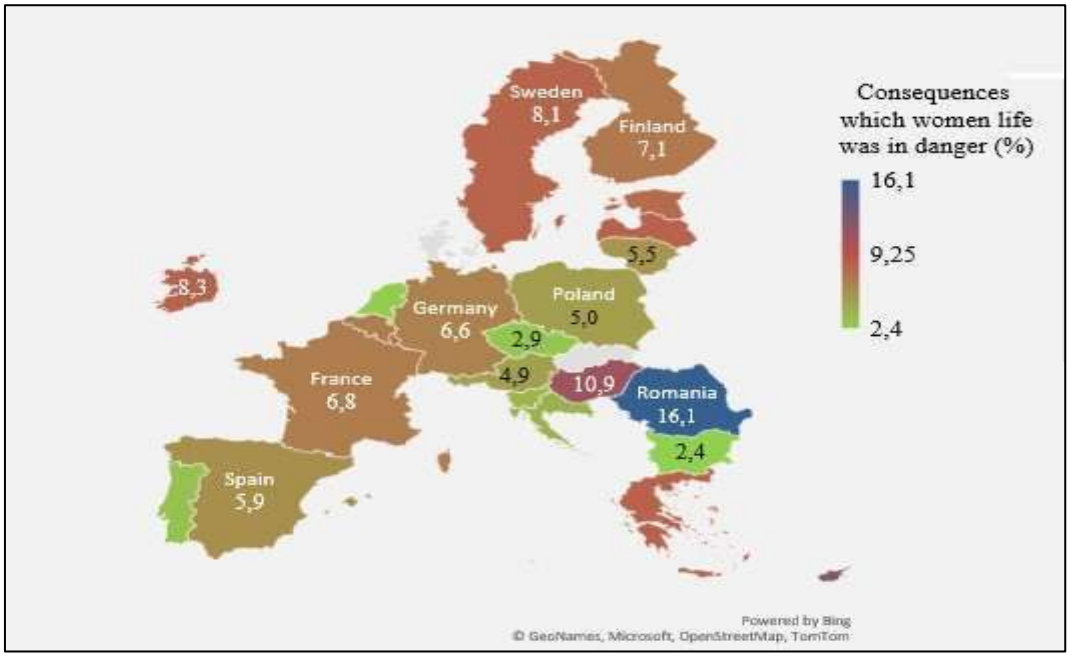

Figure 14. Geographic distribution of SWHLDC values
Source: prepared by the author and powered by Bing

By value range, the range of countries with high SWHLDC values (High) included two countries (Figure 15), Cyprus (12.3%) and Romania (16.1%). Compared to the estimated EU-averages (6.6%), in the case of countries in this group, SWHLDC values are higher than this by 9.5 percentage points in Romania and 5.7 percentage points in Cyprus.

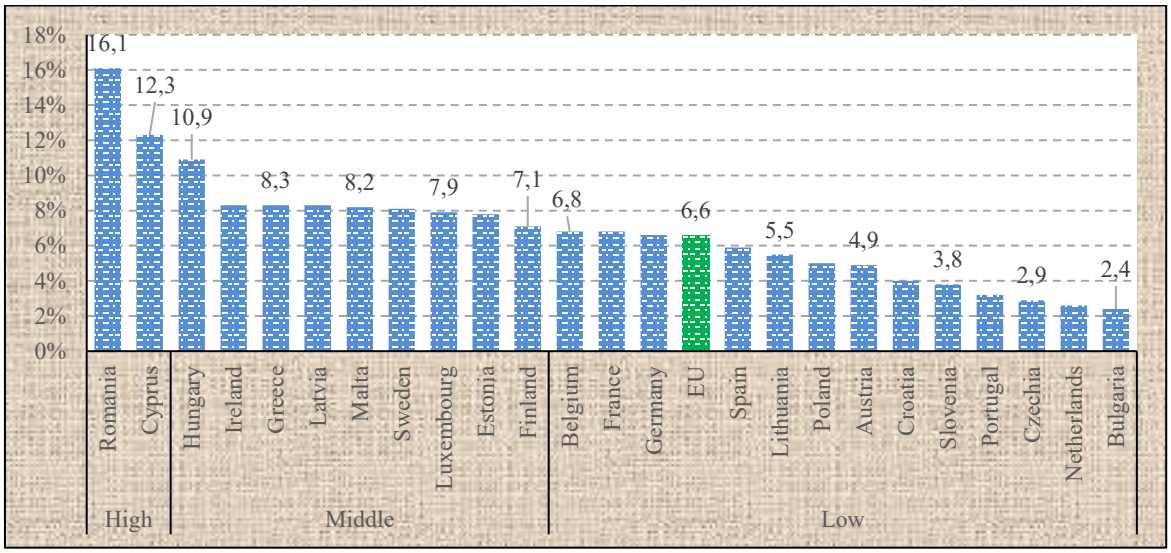

Figure 15. Ranking of states according to SWHLDC values. Source: prepared by the author

The group of countries with middle values of SWHLDC (Middle) included nine countries, the highest values of SWHLDC being recorded in Hungary (10.9%), Ireland, Greece and Latvia (each 8.3%), and the lowest in Finland (7.1%) and Estonia (7.8%). Compared to the estimated EU-averages of SWHLDC, the countries in this group record higher values ranging from 0.5 percentage points in Finland to 4.5 percentage points in Hungary.

The third group (Low) included thirteen countries, the highest values of SWHLDC being recorded in Belgium and France (each 6.8%), and the lowest in Bulgaria (2.4%), Netherlands (2.6%) and the Czechia (2.9%). This group is also characterized by the fact that it includes both countries with SWHLDC values higher than the estimated EU-averages (6.6%), but by only 0.2 percentage points, and countries with SWHLDC values lower than the estimated EU-averages, ranging from -0.7 percentage points in Spain to -4.2 percentage points in Bulgaria.

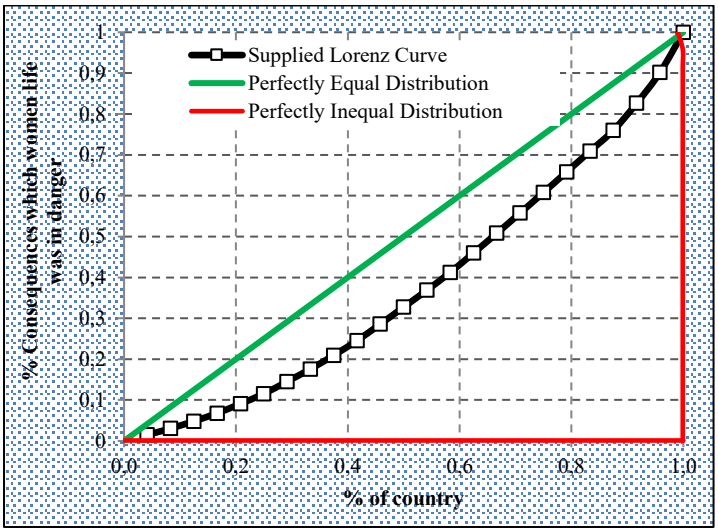

Figure 16. Lorenz curve of SWHLDV values. Source: prepared by the author

In terms of the degree of concentration, the values of the concentration coefficients, Gini Coefficient (G=0.2248), Shannon Entropy (S=3.0759) and Normalized Entropy (S_0=0.9679), as well as the Lorenz curve (Figure 16) highlight a higher degree of concentration of SWHLDC than of SWPICV, but the interval that includes the largest number of countries is also Low, the thirteen countries included in it representing 54.17% of the countries included in the analysis, while the High interval includes only two countries (9.33%).

3. Conclusions

Although the disparities between EU member states in terms of shares of ever-partnered women who have experienced violence by an intimate partner, by type of violence and by consequences of violence are significant, their degrees of concentration are not high, the lowest value of the Gini Coefficient, of 0.2248, in the case of share of ever-partnered women who have experienced consequences which her life was in danger, and the lowest, of 0.20, in the case of share of ever-partnered women who have experienced psychological violence by an intimate partner.

The shares of ever-partnered women who have experienced violence by an intimate partner, by type of violence, differ significantly both from one type of violence to another and between the countries included in the analysis. Thus, the highest values of shares of ever-partnered women who have experienced violence by an intimate partner (SWHEV) were recorded in the case of psychological violence (SWPHLV), of 52.1% (Hungary), with an amplitude of values of 33.0 percentage points, and the lowest values of SWHEV were recorded in the case of sexual violence (SWSXV), of 17.5% (Sweden), with an amplitude of values of 15.3 percentage points.

By country group, the highest SWHEV values were recorded in Hungary, Finland and Slovakia, in the case of SWPHLV, Romania and Hungary, in the case of SWPHYV, as well as Sweden and Slovakia, in the case of SWSXV. At the opposite pole, low SWHEV values were recorded in Bulgaria, Portugal and Poland, in the case of SWPHLV and SWSXV, as well as in Czechia, Bulgaria and Portugal, in the case of SWPHYV.

In terms of the consequences of intimate partner violence against women, the most frequent were physical injury or psychological consequences (SWHIPC), the difference between the highest value of SWHIPC, of 26.9% (Romania) and the lowest, of 6.7% (Bulgaria), was 20.2 percentage points. As for the second category of consequences analysed, those in which women's life was in danger, both the extreme values of SWHLDV and the range between them were lower than in the case of SWHIPC. By group of countries, the highest shares of the consequences of intimate partner violence against women were recorded in Romania, Hungary and Cyprus, and the lowest in Bulgaria, Portugal and Czechia.

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Mapping the evolution of ESG research in the retail sector: A bibliometric and conceptual analysis

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Abstract. This study provides a comprehensive bibliometric assessment of the scientific literature on "ESG retail" published between 2011 and 2024, mapping the field's conceptual evolution, thematic consolidation, and emerging research directions. Using the Web of Science Core Collection and VOSviewer for keyword co-occurrence analysis, the investigation reveals that ESG retail has transitioned from an underdeveloped topic into a mature interdisciplinary domain shaped fundamentally by the European sustainable-finance regulatory framework. The analysis identifies a coherent tripartite structure centred on: corporate performance and sustainability evaluation; investor behaviour and ethical investment motivations; and informational integrity, disclosure quality, and greenwashing risk. The chronological progression of concepts demonstrates a clear shift from early ethical considerations to methodological standardisation, disclosure consolidation and governance-oriented perspectives following the adoption of SFDR, EU Taxonomy, MiFID II, CSRD and ESRS. The findings confirm that ESG retail constitutes a stable and integrated analytical ecosystem aligned with SDG 8, SDG 12 and SDG 16, with research increasingly oriented toward materiality assessment, data comparability and sustainability-reporting governance. The study also highlights the replicability of the bibliometric model and acknowledges methodological limitations arising from database selection and keyword constraints.
Keywords: *ESG retail, bibliometric analysis, VOSviewer, corporate performance, sustainability, governance, investment behavior, SDG.*

Introduction

The evolution of sustainability principles in the economic and financial sphere has developed along a historical trajectory that begins with the consolidation of the European single market and culminates in the contemporary architecture of ESG regulation. At the same time, the gradual diffusion of sustainability principles also began to shape ESG practices within the retail sector, where transparency, consumer trust, and responsible market conduct became increasingly relevant. The foundational moment is represented by the Treaty of Rome of 1957, which established the European Economic Community and laid the institutional bases for the free movement of goods, services, capital, and people, principles that would later support the emergence of unified consumer and investor markets across the Union [1][2][3]. Subsequent milestones, such as the Single European Act of 1986, further advanced market integration and strengthened the regulatory and political dimension of European cooperation [4][5][6].

The Maastricht Treaty of 1992 institutionalized economic convergence and deepened the Union's governance architecture [7][8], while the Treaty of Lisbon of 2007 introduced a modernized legal and policy framework designed to enhance transparency, democratic accountability, and consumer protection within the internal market [9][10]. These successive treaties created the structural conditions through which sustainability, financial ethics, and retail investor protection would eventually be integrated into European law.

Building on these foundations, the EU introduced an extensive regulatory framework that redefined transparency, reporting, and investor protection. The adoption of the Sustainable Finance Disclosure Regulation (SFDR) in 2019 brought mandatory sustainability-related disclosure rules for financial intermediaries, creating unprecedented transparency in ESG communication [11]. The 2020 EU Taxonomy Regulation established a unified classification system for environmentally sustainable economic activities, providing a technical basis for evaluating financial products marketed to retail clients [12]. In parallel, MiFID II was amended in 2021 to incorporate sustainability preferences into suitability assessments, thereby integrating ESG considerations directly into investment advice and portfolio construction processes [13][14]. Corporate sustainability reporting reached a new level of standardization with the Corporate Sustainability Reporting Directive (CSRD) in 2022, followed by the introduction of the European Sustainability Reporting Standards (ESRS) in 2023, which impose granular disclosure obligations relevant for both retail and institutional stakeholders [15][16]. Moreover, retail investors were further protected by the PRIIPs framework (Regulation 1286/2014 and its 2021 amendments), designed to ensure clear, comparable, and non-misleading information regarding packaged retail and insurance-based investment products [20][21][22][23]. The most recent development, the 2023 Retail Investment Strategy, explicitly centers retail investors within EU capital markets, aiming to enhance trust, transparency, and fair treatment in the distribution of sustainable financial products [17][18][19].

The contemporary consolidation of ESG principles in the retail investment ecosystem emerged in response to growing global awareness regarding environmental and social risks, influenced strongly by the 1987 Brundtland Report on sustainable development [24] and the adoption of the 2030 Agenda for Sustainable Development [25]. At the international level, the Sustainable Development Goals established in 2015 provide a normative framework that is closely aligned with the objectives of ESG-related regulation [26]. Within this context, SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 16 (Peace, Justice and Strong Institutions) are directly relevant for the retail investment domain [27][28][29]. Together, they emphasize financial literacy, responsible market conduct, transparency, and institutional integrity, dimensions that underpin the emerging field of "ESG retail". Thus, the global normative context has reinforced the EU's orientation toward sustainable finance and the need to restructure economic practices around environmental responsibility, social fairness, and governance quality.

Within this evolving regulatory landscape, academic literature has increasingly recognized "ESG retail" as a distinct interdisciplinary field positioned at the intersection of sustainability, investment behavior, ethical communication, and market regulation. While early studies primarily examined environmental and operational aspects of retail activity, contemporary research explores deeper structural questions regarding investor motivations, information asymmetries, greenwashing risks, and the governance mechanisms underlying sustainable investment practices. This transformation has elevated ESG from a voluntary reporting framework to a strategic orientation embedded in consumer protection, disclosure obligations, and financial decision-making processes.

Accordingly, the present study seeks to provide a comprehensive bibliometric mapping of the "ESG retail" domain, assessing its conceptual evolution, thematic structure, and research trajectories. To achieve this, the analysis is guided by three core research questions: *RQ1: How has the scientific literature on ESG retail evolved conceptually and temporally between 2011 and 2024?; RQ2: What thematic clusters define the intellectual structure of the field, and how are sustainability, governance, and investor behavior interconnected?; RQ3: To what extent do the emerging themes reflect the dynamics of the European regulatory framework and the global sustainability agenda?*

Through these questions, the study positions ESG retail as a mature and expanding research field shaped simultaneously by historical institutional development, contemporary regulatory consolidation, and the global transition toward responsible and transparent financial markets.

Literature review

The literature on ESG in the retail sector has experienced accelerated development over the past decade, consolidating three major directions of evolution: operational transformation and strategic orientation through sustainability, the strengthening of transparency and corporate governance, and the behavioral dynamics of retail investors in relation to ESG information. These directions reflect both the conceptual maturation of the field and the intensification of normative, technological, and investment pressures that are redefining the structure and functioning of the contemporary retail sector.

The first direction highlights the way sustainability has become a central element of retail transformation. The foundations were established through analyses of environmental strategies and measurement instruments used by companies (Naidoo & Gasparatos, 2018) [30], later expanded through operational approaches regarding supply chain optimization and the integration of sustainable criteria into logistics flows (Sobie & Roberson, 2020) [31]. In parallel, the literature has shown that retail uses ESG not only as an efficiency tool but also as a mechanism for shaping consumer perception through coordinated corporate, product, and store-level strategies (Elg & Welinder, 2022) [32]. Consumer behavior studies demonstrate that eco-friendly initiatives influence perceived credibility, loyalty, and purchase intention (Vaitinadin, 2019 [33]; Song et al., 2024 [34]). Houston, Lin, Shan, and Shen (2023) [35] showed that ESG factors directly influence consumer preferences and behavior. Moreover, private labels play a central role in implementing ESG objectives, offering control over traceability and environmental performance (Ghiselli, 2022) [36]. Kaur and Siddhey (2025) [37] developed a concise framework for analyzing how retail companies integrate sustainability into their practices. Applied studies confirm that ESG can generate competitive advantage, both in case analyses (Mi, 2024) [38] and in global performance evaluations (Buallay, 2022) [39], while international documents provide additional clarification on the taxonomies and standards used in defining financial sustainability (OECD, 2020) [40][41].

The second major direction concerns transparency, governance, and the credibility of ESG information, a domain marked by structural challenges. Research shows considerable variation in CSR reporting quality in retail (Mayorova, 2019) [42], as well as significant discrepancies between ESG scores provided by different rating agencies, with direct implications for greenwashing risk (Kathan et al., 2025) [43]. The ESG transformation process requires phased transparency to ensure the credibility of internal changes (Bataeva, 2024) [44], yet independent reports indicate high levels of non-compliance in the claims of European retail funds (Sustainable Finance Observatory, 2020) [45]. Alamillos and de Mariz (2022) [46] highlighted that EU ESG regulations produce extraterritorial effects and influence global firms through value-chain pressures. Baicu et al. (2022) [47] showed that retail managers perceive the Green Deal both as an opportunity and as a financial and operational pressure. Against this background, legal assessments underscore increasing litigation risks, increasingly strict requirements for ESG statement accuracy, and pressures on supply chains (Hoffmann & Fraser, 2023) [48]. Convergently, technical and consulting sources show that most companies are unprepared for the wave of new reporting obligations due to gaps in data infrastructure, internal controls, and operational capacity (PwC, 2023 [49]; KPMG, 2023 [50]; Columbus Global, 2024 [51]). Sectoral assessments confirm these deficiencies, outlining the material risks specific to the retail industry (S&P Global Ratings, 2020) [52] and emphasizing the urgent need for digitalization and automation of ESG processes (Morrison & Sehgal, 2024) [53].

The third direction focuses on the behavior of retail investors, an area of research that has grown substantially in recent years. International data show that interest in ESG varies across countries, and many investors still lack sufficient information (GlobeScan, 2021) [54]. Retail investors in Central and Eastern Europe, as shown by the Polish case, express interest in ESG but few are willing to apply it when it implies reduced profits (Petelczyc, 2022) [55], whereas in Germany preferences are segmented based on ethical motivations, risk perception, and financial expectations (Heidorn et al., 2023) [56].

Retail investors consider ESG increasingly relevant, their values being correlated but difficult to satisfy through uniform measures, and some of them accept return trade-offs to support their principles. Recent literature shows that ESG disclosures do not generate detectable reactions from retail investors (Moss et al., 2023) [57]. However, other studies suggest that retail investors react to ESG information only when they perceive it as relevant for corporate financial performance (Li et al., 2024) [58]. Individual investors respond to ESG only when the information is presented in a simplified format, such as ESG rankings, which stimulate their attention and trading volume (Bazrafshan, 2023) [59], and Deka et al. (2023) [60] show that behavioral biases and risk perception significantly influence ESG decisions. Recent behavioral experiments show that nudges can increase investment engagement (Hutchings, 2025) [61], and the introduction of the "Future Generations" pillar shows that retail investors perceive intergenerational concerns as already embedded in the existing ESG structure (Benuzzi et al., 2024) [62].

Overall, these three directions illustrate the convergence between operational sustainability, corporate transparency, and investor behavior, confirming that the retail sector is profoundly shaped both by the conceptual evolution of the ESG literature in retail and by normative pressures and the global dynamics of sustainability.

Materials and Methods

The database was searched in the Web of Science Core Collection, which was selected due to its rigorous indexing standards and comprehensive coverage of high-impact scholarly publications, ensuring that the resulting dataset provides a reliable, consistent, and methodologically robust foundation for bibliometric analysis. The search used the phrase "ESG retail" in the "Topic" field to identify publications that examine the relationship between sustainability principles and the retail sector. The acronym ESG, referring to the environmental, social and governance dimensions of sustainability, is widely employed in academic and policy discourse to describe the overarching framework through which organisational responsibility is conceptualised. Applied to the retail sector, this framework delineates an expanding area of research concerned with how sustainability initiatives, investor preferences and transparency requirements interact within retail-oriented activities.

The initial search yielded 102 records. A systematic series of filters was then applied to ensure analytical consistency. Using the "Final Publication Year" indicator, records from 2025 were excluded due to ongoing indexing processes. Within the "Document Types" filter, only *Articles, Review Articles and Proceedings Papers* were retained to avoid heterogeneity generated by alternative formats. To maintain terminological consistency and facilitate comparability, only English-language publications were included. Applying these criteria resulted in a final chronological interval of 2011–2024, corresponding to the earliest relevant entries and the most recent year fully indexed in the database.

The refined dataset consisted of 62 publications, which were exported in plain-text format (Full Record and Cited References) and subsequently processed using VOSviewer (version 1.6.20), a dedicated bibliometric mapping software used to visualise thematic linkages and structural patterns within the field. The analysis employed a keyword co-occurrence method, with "All Keywords" selected as the analytical unit and the "Full Counting" method used to assign equal weight to each occurrence of a term. This methodological configuration was chosen because co-occurrence mapping enables the identification of thematic structures across the field, revealing conceptual linkages and highlighting the evolution of research trajectories related to ESG considerations in the retail sector.

Of the 358 keywords initially extracted, terms with fewer than five occurrences were excluded to minimise analytical distortion and enhance the interpretability of the resulting clusters. The threshold was established following preliminary assessments indicating that this cut-off produced the most stable and analytically coherent network configuration. The final set of 11 recurrent keywords formed the conceptual core of the field, enabling the delineation of its principal thematic areas. The bibliometric visualisations generated through VOSviewer illustrated the internal structure of the ESG retail research domain, reflecting its ongoing consolidation, diversification and maturation.

Limitations of the study

This analysis is shaped by several methodological limitations that result from the choices made in the stage of constructing the dataset and in the bibliometric processing. The exclusive reliance on the Web of Science Core Collection, selected for its rigorous indexing standards, directly limits the volume and variety of literature available for analysis. Studies indexed on other platforms such as Scopus or Google Scholar are not included in the dataset, which means that the scientific landscape regarding ESG practices in the retail sector is reflected exclusively through the perspective offered by this database. In addition, the use of the expression "ESG retail" in the "Topic" field anchors the search in a specific conceptual formulation. Works that use alternative terms or related concepts may not have been identified, influencing the way in which the thematic profile of the set is shaped.

The filtering procedures applied contribute, in turn, to the limitations of the study. The use of the "Final Publication Year" field ensured temporal coherence but led to the exclusion of 2025 publications still in the indexing process. The exclusive selection of articles, review articles, and conference proceedings provided methodological homogeneity, but eliminated types of publications that could bring complementary perspectives. The strict focus on English-language literature, necessary for maintaining terminological consistency, introduces a linguistic limitation that may exclude contributions that analyse ESG dynamics in retail markets where English is not the predominant publishing language.

The bibliometric analysis presents certain limitations as well, since the use of VOSviewer as mapping software, although it offers a solid framework for the visualization of thematic relationships, tends, through its mode of operation, to give greater visibility to terms that appear frequently. The approach based on the co-occurrence of keywords, using "All Keywords" and the "Full Counting" method, assigns the same weight to each occurrence, but ends up highlighting dominant concepts and diminishing the visibility of emerging themes. The minimum threshold of five occurrences, established following preliminary evaluations, increases the stability of the resulting network but leads to the exclusion of low-frequency terms that could signal emerging research directions in the ESG retail field. Thus, the 11 keywords describe only the dominant themes in the selected literature, without covering the entire diversity of studies that analyse ESG in the retail sector.

Results and discussion

The integrated analysis of the literature confirms that "ESG retail" has emerged as a distinct and mature field, shaped by the accelerated transformations of the European sustainable-finance framework and by the visible increase in academic interest after 2020. From a temporal perspective, the field has evolved from a marginal area into a stable research domain, consolidated as reporting obligations and transparency requirements intensified (1). The most highly cited contributions show that ESG has become the central instrument through which corporate performance, investor behaviour, and the credibility of sustainability information are analysed, confirming the theoretical maturation of the field (2). The thematic structure highlights a coherent architecture composed of three pillars: corporate performance and sustainability, behavioural dynamics of investors, and communication integrity, which reflects the convergence between academic research, European regulations, and the objectives of SDG 8, SDG 12, and SDG 16 (3).

The evolutionary analysis shows a clear transition from isolated ethical concerns to the systematic integration of ESG in investment decisions and governance mechanisms, culminating in the standardisation of reporting and the consolidation of institutional responsibility (4). The density structure confirms the centrality of ESG within the conceptual field and indicates emerging directions linked to materiality, comparability, and the governance of sustainability data, elements essential for the functioning of retail-oriented financial markets (5).

Overall, the field is configured as a stable interdisciplinary ecosystem situated at the intersection of corporate performance, investor behaviour, and informational transparency, being strengthened simultaneously by normative pressures, global sustainability orientations, and the progressive maturation of the analytical framework in the specialised literature.

1. ***Temporal evolution and conceptual emergence of ESG retail***

The evolution of publications on "ESG retail" between 2011 and 2024, presented in Figure 1, shows a clear upward trend after 2019, when the first effects of the Sustainable Finance Disclosure Regulation (SFDR) (Regulation (EU) 2019/2088) became visible, reflected in 2 publications. The rise observed in 2020, with 4 publications, corresponds to the establishment of the sustainable investment framework under the EU Taxonomy (Regulation (EU) 2020/852), while the dynamic recorded in 2021, with 1 publication, is linked to the integration of ESG criteria through the Markets in Financial Instruments Directive (MiFID II) (Regulation (EU) 2021/1253). The significant growth recorded in 2022 and 2023, with 9 and 14 publications respectively, is associated with the implementation of the Corporate Sustainability Reporting Directive (CSRD) (Directive (EU) 2022/2464) and the adoption of the European Sustainability Reporting Standards (ESRS) (Regulation (EU) 2023/2772). The sharp increase culminating in 2024, with 30 publications signalling the maturation of the field, indicates that EU reporting regulations have significantly stimulated academic interest in ESG retail.

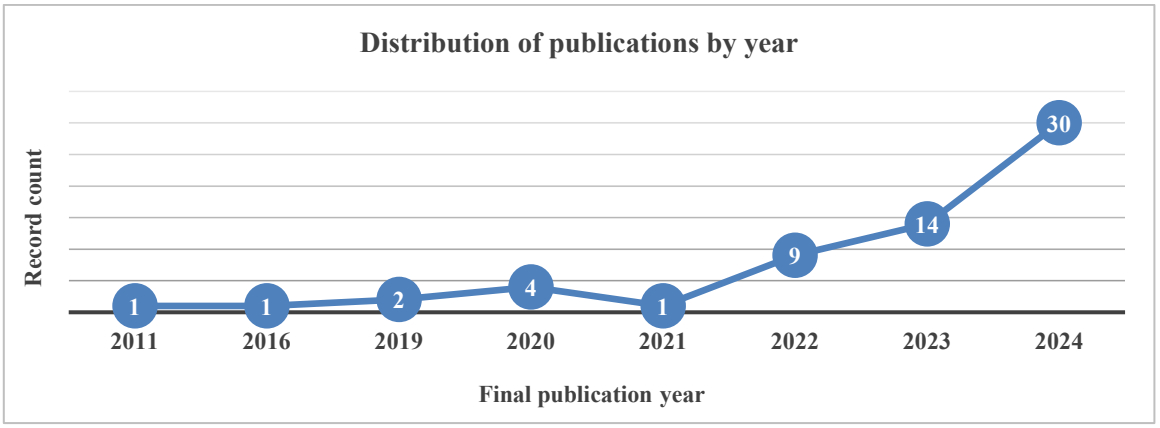

Figure 1. Distribution of publications by year on "ESG retail" (2011-2024)

Source: Authors' own research results.

2. ***Citation impact, influential contributions, and the consolidation of the field***

Table 1 synthesizes the most influential contributions to the "ESG retail" field during 2011–2024. The first three studies define the dominant conceptual directions: "Do Responsible Investors Invest Responsibly?" (Gibson Brandon et al., 2022; 108 citations) [63] highlights the discrepancies between stated ESG commitments and their actual reflection in portfolio composition; "Sustainable Finance and Fintech: Can Technology Contribute to Achieving Environmental Goals? A Preliminary Assessment of 'Green Fintech' and 'Sustainable Digital Finance'" (Macchiavello & Siri, 2022; 105 citations) [64] shows that emerging tools in sustainable finance can enhance the transparency and reliability of ESG information; and "Corporate ESG rating and stock market liquidity: Evidence from China" (He et al., 2023; 64 citations) [65] demonstrates that firms with stronger ESG performance exhibit superior stock market liquidity.

Complementary studies reinforce the theoretical architecture of the field: Busco et al. (2020) [66] examine the materiality and financial relevance of ESG disclosures; Sood et al. (2023) [67] analyze how investors prioritize sustainability criteria; Lee, Pak, and Roh (2024) [68] investigate how institutional pressures and digitalization capabilities shape ESG strategy and triple bottom line performance; Diouf, Hebb, and Touré (2016) [69] explore the drivers of socially responsible retail investment decisions; Martini (2021) [70] traces the conceptual evolution of responsible investing within the EU sustainability framework; Carlsson Hauff and Nilsson (2022) [71] assess investor perceptions of ESG mutual fund strategies; and Zhang et al. (2024) [72] evaluate the effects of ESG ratings on trading activity.

Taken together, these studies confirm the consolidation of ESG as a mature research domain that is central to understanding investor behavior, market dynamics, and the ongoing transformation of the retail sector.

Table 1. Top 10 most-cited articles in the "ESG retail" dataset (2011–2024)

No.	Title	Authors	Total Citations	Average per Year
1	Do Responsible Investors Invest Responsibly?	Brandon, Rajna Gibson; Glossner, Simon; Krueger, Philipp; Matos, Pedro; Steffen, Tom	108	27
2	Sustainable Finance and Fintech: Can Technology Contribute to Achieving Environmental Goals? A Preliminary Assessment of 'Green Fintech' and 'Sustainable Digital Finance'	Macchiavello, Eugenia; Siri, Michele	105	26,25
3	Corporate ESG rating and stock market liquidity: Evidence from China	He, Feng; Feng, Yaqian; Hao, Jing	64	21,33
4	A Preliminary Analysis of SASB Reporting: Disclosure Topics, Financial Relevance, and the Financial Intensity of ESG Materiality	Busco, Cristiano; Consolandi, Costanza; Eccles, Robert G.; Sofra, Elena	60	10
5	How does an investor prioritize ESG factors in India? An assessment based on fuzzy AHP	Sood, Kirti; Pathak, Prachi; Jain, Jinesh; Gupta, Sanjay	55	13,75
6	The interplay of institutional pressures, digitalization capability, environmental, social, and governance strategy, and triple bottom line performance: A moderated mediation model	Lee, Min-Jae; Pak, Anna; Roh, Taewoo	50	25
7	Exploring Factors that Influence Social Retail Investors' Decisions: Evidence from Desjardins Fund	Diouf, Dominique; Hebb, Tessa; Toure, El Hadji	49	4,9
8	Socially responsible investing: from the ethical origins to the sustainable development framework of the European Union	Martini, Alice	40	8
9	Is ESG mutual fund quality in the eye of the beholder? An experimental study of investor responses to ESG fund strategies	Hauff, Jeanette Carlsson; Nilsson, Jonas	33	8,25
10	Do ESG ratings improve capital market trading activities?	Zhang, Chunqiang; Hao, Dayu; Gao, Lu; Xia, Fan; Zhang, Linlang	31	15,5

Source: Authors' own research results.

3. *Thematic clusters and the structural architecture of ESG retail research*

The bibliometric analysis of the literature on "ESG retail", illustrated in **Figure 2**[1], reveals a structured thematic network organized into three major clusters, each representing a distinct analytical dimension of the field. The numbers indicate the frequency of term occurrences. The visualization generated with VOSviewer shows that ESG retail develops along three core directions: corporate performance, investor behavior and ethical orientation, and information transparency, reflecting strong coherence between

[1] The analysis was normalized by "association strength" using standard layout parameters (attraction = 2, repulsion = 0), with a clustering resolution of 1.00 and a minimum cluster size of 1. The "Merge small clusters" option was enabled to prevent network fragmentation. Visualization was weighted by "occurrences" (size = 1.21), with labels displayed as "frames" (font "Open Sans", size 1.00, maximum 35 characters) to enhance clarity and thematic coherence. Connections between terms were represented by "colored lines", applying a minimum strength threshold of 0 and a maximum of 1000 connections, while the size variation parameter was set to 1.00.

academic research, the EU's sustainable finance reforms (SFDR, EU Taxonomy, MiFID II, CSRD, ESRS) and the Sustainable Development Goals, particularly SDG 8, SDG 12 and SDG 16.

Representing the strategic and performance-oriented dimension of ESG retail, *the red cluster* highlights the central role of ESG criteria in evaluating organizational legitimacy and competitive positioning. It is defined by terms such as *"ESG" (21), "performance" (21), "impact" (16), "corporate social-responsibility" (10) and "sustainability" (8).* These concepts underline the transition toward standardized sustainability assessment, consistent with the EU Taxonomy, ESRS disclosure requirements and SDG 8, which emphasize responsible corporate performance and long-term value creation.

Reflecting the behavioral and ethical dimension of ESG, *the green cluster* focuses on investor motivations and value-based investment preferences. The presence of *"socially responsible investment" (7), "individual investors" (5) and "behavior" (5)* illustrates growing academic attention to moral reasoning, perceived risk and ethical commitment. This thematic area aligns with the MiFID II sustainability-preferences regime and is consistent with SDG 12, which promotes informed and ethically grounded consumer and investment choices.

Illustrating the informational and reputational dimension, *the blue cluster* emphasizes the importance of transparent communication for the credibility of sustainable financial products. Structured around *"retail investors" (13), "disclosure" (5) and "greenwashing" (5)*, this cluster reflects concerns about reporting integrity and misleading sustainability claims. It resonates with the disclosure obligations under SFDR, the new European anti-greenwashing guidelines and SDG 16, which foreground transparency, accountability and institutional trust.

Overall, these three clusters define a coherent conceptual structure of the ESG retail field, illustrating its evolution from corporate sustainability performance (red), to ethical investment behavior (green), and transparency and reporting integrity (blue). Together, they confirm the integrated, regulation-driven and SDG-aligned nature of ESG dynamics within the contemporary retail investment landscape.

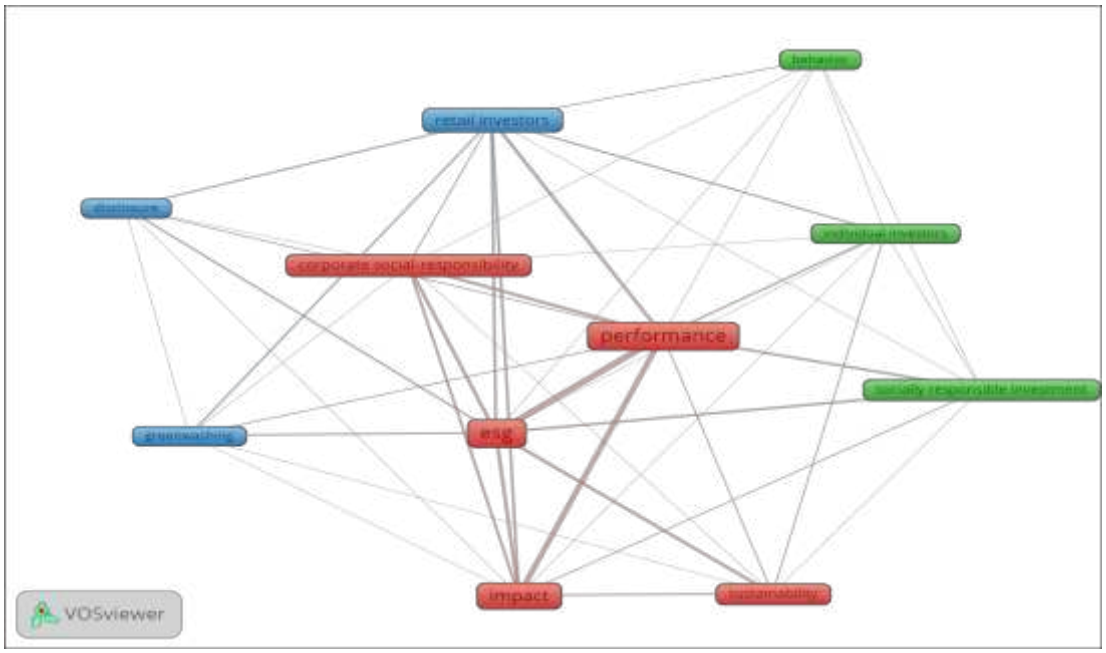

Figura 2. Network visualization of thematic mapping in VOSviewer based on keyword analysis of "ESG retail"

Source: Authors' own research results.

4. Evolutionary dynamics and the chronological progression of ESG retail concepts

Figure 3[2] illustrates the evolution of concepts associated with "ESG retail" during the period 2020–2024, through the overlay visualization generated in VOSviewer. The network presents a dense ensemble of keywords whose spatial proximity and chromatic gradation reflect both the conceptual coherence and the chronological progression of the field. The color spectrum, from cool tones (2020–2022) to warm tones (2023–2024), encodes the average publication year and allows for a clear observation of the evolutionary trajectory of research on ESG within the retail investment environment. The central terms: "ESG", "corporate social-responsibility", "performance", "impact", "retail investors", form the conceptual core of the field, indicating that ESG has become an integrative framework that unites the ethical, managerial, and communicational dimensions of retail investments, consistent with the sustainability vision advanced through SDG 12 and SDG 8.

The first thematic elements associated with the year 2021, such as *"socially responsible investment" and "behavior"*, indicate an incipient phase focused on ethical motivations and the psychological foundations of investment decisions. This early emergence aligns with the growing international emphasis on responsible consumption and ethical decision-making promoted under SDG 12. The transition toward the 2022–2023 interval, highlighted by the appearance of the terms *"ESG", "corporate social-responsibility" and "performance"*, marks the transition toward the conceptual consolidation of the field. These years coincide with the intensification of the European regulatory framework (SFDR, EU Taxonomy, MiFID II, CSRD), which facilitated the integration of ESG as an analytical and managerial instrument in the assessment of corporate sustainability and in the structure of financial products targeted at individual investors, reflecting the principles embedded in SDG 8 concerning responsible and sustainable economic performance.

Between 2023 and 2024, high-frequency terms such as *"retail investors", "disclosure", "impact", "sustainability", "greenwashing" and "individual investors"* appear, indicating a growing orientation toward communicational responsibility, transparency, and reporting. This stage reflects the maturation of the field, the shift of scientific interest toward the verifiability of ESG information, and the intensification of concerns regarding the accuracy of sustainability claims in the context of retail investments, a process accelerated by the entry into force of the ESRS standards in 2023, which introduced strict requirements for the reporting and comparability of corporate sustainability data. These developments are consistent with the transparency and accountability objectives promoted through SDG 16.

Overall, the visualization confirms a coherent evolution of research, from the absence of academic recognition (2020), to the emergence of ethical dimensions (2021), followed by conceptual formalization (2022), and subsequently thematic diversification and consolidation (2023–2024). ESG retail thus emerges as a mature interdisciplinary field in which corporate sustainability, investment psychology, and communication integrity converge within a solid analytical framework strongly shaped by European regulations, the global sustainability agenda reflected in SDG 8, SDG 12, and SDG 16, and the growing demands for transparency in financial markets.

[2] The analysis was performed using normalization by "association strength", with standard layout parameters (attraction = 2, repulsion = 0). Clustering was conducted with a resolution of 1.00 and a minimum cluster size of 1, while the option "Merge small clusters" was enabled to avoid network fragmentation. The visualization was weighted by "occurrences" (size = 1.05), and the score dimension was set to "average publication year", allowing the temporal distribution of terms to be mapped within the network. Labels were displayed as frames (font "Open Sans", maximum length 35 characters, size 1.00) to ensure clarity and visual coherence. Lines connecting the terms were drawn as colored lines, with a minimum strength threshold of 0 and a maximum of 1000 connections, while the size variation parameter was fixed at 1.00. Colors were assigned according to the "Coolwarm" overlay scheme, transitioning from blue tones representing earlier publications to red tones indicating more recent ones, thus illustrating the chronological progression of research themes.

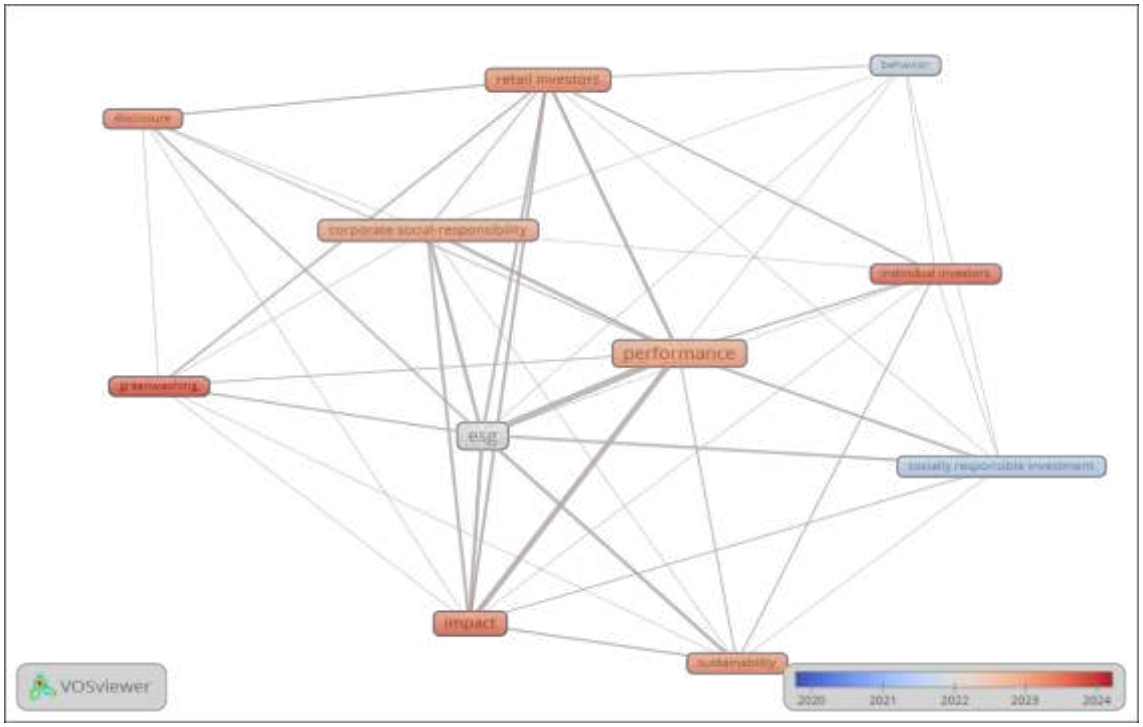

Figure 3. Overlay visualization of thematic mapping in VOSviewer for "ESG retail" (2020–2024).

Source: Authors' own research results.

5. ***Density structure, conceptual concentrations, and emerging research trajectories***

Figure 4[3] highlights the semantic concentrations in the literature dedicated to "ESG retail," outlining a solid conceptual core around the term "ESG," which attracts the densest thematic connections. The direct association with *"performance," "impact," "corporate social-responsibility," and "sustainability"* shows that the assessment of corporate performance and the integration of sustainability criteria represent the dominant direction of the field, reflecting the orientation of the European regulatory framework from the EU Taxonomy and SFDR to the CSRD and ESRS standards and maintaining a clear link with the objectives through SDG 8.

In the proximity of this core, the terms *"retail investors," "individual investors," "socially responsible investment," and "behavior"* form an area of intermediate density that captures the increasingly strong interest in the behavioral dimension of investments. The literature highlights the ways in which values, individual perceptions, and sustainability preferences influence investors' choices, a process also correlated with the principles of SDG 12, normatively strengthened through the integration of ESG preferences.

At the periphery of the network, the terms *"disclosure" and "greenwashing"* indicate intensified concerns regarding the truthfulness of information and the quality of sustainability communication. This density area signals the persistent tension between the need for transparency and the risk of strategic use of ESG terminology in the absence of real substantiation, a theme associated with SDG 16 and

[3] The analysis was conducted using normalization by "association strength", a method selected to calibrate the relationships between terms based on the intensity of their co-occurrences. The layout parameters were set to standard values, with attraction = 2 and repulsion = 0, ensuring a balanced spatial distribution of items within the network. Clustering was performed with a resolution of 1.00 and a minimum cluster size of 1, while the "Merge small clusters" option was enabled to prevent network fragmentation and preserve structural coherence. The visualization was weighted by occurrences (scale = 1.40), emphasizing the frequency of term appearance across the analyzed corpus. Labels were displayed using the "Open Sans" font, with a maximum length of 35 characters, to optimize legibility and visual consistency. The smoothing parameter was defined by a density kernel width of 2.50, allowing for a uniform distribution of semantic intensity around the most significant terms. The visualization mode was set to "item density", enabling the identification of conceptual concentrations according to research intensity. Colors were assigned according to the "Viridis" density color scheme, where low-density areas are represented in shades of blue and high-density areas in bright yellow, highlighting the points of maximum conceptual convergence.

reinforced by the strict reporting and oversight requirements introduced at the European level to combat greenwashing.

Overall, the density visualization outlines a layered thematic structure: a core oriented toward sustainability and performance, an intermediate layer centered on the behavioral dynamics of investors, and a peripheral area dedicated to the integrity of communication and informational governance. This distribution confirms the consolidation of a mature interdisciplinary field, decisively influenced by European regulations and the growing pressure for transparency and responsibility in retail financial markets.

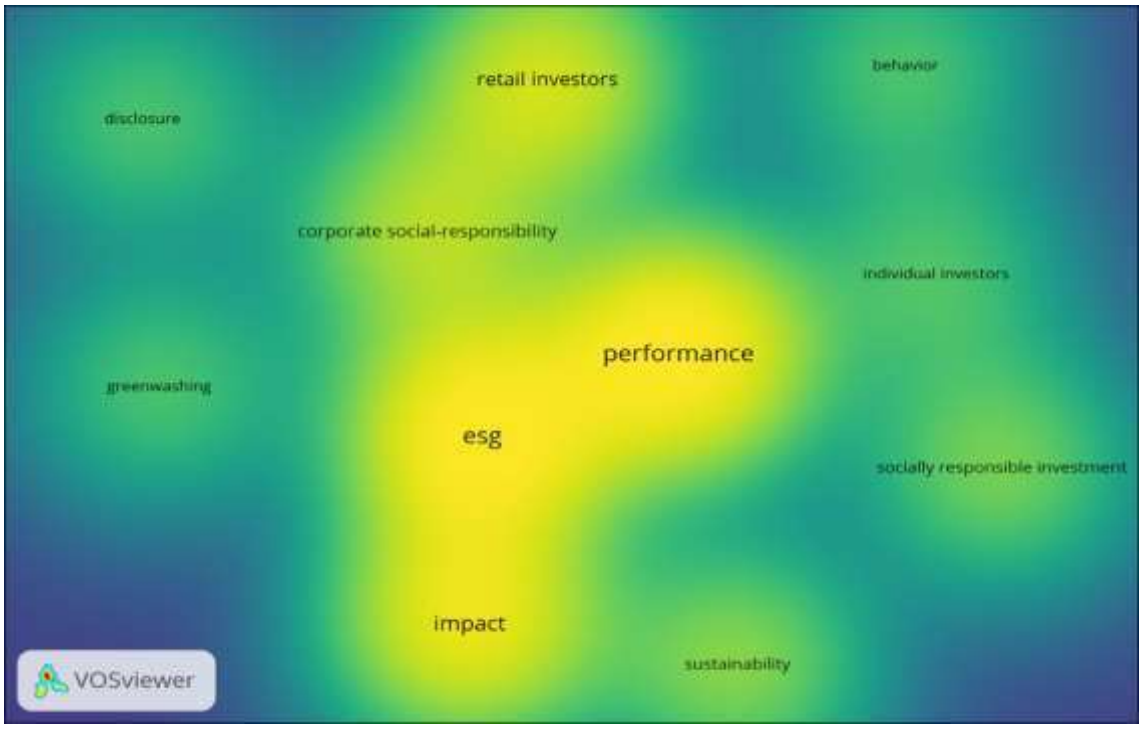

Figure 4. Density visualization of thematic mapping in VOSviewer for "ESG retail".

Source: Authors' own research results.

Conclusion

The bibliometric investigation shows that ESG retail has evolved from a marginal and poorly defined topic into a consolidated interdisciplinary field, shaped by the rapid expansion of the European sustainable finance framework and the structural transformation of investment practices in the retail sector. Regarding RQ1, the temporal and conceptual evolution of the field highlights a clear transition from an emerging phase (2011–2019), characterized by isolated theoretical contributions, to a period of accelerated growth and standardization after 2020, directly stimulated by major EU regulations such as SFDR, EU Taxonomy, MiFID II, CSRD, and ESRS. These instruments have transformed ESG from a descriptive label into a formal framework for analysis and reporting, institutionalizing its use both in academic research and in financial markets targeting retail investors.

Answering RQ2, the thematic structure identified through cluster, overlay, and density visualizations highlights a coherent tripartite architecture composed of: the integration of ESG criteria in evaluating corporate performance and sustainability; the behavioral and ethical dynamics shaping the decisions of individual and retail investors; and the informational and governance dimension centered on transparency, reporting quality, and greenwashing risk. These clusters form an interconnected system in which organizational performance, ethical investment behavior, and the integrity of communication reinforce each other, defining the intellectual core of the field. The density analysis further confirms the centrality of the term ESG, surrounded by "performance," "impact," "corporate social-responsibility," and "sustainability," while intermediate and peripheral layers reflect behavioral responses and concerns related to informational credibility.

Regarding RQ3, the results clearly show that emerging research directions are strongly shaped by the evolution of the European legislative framework and closely aligned with the global sustainability agenda, particularly SDG 8, SDG 12, and SDG 16. These goals, focused on sustainable economic performance, responsible consumption and production, and institutional transparency, are directly reflected in the dominant themes in the literature, from performance evaluation and investment ethics to sustainability information governance and anti-greenwashing mechanisms. The adoption of ESRS in 2023 has further accelerated scientific attention on data comparability, materiality assessment, and accountability in financial markets aimed at retail investors.

Overall, the findings show that retail ESG has formed as a mature analytical ecosystem in which corporate sustainability, investor behavior, and transparency obligations are deeply interdependent. Its continued development is driven simultaneously by regulatory pressure, global sustainability imperatives, and the growing demand for reliable, comparable, and verifiable ESG information in retail-oriented financial environments. As the field advances, future research will likely deepen methodological standardization, data governance, behavioral responses to sustainability information, and the evolving relationship between regulation and market practices, thus contributing to a more transparent, responsible, and resilient financial system.

The bibliometric model used demonstrates strong methodological value and can be replicated in other areas of sustainable finance and corporate governance. However, reliance on the Web of Science database, the strict use of the expression "ESG retail," and the minimum term frequency threshold partially limit the representativeness of the analyzed dataset. These limitations do not affect the robustness of the conclusions but indicate the need for future research to expand through additional bibliographic sources and comparative analyses for a broader and more accurate understanding of ESG dynamics in the retail sector.

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Behavioural economics in agroecological payments – what drives farmers' decisions?

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Abstract. Agroecological payment schemes are key policy instruments for promoting sustainable farming and biodiversity protection, yet participation among farmers remains inconsistent. This study applies a behavioural economics perspective to examine how psychological, social, and contextual factors influence engagement with such schemes. Drawing on an integrated framework that combines Prospect Theory, the Theory of Planned Behaviour, and Nudge Theory, the research synthesises empirical evidence from the scientific literature. The analysis identifies loss aversion, present bias, and status quo preferences as major cognitive barriers, while social norms, positive attitudes, and framing effects can encourage adoption.
Keywords: behavioural economics, agroecology, payment schemes, farmers' behaviour, Prospect theory, Theory of planned behaviour, Nudge Theory

Introduction

Agroecological payment schemes operate as a vital tool which promotes environmentally friendly farming methods while protecting biodiversity across Europe and other parts of the world. While traditionally structured around economic incentives, these payment schemes increasingly highlight the significant role of behavioural economics in influencing farmers' participation decisions. Farmers base their choices on factors beyond economic logic because their decisions are shaped by cognitive biases together with social norms, trust and personal drive.

Classic economic models assume that farmers act rationally, maximising profits and minimizing costs. In reality, however, many decisions in agriculture are influenced by social norms of behaviour, and farmers often act intuitively, guided by previous experience, emotions, or fear of change. This calls for the application of behavioural economics, which represents an intersection between economics and psychology and studies the actual behaviour of economic agents. In the context of the agri-environmental schemes of the Common Agricultural Policy (CAP), this knowledge is key to understanding the motivation (or lack thereof) of farmers to participate.

Behavioural economics reveals the intricacies of decision-making through its study of psychological and social factors that affect human choices. The Prospect Theory developed by Kahneman and Tversky [1] shows that people perceive losses as more significant than gains which makes farmers highly reactive to potential risks from adopting new practices. The concept of loss aversion stands out as a major obstacle to adopting agroecological practices according to multiple studies [2], [3], [4]. Duquette et al. [5] further highlight present bias, noting that farmers choose short-term expenses over delayed advantages, often overlooking environmental and economic benefits. Some factors that determine how

farmers respond to incentive programs are related to specific economic, historical and cultural national characteristics. The implementation of certain agri-environment measures in Bulgaria for instance frequently depend on farmers having long-term contractual agreements or land ownership [6]. In a recent study, the authors Kabadzhova et al. [7] concluded that farmers from the region of Blagoevgrad and Kyustendil are more likely to implement agroecological practices based on the financial support rather than internal drivers such as environmental and health concerns. Stauder [8] discusses how farmers' decisions are strongly influenced by cultural beliefs and emotional reactions stemming from anger, stress, perceived technical difficulties, and increased workload. Research by Palm-Forster et al. [9] and Dessart et al. [3] shows that farmers participate in agroecological programs because they are susceptible to cognitive biases that include both anchoring and framing effects. Kuhfuss et al. [10] demonstrate that farmers choose their actions through the influence of social norms and their peers. In addition to these findings, according to Tran-Nam et al. [11] visible participation of peers reduces psychological and informational barriers, which makes the adoption of practices more likely when community members who already apply these methods set an example.

This research bases its analysis on integrated theoretical framework combining Prospect Theory [1], the Theory of Planned Behaviour [12], and Nudge Theory [13] to explain the behavioural mechanisms which shape farmers' decisions toward agroecological payment schemes. While each framework addresses decision-making from a different angle, together they provide a comprehensive understanding of how cognitive, social, and contextual factors interact in shaping farmers' choices. The aim of this research is to examine how perceptions of risk and loss, attitudes and peer influences, and policy design elements affect farmers' willingness to adopt environmentally sustainable practices.

Methodology

This study adopts a literature analyses methodology to examine the behavioural drivers influencing farmers' participation in agroecological payment schemes. Rather than relying on primary survey data, the research builds upon a synthesis of empirical and conceptual literature, drawing together insights from behavioural, agricultural, and environmental economics in order to develop an integrated conceptual explanation of decision-making in this context. The literature search was carried out between March and September 2025 across the following academic databases: Scopus, Web of Science, ScienceDirect, SpringerLink, Taylor & Francis Online, Wiley and Google Scholar. Search terms were combined using Boolean operators and included: "agroecological payments" OR "agri-environmental schemes", "farmers' decision-making" OR "participation", "behavioural economics" OR "loss aversion" OR "risk perception", "social norms" OR "attitudes", "nudge" OR "framing" OR "choice architecture", "prospect theory" AND "theory of planned behaviour" AND "nudge theory". The selection process involved: (1) initial screening of titles and abstracts and (2) full-text evaluation based on conceptual relevance. 58 studies were reviewed in total of which 27 were included in the final synthesis. Studies were included if they examined behavioural mechanisms in farmers' decision-making toward agri-environmental or agroecological incentives, provided empirical or experimental evidence, and were published in peer-reviewed journals. The review also targeted studies that emphasise European contexts to align with the policy framework of the Common Agricultural Policy (CAP). Excluded were studies focusing solely on technological adoption without behavioural analysis. Studies were analysed around three core conceptual categories derived from the integrated theoretical framework: (1) Cognitive drivers (risk perception, loss aversion, temporal discounting); (2) Social and normative drivers (attitudes, identity, peer influence); (3) Contextual and institutional drivers (contract design, framing, administrative burden). Patterns, convergences, and divergences were identified across studies, and these were used to develop a conceptual model that explains how behavioural mechanisms shape participation in agroecological payment schemes.

While this review does not claim to be exhaustive, the transparent documentation of the scope of the search, the selection criteria, and the thematic synthesis enhance the reliability of the results and allow for their replication or extension in future studies.

Theoretical and Conceptual Framework

The integration of Prospect Theory, Theory of Planned Behaviour and Nudge Theory is applied in the current study to demonstrate how behavioural elements affect farmers' participation in agroecological payment schemes by capturing the interplay between cognitive biases, social-psychological influences, and contextual policy design.

1.1. Prospect Theory

The Prospect Theory [1] explains that people judge value by reference points rather than absolute values, and that losses affect them more strongly than gains, according to the principle of loss aversion - losses carry greater psychological weight than equivalent gains. In the agricultural context, farmers often view short-term investments or yield reductions as potential losses relative to their current practices. Any change that introduces uncertainty—such as adopting an agroecological practice or enrolling in an agri-environmental payment scheme—is initially perceived as a potential loss, even if expected monetary returns or environmental benefits may eventually be higher. The Perception of risk and lack of control explain the reluctance for adaptation of conservation measures or result-based schemes [14]. Bocquého et al. [2] compared Expected Utility and Prospect Theory models in a field experiment with French farmers and found that the latter fits behaviour substantially better. Farmers displayed strong loss aversion coefficients (≈2) and probability weighting, suggesting they overweight low-probability adverse outcomes. This means that even minimal risk of yield loss or contract penalty can discourage participation in agri-environmental schemes. In the context of result-based agri-environmental payments, Dessart et al. [3] noted that loss aversion leads farmers to prefer action-based schemes (where payments are guaranteed upon performing specific practices) rather than outcome-based ones (where payment depends on environmental results). Since outcomes are uncertain and can be affected by weather or ecological variability, farmers perceive a higher probability of loss of payment, which discourages them from participating. A closely related cognitive bias—status quo bias—further compounds these effects. Ruto & Garrod [15] show that farmers display a strong preference for the status quo in choice experiments on agri-environmental contracts, even when new options offer superior expected income. This conservative decision-making pattern however does not reflect irrationality, but rather loss avoidance—the desire to minimize regret and uncertainty. Furthermore, transaction costs and psychological commitment reinforce this cognitive inertia [16], [17]. Administrative complexity, delayed payments, and opaque contract conditions increase perceived risk and reduce institutional trust, thereby magnifying loss aversion [17], [18]. Conversely, when schemes are designed to reduce bureaucratic burden, increase procedural clarity, or provide collective or peer-based participation mechanisms (via group contracts), the psychological distance to the new behaviour diminishes, making adaptation more acceptable [10], [11].

Prospect Theory provides a powerful lens to explain why limited participation in agri-environmental schemes is not solely a function of inadequate financial incentives, but rather reflects underlying cognitive and normative constraints. Empirical work across Europe demonstrates that loss aversion, reference dependence, and status-quo bias consistently shape adoption patterns [3], [19]. Recognizing these behavioural dynamics is therefore essential for developing interventions that are behaviourally congruent, such as emphasizing avoided losses rather than gains, ensuring contract transparency and timely compensation, and embedding coordination within trusted social networks [17].

1.2. Theory of Planned Behaviour

The Theory of Planned Behaviour (TPB) extends the cognitive model by adding social and motivational elements which shape decision-making behaviours. According to Ajzen [12] behaviour results from attitudes (toward the behaviour), subjective norms (perceived social pressure to perform or not perform the behaviour) and perceived behavioural control (the individual's confidence in their ability to execute the behaviour). Farmers' environmental attitudes determine their willingness to adopt sustainable practices but social norms formed by peer actions, family expectations and professional relationships shape the perception of what people consider socially acceptable behaviour. Research indicates that

farmers who observe others adopting ecological practices become more inclined to accept potential risks and develop greater confidence in their abilities [10]. In agricultural adoption studies, TPB has been widely used to explain farmers' uptake of new practices. For example, Bechini et al. [20] examine farmers' barriers and drivers towards the adoption of a number of management practices on dairy farms in northern Italy and found that difference between adopters and non-adopters is the opinion of members of their community. Similarly, Daxini et al. [21] concluded that farmers who feel a higher degree of social pressure or approval are more likely to follow a management plan for the use of fertilizers. The role of subjective norms becomes particularly salient in contexts where farmers collaborate or engage in shared land management. Tran-Nam and Tiet [11] show that organic farming adoption is strongly influenced by peer endorsement and knowledge-sharing networks, where seeing others adopt reduces perceived risk and legitimizes change. Thus, rather than being individual decisions driven solely by economic optimisation, participation in agroecological schemes emerges as a socially embedded process shaped by expectations, reputation, and shared cultural meanings. Further, Eichhorn et al. [22] identifies that perceived pride and recognition derived from participating in result-based agri-environment schemes strengthens commitment, suggesting that self-identity rewards can reinforce environmental action. Perceived behavioural control — farmers' assessment of whether they have the time, resources, capacity, and institutional support to implement new practices — is often the determining factor between intention and action. Administrative burden, lack of advisory support, and uncertainty about practical implementation weaken perceived control, thereby inhibiting adoption even when attitudes are favourable [3]. Conversely, accessible advisory services, clear guidance, and simplified scheme requirements strengthen perceived capability and translate intention into practice [17].

Taken together, these findings underscore that adoption of agroecological practices depends fundamentally on whether farmers: (1) believe the practice is valuable (attitude), (2) perceive it to be socially supported (subjective norms), and (3) feel capable of carrying it out under real-world constraints (perceived behavioural control). Therefore, the Theory of Planned Behaviour highlights the social and psychological structure within which behavioural change occurs, emphasizing that effective agri-environmental policies must engage not only economic motivations but also identity, trust, peer dynamics, and the practical conditions of everyday farming.

1.3. Nudge Theory

Nudge Theory [13] emphasizes that behaviour is shaped not only by conscious reasoning, but also by the way choices are structured within the decision-making environment. Rather than altering financial incentives, nudges work by modifying the "choice architecture" in which decisions occur, guiding individuals toward socially beneficial behaviour while preserving freedom of choice. This theory extends the framework to the political and institutional level by highlighting that the way decisions are formulated or presented - default settings, order of options, wording and framing, highlighted reminders, can significantly change behavioural outcomes without altering the structure of incentives. In agroecological settings, this means that even if schemes are financially equivalent, farmers respond differently depending on how the payment or decision is framed. This requires governments to be more flexible and use a wider range of instruments—not only subsidies and regulations, but also behavioural policies that nudge farmers toward better decisions without restricting their freedom of choice [23]. For example: defaults / automatic enrolment can reduce the friction associated with opting in (e.g. in conservation auctions or environmental contracts); framing payments as "avoiding losses" can be more motivating rather than framing as "gaining rewards", due to loss aversion; salience and reminders (e.g. text-based nudges, checklists) can serve as a method to counteract inattention or procrastination. Empirical evidence in agriculture supports these ideas: Kuhfuss et al. [10] explore nudges, social norms, and permanence in agri-environmental schemes, showing that conveying how many farmers continue after contracts can influence intentions to maintain practices. Moreover, nudge designs can help overcome the "end-of-contract" problem: farmers often drop ecological practices after payments end. Providing information about community norms or future benefits can increase permanence post-

contract. In Sicily, Vella et al. [24] demonstrate how nudges can encourage adoption of PiWi grape varieties, showing that framing and interface design impact uptake.

Additionally, nudges can play an important role in enhancing agricultural policy. Research on nudges in agricultural policy primarily examines their effectiveness—whether and to what extent they influence farmers' behaviour—and their cost efficiency as policy instruments. By simplifying compliance and reducing bureaucratic complexity, nudges may lower both public and private transaction costs, thereby improving the overall efficiency of agri-environmental policy implementation [25].

Nudge Theory demonstrates that the structure and presentation of policy options profoundly shape farmers' decisions. Behaviourally informed agri-environmental schemes therefore can benefit from: (1) simplified administrative procedures, (2) framing incentives in ways that resonate with farmers' values and identities, and (3) highlighting the potential to reduce transaction costs. These strategies complement, rather than replace, financial compensation, providing a more behaviourally realistic approach to designing effective and enduring agroecological interventions.

1.4. Conceptual model

The perspectives of Prospect Theory, Theory of Planned Behaviour and Nudge Theory allow for a comprehensive understanding of farmers' behavioural dynamics. The conceptual model (Figure 1) synthesizes these three interrelated mechanisms. Cognitive drivers (loss aversion, present bias), social drivers (attitudes, norms, perceived control), and contextual drivers (framing, defaults, institutional design) jointly influence the farmers' decision to participate in agroecological payment schemes.

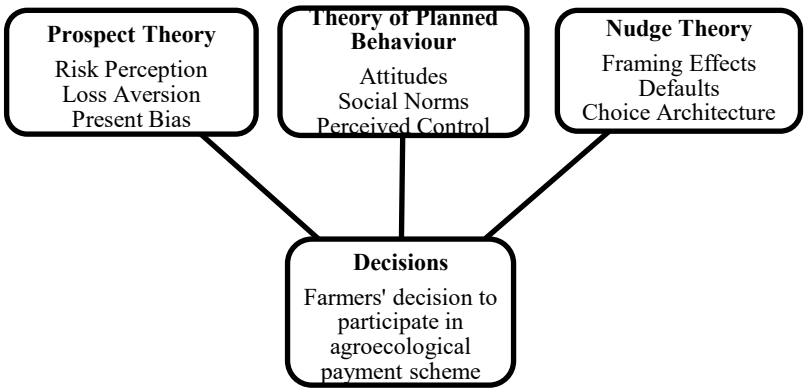

Figure 1. Conceptual model: Behavioural drivers of farmers' decisions for participation.

The conceptual model illustrates how the three theoretical pillars—Prospect Theory, the Theory of Planned Behaviour, and Nudge Theory interact in a layered and mutually reinforcing manner, producing a decision environment in which adoption is more or less likely depending on how these mechanisms align.

At the cognitive level, Prospect Theory explains how farmers evaluate the potential consequences of adopting agroecological practices. Farmers tend to reference their current production system as a baseline; any deviation from this established state is interpreted in terms of potential loss. Because loss aversion and present bias generally outweigh future environmental or economic gains, farmers may view participation as risky or burdensome—even when payment levels or environmental advantages appear objectively beneficial. This cognitive framing forms the initial perceptual filter through which policy options are viewed.

The Theory of Planned Behaviour adds a social and motivational dimension to this evaluation. Once risks and potential outcomes have been mentally framed, decisions depend on farmers' attitudes toward agroecological practices, the social norms communicated within their peer networks, and their perceived capacity to implement new requirements. Positive environmental attitudes do not necessarily result in

action unless subjective norms and perceived behavioural control are strong. Thus, even when loss aversion is reduced, low perceived feasibility or lack of social endorsement can stall adoption. In this way, the TPB component is sequentially connected to cognitive evaluations but also feeds back by shaping how risks and benefits are interpreted (e.g., trusted peers adopting reduces perceived risk).

Nudge Theory operates at the contextual level, shaping how choices are presented and processed. Interventions such as simplified administrative procedures, transparent contract terms, or collective enrolment options adjust the "choice architecture" surrounding decision-making. These changes influence both cognitive and social dimensions: simplifying procedures reduces the psychological cost associated with loss aversion, while norm-based nudges reinforce the social desirability and legitimacy of participation. In this sense, nudges function as cross-cutting mechanisms that modify both risk perception and social meaning simultaneously.

These three components form a reinforcing system in which risk perceptions (Prospect Theory), social expectations and perceived capability (Theory of Planned Behaviour), and decision context (Nudge Theory) interact to either strengthen or weaken commitment to adoption (Table 1).

Table 1. Interaction structure of the behavioural reinforcement system in agroecological scheme adoption.

Component	Influence	Reinforcement
Cognitive evaluation of risk (Prospect Theory)	Determines whether adoption appears safe or risky	Influences attitudes and how norms are interpreted. Determines how framing in policy nudges is received.
Formation of intention (Theory of Planned Behaviour)	Determines whether the farmer wants and believes they can adopt	Influences how risks and incentives are interpreted. Strong norms and perceived feasibility reduce loss aversion and make nudges more effective.
Decision environment (Nudge Theory)	Makes adoption easier, clearer, or socially supported	Simplifies participation → increases perceived control and lowers perceived loss → makes social approval more influential.

Over time, this system can produce feedback loops. When some farmers adopt and experience positive outcomes, peer norms shift, which reduces perceived risk and increases perceived behavioural control for others—making future adoption more likely. On the other hand, if farmers encounter administrative burdens or inconsistent payments, risk perceptions intensify and norms shift toward resistance, reinforcing the status quo.

Finally, the strength and direction of these mechanisms are moderated by structural and contextual factors such as farm size, economic vulnerability, advisory access, institutional trust, and local landscape conditions. These elements determine whether farmers interpret policy signals as opportunities or risks, shaping both the speed and extent of adoption.

Discussion

These findings underscore that participation in agroecological payment schemes cannot be understood solely through economic rationality. Instead, adoption emerges from the interaction of cognitive, social, and contextual influences that shape how farmers perceive, evaluate, and act upon policy opportunities. This relationship is captured in the conceptual model, which synthesizes insights from Prospect Theory, the Theory of Planned Behaviour, and Nudge Theory to show how behavioural mechanisms jointly contribute to farmers' decisions.

The three theoretical lenses used in this study highlight different but complementary dimensions of farmers' decision-making. Prospect Theory emphasizes how farmers' evaluations of agroecological practices are shaped by perceived risks and the tendency to avoid potential losses relative to familiar production and management practices. The Theory of Planned Behaviour brings attention to the role of

attitudes, peer expectations, and perceived capability in determining whether these evaluations translate into actual intentions. Nudge Theory focuses on how the structure of the policy environment—such as the clarity, simplicity, and social framing of scheme requirements—can facilitate or hinder the move from intention to adoption. Together, these frameworks show that participation outcomes arise from the interaction of cognitive assessments, social influences, and institutional design conditions.

To synthesize the behavioural evidence across the three theoretical strands (Prospect Theory, Theory of Planned Behaviour, Nudge Theory) a consolidated overview is presented in Table 2. The table groups the reviewed studies into theoretical clusters, highlighting the dominant behavioural mechanisms identified in each, along with their corresponding policy implications.

Table 2. Synthesis of key behavioural patterns and policy implications identified in the literature.

Representative Studies	Theory Cluster	Key Behavioural Findings	Policy Implications
Bocquého et al. (2014); Duquette et al. (2012); Rommel et al. (2022); Dessart et al. (2019); Canessa et al. (2024); Klebl et al. (2024); Schaub et al. (2023); Ruto & Garrod (2009)	Prospect Theory	Farmers are reluctant to incur losses, overweight short-term risks, and show a strong dependence on references. Uncertainty, administrative complexity, and delayed payoffs reinforce the perception of losses. Risk preferences vary depending on the context, and psychological barriers reduce the willingness to adopt new practices.	Reducing uncertainty and risk of losses; stabilizing payments; simplifying contracts; increasing transparency; using framing to highlight avoided losses rather than potential gains; adapting AES design to regional risk profiles.
Daxini et al. (2019); Stauder (2023); Massfeller et al. (2022); Eichhorn et al. (2024); Tran-Nam & Tiet (2022); Bechini et al. (2020); Klebl et al. (2024); Dessart et al. (2019)	Theory of Planned Behaviour	Attitudes, social norms, and perceived behavioural control strongly shape adoption intentions. Peer influence, moral approval, feasibility perceptions, workload concerns, and advisory support are decisive drivers. Identity elements such as being a 'good farmer' and social recognition also matter.	Strengthening advisory systems; using peer learning; using identity-based messaging; enhancing training; reducing administrative burdens; improving clarity of communication; supporting farmers' sense of capability.
Kuhfuss et al. (2016); Palm-Forster & Messer (2021); Vella et al. (2025); Byfuglien et al. (2025); Wittstock et al. (2022); Mettepenningen et al. (2009); Schaub et al. (2023); El Benni et al. (2025); Dessart et al. (2019)	Nudge Theory	Behaviour is shaped by framing, defaults, social cues, administrative simplicity, and cognitive load. Collective bonuses, simplified forms, adaptation framing, and salience effects improve participation. Administrative burdens discourage engagement, while well-designed nudges reduce friction.	Using framing interventions; streamlining procedures; reducing transaction costs; utilizing collective incentives; designing choice environments to make sustainable options easier and more intuitive; incorporating nudges into CAP.

By combining findings across multiple empirical and conceptual contributions, Table 2 maps out how cognitive, social, and contextual drivers shape farmers' engagement with agroecological payment schemes. Rather than treating these studies as isolated insights, the table emphasises the emerging patterns across the literature and clarifies how distinct behavioural mechanisms converge toward similar or complementary policy design implications.

Evidence from the reviewed literature demonstrates that farmers' decisions toward agroecological payments emerge from the interaction between cognitive framing of risks and rewards, social reinforcement through norms and identity, and contextual facilitation through institutional design. This underscores the need for multilevel approaches that integrate these behavioural mechanisms within policy frameworks [19], [26]. Such findings strengthen the theoretical argument that addressing only the economic dimension of agri-environmental participation is insufficient.

Insights from Prospect Theory suggest that farmers' risk perception, loss aversion, and present bias substantially influence their willingness to participate in agroecological schemes. Farmers tend to evaluate outcomes relative to a reference point—their current management practice. Consequently, the adoption of new agroecological measures is frequently perceived as a potential "loss" until tangible benefits are realized. Bocquého et al. [2] and Duquette et al. [5] demonstrate that many farmers give disproportionate weight to immediate costs while discounting future gains. More recent European evidence reinforces this behavioural pattern: Canessa et al. [26] highlight that institutional trust and contract design shape how cognitive biases influence adoption behaviour, whereas Klebl et al. [19] identify risk perception and uncertainty as persistent psychological constraints on biodiversity-oriented farming decisions across Europe.

The social dimension, grounded in the Theory of Planned Behaviour, emphasizes that attitudes, subjective norms, and perceived behavioural control are decisive in shaping environmental intentions. Empirical evidence from Daxini et al. [21] and Stauder [8] shows that favourable attitudes and peer endorsement significantly enhance participation, while social recognition and perceived pride further strengthen commitment to result-based schemes [22]. These findings indicate that agroecological adoption is situated within shared social and cultural frameworks rather than driven solely by individual economic rationality.

At the contextual level, Nudge Theory highlights how institutional framing, procedural design, and administrative complexity shape farmers' engagement with agroecological schemes. Kuhfuss et al. [10] demonstrate that social nudges, such as collective bonuses, can significantly increase enrolment, while Palm-Forster and Messer [9] show that framing and default mechanisms enhance participation in conservation programs. Recent European studies find that adaptation-oriented policy framing strengthens farmers' support for climate measures [27], and that procedural simplicity and transparent communication reduce cognitive load and transaction costs, thereby improving uptake [17]. Together, these findings confirm that choice architecture—the way policy options are structured and presented—can be as influential as financial incentives in determining behavioural outcomes.

The synthesis in Table 2 shows that behavioural constraints such as loss aversion, perceived effort, social validation, and administrative burden operate simultaneously rather than in isolation. As a result, effective policy design must address these intertwined mechanisms rather than rely on financial incentives alone. The table thus highlights a shared conclusion across the literature: reducing friction, strengthening farmer confidence and social support, and reframing choices in a way that aligns with farmers' cognitive tendencies are critical levers for enhancing the uptake and effectiveness of agroecological schemes. Overall, the adoption of agroecological measures is most likely when farmers see the practice as low-risk, socially valued, and administratively feasible, underscoring the need for behaviourally informed policy strategies.

Conclusions

The integration of behavioural insights provides a richer and more realistic understanding of farmers' decisions regarding agroecological payments. Farmers' participation is not solely determined by the magnitude of subsidies but by how these incentives are perceived, socially reinforced, and contextually framed. Consequently, policies that account for behavioural realities—by reducing perceived losses, strengthening social norms, and designing intuitive programme structures—are likely to achieve higher participation and more durable environmental outcomes.

To translate these behavioural insights into practice, agroecological payment schemes should incorporate design elements that reduce perceived risk, strengthen social support, and simplify

participation. First, schemes can minimize short-term uncertainty by offering guaranteed baseline payments, timely disbursement schedules, and clear contractual terms, thereby reducing loss aversion and perceived financial exposure [16], [17]. Second, governments and advisory services should prioritize practical support and hands-on extension, including demonstration farms and locally embedded advisors, which have been shown to enhance perceived behavioural control and intention–action conversion [21]. Finally, elements of choice architecture, such as simplified documentation, pre-filled forms, or default participation options where appropriate, can lower administrative and cognitive barriers, making environmentally beneficial choices easier to adopt [9]. Collectively, these measures move beyond increasing payment levels alone and align policy design with how farmers actually perceive, evaluate, and enact change.

This study contributes to the growing intersection of behavioural economics and agricultural policy by offering an integrative framework that explains farmers' decisions in agroecological payment schemes through the combined lenses of Prospect Theory, the Theory of Planned Behaviour, and Nudge Theory. Whereas most previous studies have examined these frameworks in isolation, this research synthesizes them into a single conceptual model, illustrating how cognitive biases, social influences, and contextual design factors jointly determine adoption behaviour.

While the conceptual model offers a comprehensive behavioural interpretation, several limitations must be acknowledged. The study relies primarily on secondary sources, which may introduce selection and publication biases. Empirical validation remains necessary to test the strength and interaction of these behavioural mechanisms across contexts.

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Rethinking Transport Systems for Low-Carbon Urban Futures

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Abstract. Transport systems are vital for urban economies yet remain major contributors to greenhouse gas emissions. This paper investigates pathways toward low-carbon mobility through literature review and applied analysis. International research highlights the importance of multimodal hubs, digitalized rail, alternative fuels, and integrated policies that combine technological innovation with social inclusion. A case study from Buzău, Romania, analyses the modernization of Line 10 through electric buses, dedicated lanes, and the UTOPIA intelligent traffic management system. Findings indicate that infrastructure improvements alone generate limited efficiency, whereas active traffic light prioritization increases commercial speed by approximately 2 km/h and reduces travel times by 8–12%, even with route extensions. The results underline that sustainable urban mobility depends on coordinated infrastructure, intelligent digital control, and inclusive governance to achieve environmental and social gains.
Keywords: *transport system, synergy, urban, law carbon economy, decarbonisation.*

Introduction

The pursuit of low-carbon urban represents a societal transformation that extend across every level of human activity, from individual mobility choices to the design of entire metropolitan systems as (Olazabal & Pascual, (2015) or Lehmann, (2013) argues. Transport presents one of the greatest challenges in this transition and it is indispensable to modern economies and social life, yet it is also among the largest and fastest-growing sources of greenhouse gas emissions. Addressing this paradox requires strategies that go beyond incremental change and instead embrace systemic innovation. Emerging pathways include reimagining urban form through new models of mobility and land use, shifting toward pulse-based or on-demand transport systems, embedding sustainability principles within education, and deploying advanced planning frameworks that anticipate long-term environmental and social needs as is highlighted in (Knoflacher, (2007); Sclar & Touber, (2011); Hook et al. (2025).

Despite the rapid expansion of scholarship on low-carbon urban mobility, three structural limitations remain visible in the existing literature. First, empirical imbalance persists in terms of urban scale and geography.

The majority of studies (Morichi, (2005); Knoflacher, (2007); Peckett & Lyons (2021); Umrigar & Pitroda, (2023); Rochaet al (2023); Casavola et al (2024); Choi et al.(2025)) focus on large metropolitan regions in Western Europe or Asia, where advanced Bus Rapid Transit systems, extensive rail infrastructure, and high institutional capacity provide favourable conditions for systemic experimentation. Medium-sized cities, particularly in Eastern Europe are significantly underrepresented and face distinct structural constraints: limited fiscal capacity, incremental infrastructure development, fragmented governance, and slower digital transformation. The absence of field-based evidence from this category of cities constitutes a notable gap, especially given their relevance for achieving European Union climate and cohesion objectives, this research provides real-world validation of partial corridor segregation, where dedicated lanes cover approximately 17% of the total route. Much of the international literature assesses either full segregation or theoretical capacity gains under idealized assumptions and analysing performance outcomes in a mixed-traffic regime with limited physical prioritization, the study offers a more realistic representation of policy implementation constraints typical of medium-sized European cities with limited spatial and financial resources. Second, the intervention logic in the literature is often system-level and fully developed as many analyses evaluate complete BRT corridors, comprehensive electrification strategies, or large-scale ITS deployments. In contrast, real-world modernization in medium-sized cities typically unfolds gradually, through partial corridor segregation, phased route extensions, and stepwise digital activation. There is limited empirical research that isolates and quantifies the relative contribution of complementary measures, specifically dedicated bus lanes and traffic signal priority, when introduced sequentially under mixed-traffic conditions. Most studies treat these interventions as integrated components of mature systems rather than as incremental measures whose individual and cumulative impacts must be distinguished.

International comparisons indicate that walking is more prevalent in Europe, Japan, and North America than in cities of the developing world (Glazebrook & Newman, 2018). Approximately 10% of all journeys in the United States, United Kingdom, and Germany are undertaken by foot, but the analogous statistic in China is estimated at only 0.5%. The cycling shares vary from 0.4% to 18%, with the largest percentages observed in China and the Netherlands (Lefèvre, 2010).

Urban planning has effectively addressed increasing urban heat, traffic congestion, transport emissions, and social isolation only via the integration of networks, land use, public social services, public open spaces, and utilities. The 'Coalition for Urban Transitions' fosters collaboration among governments, private investors, developers, and communities to promote transformative national urban development, emphasizing housing and affordability to support sustainability objectives, including decarbonization. The conventional highway paradigm of urban growth, which facilitated rising affluence, automobile ownership, and petroleum use, fails to tackle global warming, urban air pollution, the availability of cheap housing for all, or significantly diminished congestion (Glazebrook & Newman, 2018). Two options dictate the framework for new developments, districts, and suburbs: either increase density within the current urban structure to enhance social and economic sustainability or create a new urban design that reduces reliance on private automobiles. Future urban expansion is a significant problem for industrialized, growing, and developing economies, and is the focal point of Green Growth and other projects.

Transportation in urban areas unites the land-use, transportation, social, environmental, and economic facets of a metropolis. Location efficiency, excellent design, a balance of amenities and variety, and innovation are the four pillars of constrained urban growth that cities must adhere to if they are to grow efficiently and entice and manage the massive rural-to-urban movement that will occur in the next century. As a whole, low-carbon fuels, changes in travel behaviour, and improvements to vehicle economy are not going to be enough to meet transport-related climate objectives (Jia Wang & Moriarty, 2017). There are new transportation solutions that show promise for a sustainable future (Glazebrook & Newman, 2018). More adaptable and versatile infrastructures are becoming a reality in cities throughout the globe because too smart transport systems, which include smart cars, plains, and traffic conditions.

The transition toward sustainable and low-emission transport has been explored from multiple disciplinary perspectives including engineering, urban planning, and social sciences and yet most research continues to focus on large metropolitan areas in Western Europe or Asia (Orozco et al., 2021). By contrast, medium-sized cities in Eastern Europe remain underrepresented in empirical research on digitalization and transport decarbonization. These cities often face structural challenges such as limited financial capacity, fragmented governance, and slow adaptation of intelligent transport systems (ITS). This imbalance represents a significant research gap, considering that medium-sized urban centers play a crucial role in achieving the European Union's regional climate objectives (Bustos-Turu et al., 2023).

The specific research gap identified in this study concerns the lack of comparative analyses that isolate the relative contribution of two complementary interventions, dedicated bus lanes and traffic signal priority, under mixed-traffic conditions, where infrastructural improvements are introduced gradually and transit routes undergo realignment. Most existing studies have concentrated on fully developed Bus Rapid Transit (BRT) systems or theoretical simulations, without documenting the incremental or cumulative effects of these measures during transitional phases of urban modernization. Researches on Transit Signal Priority remains dominated by algorithmic modeling and simulation-based evaluations, with few field studies addressing conventional bus operations.

Accordingly, the central research hypothesis of this study is that the combined deployment of intelligent traffic management technologies and dedicated public transport infrastructure leads to measurable improvements in overall system efficiency and enhances users' perception of public transport as a reliable, sustainable alternative to private car use.

Literature review

The development of low-carbon transport systems in urban environments constitutes a complex and rapidly evolving research field, requiring the integration of technical innovation, advanced modeling methodologies, and coherent policy frameworks. This domain lies at the intersection of urban planning, energy systems, and data-driven mobility analysis, reflecting both the urgency of climate mitigation and the challenges of ensuring equitable urban transitions. The European Union's pursuit of a low-carbon transport sector is characterized by a combination of infrastructure modernization, technological advancement, and regulatory alignment, all directed toward achieving climate neutrality by 2050. This agenda recognizes the complexity of transport decarbonization and underscores the need for integrated, cross-sector approaches that link urban mobility, long-distance travel, and freight transport under a unified sustainability framework.

A central pillar of EU efforts lies in the promotion of multimodal mobility, where well-designed interchange hubs are seen as catalysts for behavioral and systemic shifts. Conticelli et al. (2021) present a methodological framework for assessing the effectiveness of policy measures and design interventions at these hubs, demonstrating how their configuration can directly influence user adoption of sustainable modes. By enabling seamless transfers between rail, bus, cycling, and other low-emission alternatives, multimodal hubs reduce the dominance of single-mode, carbon-intensive travel and promote a more balanced mobility ecosystem across European cities.

Waterborne transport, a sector integral to European trade and logistics, is another priority area for decarbonization. Fuel diversification represents a further cornerstone of the transition. Navas-Anguita et al. (2021) examine the role of hydrogen, with particular attention to blue hydrogen produced via steam methane reforming coupled with carbon capture and storage (CCS). Their modeling of Spain's transport energy system highlights how CCS retrofits could reinforce the European Hydrogen Strategy, offering a bridge solution while renewable-based green hydrogen matures. Rail transport, traditionally a lower-emission alternative to road and air, is being redefined through the application of Industry 4.0 technologies. Gerhátová et al. (2021) discuss digitalization, automation, and predictive maintenance tools that can boost operational efficiency and reduce energy consumption in railway systems.

Urban mobility presents perhaps the most immediate decarbonization challenges, as cities must reconcile rising demand with stringent emission reduction targets. Byrne et al. (2021) explore urban

transport scenarios in Germany, showing that while multiple pathways exist, the optimal balance between public transport, shared mobility, and electrification remains uncertain.

Vehicle technology also continues to advance in parallel with systemic changes. Puškár et al.(2024) propose hybrid low-temperature combustion systems designed to achieve near-carbon-neutral performance. Orozco et al. (2021) stress the growing relevance of multimodal urban mobility and multilayer transport networks, pointing out that the fusion of real-world mobility data with system-level modeling provides new pathways for sustainable transportation design. Their work illustrates how insights from complex systems theory and urban data science can illuminate individual travel behaviors across diverse transport modes, which is fundamental for shaping efficient and low-emission mobility strategies in cities.

At the policy interface, Sareen et al. (2022) introduce the concept of double energy vulnerability in disadvantaged neighborhoods undergoing low-carbon transport transitions. While digitalized electric infrastructures represent a cornerstone of decarbonization, they argue that such systems may unintentionally intensify energy poverty, particularly in marginalized urban areas. This highlights the necessity of socially inclusive low-carbon policies that protect vulnerable groups while enabling systemic transformation. Similarly, Kariuki et al. (2017) expand this discussion to developing countries, emphasizing the role of integrated policy packages as levers for low-carbon transport. They argue that fragmented or isolated interventions cannot generate meaningful progress, whereas coordinated frameworks can establish robust, environmentally sustainable transport systems. Complementing this policy focus, Bustos-Turu et al. (2023) present SmartCityModel, an agent-based decision-support platform designed to simulate energy and transport electrification pathways. By accounting for diverse socio-demographic and technical variables, the model enables fine-grained scenario testing, providing a bottom-up perspective crucial for planning resilient low-carbon energy systems at the city level.

Passenger demand forecasting emerges as another decisive factor for energy optimization in transport systems. The complexity of planning large-scale transport infrastructure is illustrated by Okonta et al.(2025), who apply systems thinking to analyze stakeholder dynamics in the railway sector of Milton Keynes. Their findings show that long-term low-carbon transitions depend not only on technology but also on aligning diverse institutional and social actors. Building on this, Luo et al. (2023) advance a coordinative planning framework that integrates electrified public transport with renewable energy generation and urban energy networks. Employing optimization techniques such as Benders decomposition and Lagrangian relaxation, they demonstrate how cross-sector coupling accelerates multi-energy system decarbonization in cities.The material dimension of urban electrification also requires careful attention. Li et al. (2025) examine Beijing's electric bus fleet, assessing mineral demand and recycling potential. They reveal that resource scarcity and circularity strategies are now critical components of urban low-carbon transitions, as large-scale electrification depends not only on technological adoption but also on sustainable mineral management. Finally, Wu et al. (2025) explore hybrid passenger–freight bus operations in urban–rural settings. Their bilevel optimization model supports dynamic vehicle allocation and collaborative scheduling, improving both economic viability and low-carbon performance. This line of research highlights how system-wide resource reconfiguration can contribute to efficiency gains while simultaneously advancing environmental objectives.

2. Data and Research Methodology

This study was designed to evaluate how the introduction of dedicated bus lanes and intelligent traffic signal priority can improve the efficiency of public transport in a real urban environment

The study adopts a quasi-experimental, longitudinal before–after research design to assess the causal impact of infrastructural and digital traffic management interventions on the operational performance of urban public transport. The analytical framework is structured to isolate and quantify the individual and cumulative effects of two complementary measures: (i) the introduction of dedicated bus lanes and (ii) the activation of dynamic traffic signal priority within an intelligent transport system (ITS). Given the impossibility of implementing randomized controlled conditions in a real urban environment, a natural experiment was exploited, using temporal variation in policy implementation across three distinct

operational configurations. This approach allows for inferential comparison under real-world traffic conditions while maintaining ecological validity.

Given the structural and ethical constraints that prevent randomized controlled experimentation in live urban traffic systems, the research exploits a natural experiment generated by the staged modernization of Line 10 in the municipality of Buzău between 2023 and 2025. The sequential implementation of two distinct measures—partial corridor segregation through a dedicated bus lane and subsequent activation of dynamic traffic signal priority via the UTOPIA intelligent traffic management system—provides temporal policy variation suitable for inferential comparison under real-world conditions.

The analytical framework is structured to isolate both the marginal and cumulative effects of these interventions. Three operational scenarios are defined. The baseline scenario (S_0, 2023) represents mixed-traffic operation without any form of dedicated lane or signal priority. The second scenario (S_1, 2025) introduces a dedicated bus lane along approximately 17% of the corridor while maintaining conventional signal control. The third scenario (S_2, 2025) retains the dedicated lane and activates dynamic traffic signal priority at equipped intersections. This staged configuration enables structured difference-based comparisons: the contrast between S_1 and S_0 estimates the isolated contribution of physical lane segregation; the contrast between S_2 and S_1 captures the additional marginal impact of intelligent signal priority; and the difference between S_2 and S_0 reflects the cumulative systemic effect.

The empirical investigation focuses on Line 10, a strategically important corridor connecting the southern industrial area with northern residential neighborhoods and intersecting key commercial, educational, and administrative nodes. The line was selected due to its high passenger relevance, corridor centrality within the urban transport network, and the availability of consistent operational data across comparable time intervals. Importantly, the 2025 configuration includes route extension of approximately one kilometer and the introduction of additional stations in high-demand areas. This structural expansion imposes upward pressure on total travel time and therefore reinforces a conservative interpretative logic: any reduction in travel duration or increase in commercial speed under the new configuration indicates a robust efficiency gain rather than a simplification effect.

Operational data were provided by the municipal public transport operator and include semi-trip duration (terminal-to-terminal travel time), commercial speed, station dwell times, and segment distances. Observations were recorded for both directions of operation (Ring 1 and Ring 2) and at three representative time intervals: morning peak (08:00), midday off-peak reference (12:00), and afternoon peak (16:00). This temporal stratification captures congestion variability and allows evaluation of intervention performance under heterogeneous traffic intensity conditions.

Two primary performance indicators were selected to reflect corridor-level operational efficiency. The first is semi-trip duration, defined as the total time required to complete one directional run between terminal stations, including dwell times at intermediate stops. This indicator captures cumulative delay effects arising from congestion and intersection control. The second is commercial speed, calculated as route length divided by total operational time and expressed in km/h. Commercial speed integrates both movement and stopping time and serves as a direct proxy for service competitiveness, reliability, and user-relevant efficiency. These indicators were deliberately chosen because they reflect passenger-perceived service quality and network throughput capacity rather than abstract modeling constructs.

The analytical procedure involved sequential data validation, inter-scenario comparison, and percentage-difference estimation. Distances and time measurements were cross-checked to ensure internal consistency across scenarios. No artificial normalization was applied to offset the 2025 route extension; instead, the analysis maintains structural comparability while preserving the conservative evaluation framework. Efficiency gains are therefore interpreted as net improvements occurring despite increased corridor length and operational complexity.

Under Scenario S_2, traffic signal priority operates through an integrated detection and adaptive control mechanism. Buses are identified via GPS-based tracking and intersection-level sensors, triggering a priority request to the central control system. The algorithm evaluates real-time traffic conditions and grants either conditional or absolute priority by adjusting signal phases to minimize

stopping time. After bus passage, the system restores baseline signal cycles and records operational data for monitoring. Along Line 10, priority-enabled segments cover approximately 2,400 meters, corresponding to nearly 17% of the total route length, allowing assessment of localized digital intervention within a predominantly mixed-traffic environment.

Although the design enhances internal validity through staged intervention comparison and real operational measurement, certain limitations remain. The study does not model passenger demand elasticity, modal shift behavior, or lifecycle emission reductions. The focus is confined to operational efficiency indicators, which serve as necessary but not sufficient conditions for long-term decarbonization. Nevertheless, the quasi-experimental framework, combined with conservative causal interpretation and corridor-level performance metrics, provides a robust empirical basis for evaluating incremental modernization strategies in medium-sized urban environments.Still, the analysis is limited to operational performance indicators, specifically semi-trip duration and commercial speed and these metrics capture service efficiency and temporal reliability but do not directly account for passenger demand elasticity, occupancy rates, boarding/alighting dynamics, or perceived service quality. Consequently, while improvements in speed and travel time are strong predictors of increased attractiveness, the study does not empirically model behavioral shifts from private car use to public transport. The methodological approach emphasizes operational efficiency metrics rather than abstract system modeling where the semi-trip duration and commercial speed were selected because they directly reflect passenger-relevant service quality and network throughput capacity. These indicators are sensitive to both lane separation and signal delay reductions, making them appropriate for intervention-level evaluation and in this context the research design incorporates a conservative interpretative stance. Since the 2025 route configuration includes extension and additional stops, the structural conditions impose upward pressure on travel time. Therefore, any reduction in duration or increase in commercial speed is interpreted as a robust efficiency gain rather than a byproduct of route simplification. This methodological conservatism reduces the risk of overstating intervention effects.

The research design integrates staged intervention analysis, corridor-based longitudinal observation, and performance indicator comparison within a quasi-experimental framework. It is specifically tailored to evaluate incremental modernization strategies in medium-sized urban environments where digital transformation and infrastructural adaptation occur progressively rather than through comprehensive system redesign.

3. Analysis of the impact of prioritizing public transport circulation in the context of Rethinking Transport Systems for Low-Carbon Urban Futures[1]

3 .1 General analysis framework

The research analysis presents a case study focused on Line 10 in the municipality of Buzău, carried out in the context of recent infrastructure modernization interventions and the introduction of intelligent traffic management solutions. Line 10 was selected due to its high usage and extensive route, which crosses various areas of the city and connects multiple points of interest, such as residential neighbourhoods, public institutions, and commercial areas. The study aims to compare travel times in three distinct scenarios, analysed over the course of a day, at times relevant to urban traffic intensity. It takes into account the effects of route extension, the introduction of dedicated lanes, and the activation of traffic light priority on public transport operations. In the municipality of Buzău, between 2016 and 2024, a large-scale project was carried out to modernize the equipment for controlling and coordinating road traffic. The project, entitled "Intelligent traffic, management, and monitoring system based on innovative solutions for efficiency and pollution reduction in the municipality of Buzău," provided for the modernization of 24 intersections through the introduction of intelligent traffic light equipment,

[1]This section is based on the research results carried on during the M.Sc. thesis called "Accessibility and attractiveness in sustainable urban mobility systems", National University of Science and Technology Polytechnic Bucharest, Faculty of Transport, Master's program in Urban Transport and Traffic.

vehicle detection sensors, automatic license plate recognition (LPR) systems, video cameras, and a digital platform for real-time data control and analysis, operated from a modern command centre.

The need for the project was determined by a number of problems identified in the urban road network: traffic congestion during peak hours, long travel and waiting times for public transport, and the lack of a coherent system for coordinating traffic lights, monitoring, and real-time information. As can be seen in Figure 1, public transport is used for only about 19% of citizens' journeys, with walking and private cars being preferred. One of the reasons for this low percentage is that, in the absence of measures to prioritize public transport over private vehicles, public transport vehicles are affected by the same problems of traffic congestion, long travel times, and low traffic speeds. In this situation, citizens prefer to use their own cars for long-distance trips and walking for medium and short-distance trips.

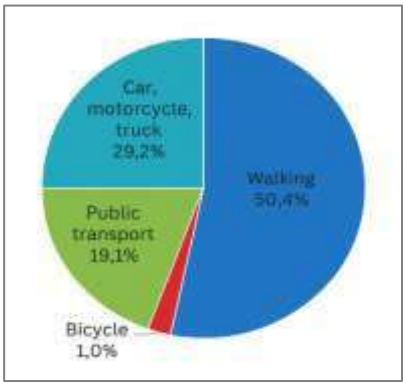

Figure 1. Distribution of trips by mode of transport in the city of Buzău, 2016. (S.C. Urban Scope S.R.L., 2017)

The main goal of implementing the intelligent traffic management system is to improve the efficiency of urban mobility by adopting modern technological solutions that meet the current needs of traffic and citizens. Expectations are primarily focused on reducing travel times, especially for public transport, which must become faster, more predictable, and more attractive to the population. Another major objective is to reduce greenhouse gas emissions and noise pollution by reducing unnecessary stops at traffic lights and encouraging the transition from private car transport to public transport. By reducing waiting times and fuel consumption, a direct impact on air quality and energy efficiency in the city is expected. In addition to environmental benefits, the aim is to increase road safety through video monitoring of intersections and the integration of warning systems for pedestrians and drivers.

The purpose of the case study is to present the impact of dedicated public transport infrastructure. TransBus operator line 10 will be analysed by comparing travel times between terminal stations before and after the project's implementation, at different times and in several scenarios, such as with or without priority at traffic light intersections. The study aims to highlight the actual impact of the investment on the attractiveness of public transport. Line 10 was selected for the study due to its strategic importance in the transport network of the municipality of Buzău. The route connects the southern industrial area with the northern residential neighbourhoods and includes several commercial and administrative points of major interest. Table 1. presents the characteristic data for the line for the year 2023, before the completion of the project.

Tables 1–4 show the semi-trip times on Line 10 in two operating scenarios: 2023 and 2025 without activating public transport priority at intersections. The values for both directions of traffic (Ring 1 and Ring 2) are included, reported for three hourly intervals: 08:00, 12:00, and 16:00. The data allow for the observation of variations in duration depending on the time of day, direction of travel, and specific operating conditions, providing an objective framework for the comparative analysis of public transport performance in the two periods analysed.

Table 1. The main characteristics of Ring 1 in 2023

Station name	Distance [m]	Time [min]			Station dwell time [min]
		Time			
		8:00	12:00	16:00	
Brăilei Road	0	0	0	0	0
Mariage Restaurant	750	2	2	2	0.25
Marghiloman Park	600	3	3	3	0.25
CFR High School	300	4	4	4	0.25
Horticulture	550	5	5	5	0.25
Mitran	450	7	7	7	0.25
High School 1	400	8	8	8	0.25
Dorobanți Market	300	9	9	9	0.25
Dorobanti intersection	400	11	11	11	0.25
Broșteni	400	12	12	13	0.25
Contactoare	700	15	14	16	0.5
Bazar	600	18	17	19	0.5
Cathedral	600	22	20	22	0.25
RAM	400	25	22	25	0.25
ACR	600	28	24	28	0.25
BIG	500	32	27	31	0.25
Drăgaică	1000	39	32	38	0.25
Alison	650	42	34	40	0.25
Gerom 1	350	43	35	41	0.25
Gerom 2	200	44	36	42	0.25
Mihai Viteazu	300	45	37	43	0.25
High School 7	400	46	38	44	0.25
Rotec	250	47	39	45	0.25
Constam	450	48	40	46	0.25
Cibela	300	49	41	47	0.25
Apcarom 2	350	50	42	48	0.25
Brăilei Road	1400	53	44	51	0.25
Total	13200				7
Total half race [min]		60	51	58	
Commercial speed [km/h]		13.2	15.5	13.7	

Table 2. The main characteristics of Ring 2 in 2023

Station name	Distance [m]	Time [min]			Station dwell time [min]
		Time			
		8:00	12:00	16:00	
Aromet	0	0	0	0	0
Apcarom 2	750	2	2	2	0.25
Cibela	250	3	3	3	0.25
Constam	300	4	4	4	0.25
Agrana	250	5	5	5	0.25
High School 7	450	6	6	6	0.25
Mihai Viteazu	400	7	7	7	0.25
Gerom	300	8	8	8	0.25
Ductile	400	9	9	9	0.25
Alison	250	10	10	10	0.25
Casa de pensii	450	13	12	13	0.5

Station name	Distance [m]	Time [min]			Station dwell time [min]
		Time			
		8:00	12:00	16:00	
BIG	1100	18	16	22	0.25
ACR	700	21	18	25	0.25
McDonald's	500	24	21	28	0.5
Bazaar	900	31	26	36	0.5
Sports Hall	750	35	29	40	0.25
Broșteni	500	36	30	41	0.25
Dorobanti intersection	400	38	32	43	0.25
Dorobanți Market	400	39	33	45	0.25
High School 1	300	40	34	46	0.25
Mitran	400	41	35	47	0.25
Horticulture	450	43	36	49	0.25
CFR High School	600	44	37	50	0.25
Marghiloman Park	300	45	38	51	0.25
Apcarom 1	450	47	39	53	0.25
Aromet	850	49	41	55	0.25
Total	12,400				7
Total half race [min]		56	48	62	
Commercial speed [km/h]		13.3	15.5	12.0	

Table 3. The main characteristics of Ring 1 in 2025

Station name	Distance [m]	Time [min]			Station dwell time [min]
		Time			
		8:00	12:00	16:00	
Brăilei Road	0	0	0	0	0
Mariage Restaurant	750	2	2	2	0.25
Marghiloman Park	600	3	3	3	0.25
CFR High School	300	4	4	4	0.25
Pitar Moș	150	5	5	5	0.25
High School 1	850	8	8	8	0.25
Dorobanți Market	300	9	9	9	0.25
Dorobanți intersection	400	11	11	11	0.25
Broșteni	400	12	12	13	0.25
Contactoare	700	15	14	16	0.25
Bazar	600	18	16	19	0.5
CEC	600	21	19	22	0.25
McDonald's	400	23	21	24	0.25
ACR	600	25	23	26	0.25
LIDL	500	27	25	28	0.25
Kaufland South/E85	700	30	27	30	0.25
CIT Buzău	200	31	28	31	3
PECO	300	32	29	32	0.25
Drăgaica	1300	38	33	37	0.25
Alison	650	41	35	40	0.25
Gerom 1	350	42	36	41	0.25
Gerom 2	200	43	37	42	0.25
Mihai Viteazu	300	44	38	43	0.25
High School 7	400	45	39	44	0.25

Station name	Distance [m]	Time [min]			Station dwell time [min]
		Time			
		8:00	12:00	16:00	
Rotec	250	46	40	45	0.25
Constam	450	47	41	46	0.25
Cibela	300	48	42	47	0.25
Apcarom 2	350	49	43	48	0.25
Brăilei Road	1400	52	45	50	0.25
Total	14300				10
Total half race [min]		62	55	60	
Commercial speed [km/h]		13.8	15.6	14.3	

Table 4. The main characteristics of Ring 2 in 2025

Station name	Distance [m]	Time [min]			Station dwell time [min]
		Time			
		8:00	12:00	16:00	
Aromet	0	0	0	0	0
Apcarom 2	750	2	2	2	0.25
Cibela	250	3	3	3	0.25
Constam	300	4	4	4	0.25
Agrana	250	5	5	5	0.25
High School 7	450	6	6	6	0.25
Mihai Viteazu	400	7	7	7	0.25
Gerom	300	8	8	8	0.25
Ductil	400	9	9	9	0.25
Alison	250	10	10	10	0.25
Casa de pensii	450	12	12	13	0.5
Kaufland South/E85	1700	19	17	23	0.25
CIT Buzau	200	20	18	24	3
PECO	300	21	19	25	0.25
LIDL	550	23	21	27	0.25
ACR	700	25	23	29	0.25
McDonald's	500	27	25	31	0.5
Bazar	900	32	29	36	0.5
Sports Hall	750	36	32	40	0.25
Brosteni	500	37	33	41	0.25
Dorobanti intersection	400	39	35	43	0.25
Dorobanti Square	400	40	36	45	0.25
High School 1	300	41	37	46	0.25
CFR High School	1000	43	39	48	0.25
Marghiloman Park	300	44	40	49	0.25
Apcarom 1	450	46	41	51	0.25
Aromet	850	48	43	53	0.25
Total	13600				10
Total half race [min]		58	53	63	
Commercial speed [km/h]		14.1	15.4	13.0	

Priority for public transport within the UTOPIA system works through an integrated mechanism for detecting, analysing, and adapting traffic lights in real time. Buses are automatically detected before they reach an intersection, either by sensors mounted in the road or by the GPS tracking system integrated into the vehicles. Once a public transport vehicle is identified, it sends a priority request to the intersection controller and the system command centre.

The algorithm analyses this request together with existing traffic flows and decides whether to grant absolute priority (by interrupting other flows) or conditional priority (inserting the bus into a green phase without significantly affecting other traffic participants). Depending on the context at the intersection, the system automatically adjusts the duration of the traffic light phases so that the bus can pass without stopping or with minimal delay. After the bus has passed, the traffic light cycle returns to normal, and data about this manoeuvre is recorded for monitoring and analysis. This approach contributes significantly to reducing delays in public transport and increasing its attractiveness, without significantly compromising the overall flow of road traffic. Along line 10, the length of the route where public transport can benefit from priority at intersections is 2400 m, which for ring 1 represents 16.8% of the total route length and 17.7% for ring 2.

Tables 5 and 6 show the semi-trip times on Line 10 in 2025, under conditions of active priority for public transport. Both directions of traffic (Ring 1 and Ring 2) are included, at 08:00, 12:00, and 16:00. The data reflects the performance of the line in a context where the extended route and dedicated lane are constant, and the distinctive element is the activation of priority at intersections.

Table 5. The main characteristics of Ring 1 in 2025 with priority at intersections

Station name	Distance [m]	Time [min]			Station dwell time [min]
		Time			
		8	12:00	4:00	
Brailei Road	0	0	0	0	0
Mariage Restaurant	750	2	2	2	0.25
Marghiloman Park	600	3	3	3	0.25
CFR High School	300	4	4	4	0.25
Pitar Mos	150	5	5	5	0.25
High School 1	850	8	8	8	0.25
Dorobanti Square	300	9	9	9	0.25
Dorobanti intersection	400	11	11	11	0.25
Brosteni	400	12	12	13	0.25
Contactoare	700	15	14	16	0.25
Bazar	600	18	16	19	0.5
CEC	600	20	18	21	0.25
McDonald's	400	21	19	22	0.25
ACR	600	22	20	23	0.25
LIDL	500	23	21	24	0.25
Kaufland South/E85	700	25	22	25	0.25
CIT Buzau	200	26	23	26	3
PECO	300	27	24	27	0.25
Dragaica	1300	33	28	32	0.25
Alison	650	36	30	35	0.25
Gerom 1	350	37	31	36	0.25
Gerom 2	200	38	32	37	0.25
Mihai Viteazu	300	39	33	38	0.25
High School 7	400	40	34	39	0.25
Rotec	250	41	35	40	0.25
Constam	450	42	36	41	0.25
Cibela	300	43	37	42	0.25
Apcarom 2	350	44	38	43	0.25
Brailei Road	1400	47	40	45	0.25
Total	14300				10
Total half race [min]		57	50	55	
Commercial speed [km/h]		15.1	17.2	15.6	

Table 6. The main characteristics of Ring 2 in 2025 with priority at intersections

Station name	Distance [m]	Time [min]			Station dwell time [min]
		Time			
		8	12:00	4:00	
Aromet	0	0	0	0	0
Apcarom 2	750	2	2	2	0.25
Cibela	250	3	3	3	0.25
Constam	300	4	4	4	0.25
Agrana	250	5	5	5	0.25
High School 7	450	6	6	6	0.25
Mihai Viteazu	400	7	7	7	0.25
Gerom	300	8	8	8	0.25
Ductil	400	9	9	9	0.25
Alison	250	10	10	10	0.25
Casa de pensii	450	12	12	13	0.5
Kaufland South/E85	1700	19	17	23	0.25
CIT Buzau	200	20	18	24	3
PECO	300	21	19	25	0.25
LIDL	550	23	20	27	0.25
ACR	700	24	21	28	0.25
McDonald's	500	25	22	29	0.5
Bazar	900	28	24	32	0.5
Sports Hall	750	31	26	35	0.25
Brosteni	500	32	27	36	0.25
Dorobanti intersection	400	34	29	38	0.25
Dorobanti Square	400	35	30	40	0.25
High School 1	300	36	31	41	0.25
CFR High School	1000	38	33	43	0.25
Marghiloman Park	300	39	34	44	0.25
Apcarom 1	450	41	35	46	0.25
Aromet	850	43	37	48	0.25
Total	13600				10
Total half race [min]		53	47	58	
Commercial speed [km/h]		15.4	17.4	14.1	

The modernization of urban infrastructure and the extension of Line 10 have led to significant changes in urban travel. However, in the absence of explicit prioritization of public transport at traffic light intersections, the operational efficiency of Line 10 remains below expectations, despite the modernization of the bus fleet and the adaptation of the route. A comparative analysis of public transport performance on Line 10 in the municipality of Buzău in 2023, and 2025, in a scenario where the UTOPIA system does not give priority to buses at traffic lights, but in which the dedicated lane is already implemented on 17% of the route, highlights a series of partial but insufficient progress to ensure integrated urban efficiency.

In 2023, public transport operated in a completely mixed traffic regime, without any form of prioritization or separation. Under these conditions, according to Figure 2, the average commercial speed of buses on the analyzed line ranged between 13.2 and 15.5 km/h on Ring 1 and between 12 and 15.5 km/h on Ring 2, depending on the time of day. The average travel time for a half-trip ranged

between 51 and 60 minutes, as shown in Figure 3, due to traffic congestion during peak hours and the lack of dedicated corridors.

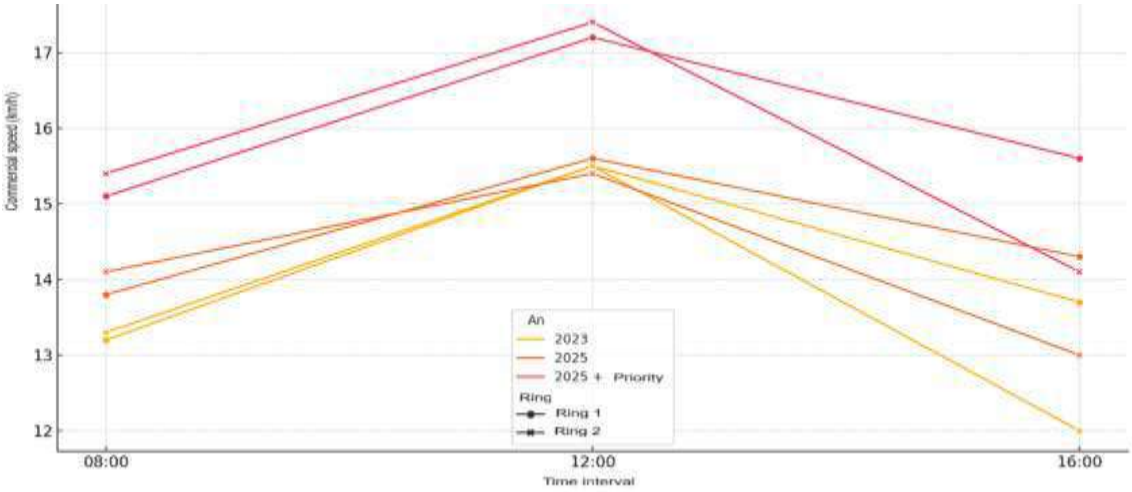

Figure 2. Variation in commercial speed

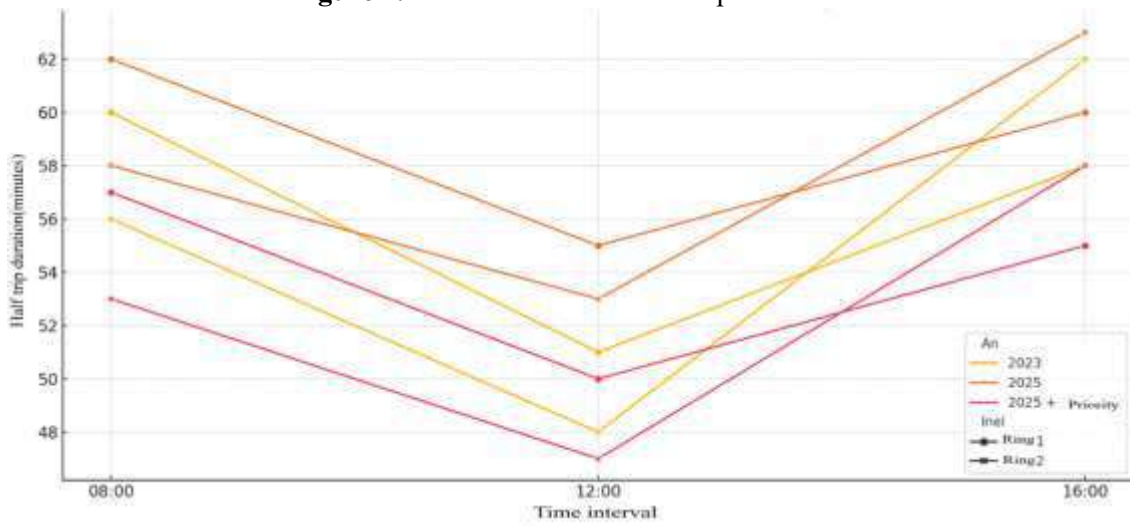

Figure 3. Duration of half-trips.

In 2025, without priority at intersections but with a dedicated lane over a length of 2,400 m (approximately 17% of the route), there is a slight improvement in traffic parameters. The average commercial speed increased during peak hours by 0.6–0.8 km/h, and the semi-trip duration remained relatively constant compared to 2023, despite the physical extension of the route by more than one kilometer. These data demonstrate that the dedicated lane has a positive impact, especially in segments where it is continuous and well-defined, reducing queueing times.

However, in the absence of dynamic prioritization at traffic light intersections, the benefits of the dedicated lane are diminished by the frequency of forced stops at red lights, which continue to affect the predictability and total duration of trips. The dedicated lane ensures smoother traffic flow in some sections, but does not completely solve the congestion at intersections, where general traffic flow inevitably interferes with that of buses. From this perspective, progress is real, but fragmented and incomplete.

It is also important to note that in 2025, the route of Line 10 includes several new stations, introduced in areas of high interest (e.g., Kaufland Sud, CIT Buzău), which generates a natural increase in total duration, but also an increased potential to attract users. In the absence of a compensation mechanism, such as intelligent prioritization, this expansion turns from an opportunity into an operational burden, which can limit the overall efficiency of the service. Compared to 2023, the 2025 scenario without the activation of traffic light priority ( ), but with the introduction of a dedicated lane, brings a partial improvement in public transport performance, highlighted in commercial speed. However, the total duration of journeys remains roughly the same or slightly longer than in the past, suggesting that the physical infrastructure, in the absence of a digital measure to coordinate flows, is not sufficient to generate systemic changes.

In 2025, in the traffic light priority scenario, an average of between 15.1 and 17.4 km/h was achieved. This increase of approximately 2 km/h compared to 2023 data indicates a considerable improvement in service efficiency, contributing to shorter travel times and more predictable schedules. Between 12:00 p.m. and 1:00 p.m., the gains are most noticeable, suggesting that outside of peak hours, the UTOPIA system manages to improve traffic light efficiency with increased performance.

Comparing the total duration of semi-trips, it can be seen that in 2025, in the prioritization scenario, the duration decreases to 53-57 minutes. This means a time saving of between 5 and 7 minutes per semi-trip compared to 2023, representing a reduction of between 8 and 12% in total duration. Given that the length of the route increased in 2025 with the introduction of additional stations, these results are even more significant. In practice, the dedicated infrastructure and priority at traffic lights compensated not only for congestion but also for the physical extension of the route. In these segments, speed and regularity are optimized, and deviations are reduced. This improves not only the duration but also the uniformity of journey times, which is essential for user loyalty. In conclusion, the implementation of the dedicated lane and the intelligent traffic management system in Buzău has led to a measurable increase in public transport performance.

In Figure 4, the 2025 scenario with priority for buses brings the greatest reductions in travel time, especially between 12:00 p.m. and 1:00 p.m., with a saving of approximately 4 minutes per half-trip. In contrast, the scenario without priority actually shows increases in travel time compared to 2023 in some intervals (for example, at 16:00, the time is more than 3 minutes longer). These data confirm that dynamic prioritization at intersections is essential for dedicated infrastructure to generate real benefits in urban mobility.

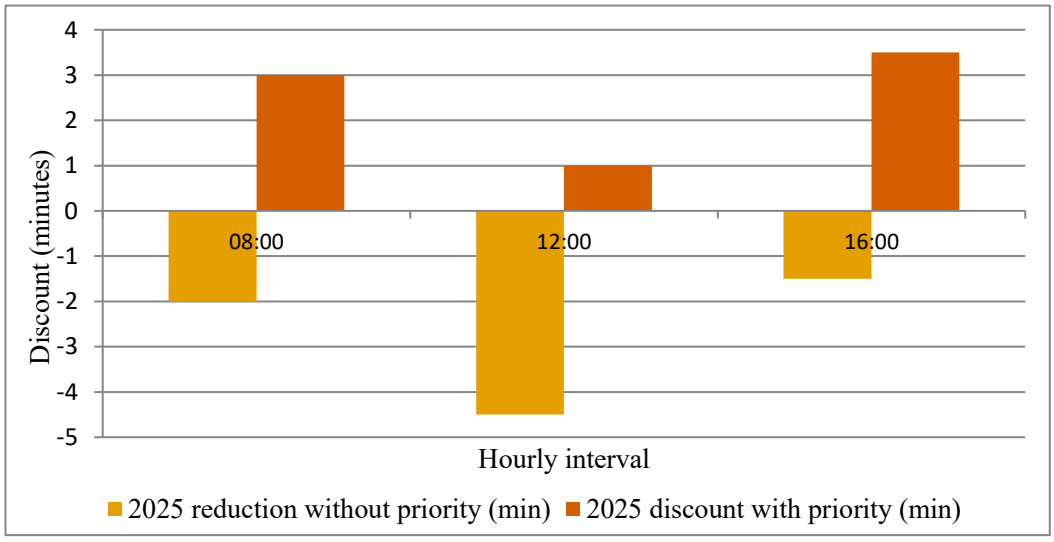

Figure 4. Reduction in semi-trip duration in 2025 compared to 2023

Based on these conclusions, it is recommended to maintain and improve the model implemented across the entire urban network, as the prioritization system is already operating on all public transport lines in the city. Continuous performance monitoring is necessary, using data provided by the NEXT platform, as well as periodic adjustment of traffic light parameters according to traffic flow developments. At the same time, a coherent public communication strategy can contribute to increasing the use of public transport and strengthening an urban culture oriented towards sustainable mobility.

Conclusions

The transition toward low-carbon urban transport requires an integrated perspective that links infrastructure, technology, and governance. The case study of Line 10 in Buzău illustrates both the opportunities and the limitations of current approaches. On one hand, the modernization of the bus fleet with electric vehicles and the introduction of dedicated lanes represents clear steps toward cleaner and more efficient mobility. On the other hand, the analysis shows that these measures alone are insufficient to achieve significant reductions in travel times and to make public transport an attractive alternative to private cars. The improvements emerged only when intelligent traffic management through the UTOPIA system was activated. By granting buses dynamic priority at intersections, commercial speeds increased by approximately 2 km/h, and average travel times fell by 8–12%, even though the route length was extended with additional stations. These results underline that digital control and adaptive coordination of traffic flows are essential complements to physical infrastructure. Without them, congestion at intersections and unpredictable delays continue to undermine the efficiency of public transport.

From a policy perspective, the Buzău case demonstrates that local governments can achieve tangible results by combining infrastructure modernization with smart digital tools and these measures must be embedded in a broader strategy that also includes continuous monitoring of system performance, periodic recalibration of traffic management parameters, and active communication with citizens to encourage behavioral shifts toward public transport. Looking ahead, further research should investigate how intelligent traffic systems can be scaled across entire urban networks and how they can be integrated with renewable energy sources to optimize both mobility and energy use. Equally important is the study of user responses: as reliability and predictability increase, public perception of public transport may shift, creating the social foundation for long-term decarbonization.

In conclusion, the evidence from Buzău reinforces the central argument of this paper: sustainable urban mobility is not the result of single interventions but of synergistic strategies. Infrastructure, digital intelligence, and governance must work together to generate lasting environmental and social benefits, transforming public transport into the backbone of low-carbon urban futures.

Limitations and Future Research Directions

This study has several limitations that constrain the scope and generalizability of its findings. The empirical analysis is based on a single medium-sized Eastern European city operating under partial corridor segregation in a mixed-traffic environment, limiting external validity given cross-city institutional and fiscal heterogeneity. The intervention focus is restricted to incremental measures—dedicated bus lanes and Traffic Signal Priority—without incorporating broader structural reforms, thereby only partially capturing system-level and long-term modal effects. The evaluation emphasizes short- and medium-term operational indicators within a quasi-experimental before–after framework; although this design strengthens internal validity, residual confounding cannot be fully excluded. Moreover, environmental, behavioral, and equity dimensions are only marginally addressed.

Future research should adopt comparative multi-city designs, extend longitudinal observation periods, and employ more robust causal inference methods to improve attribution precision. Integrating operational data with environmental, behavioral, and system-level modeling frameworks would enable a more comprehensive assessment of staged transit modernization strategies in resource-constrained, non-metropolitan contexts.

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Disparities among EU Countries in the Circular Economy Framework: an Entropy-Based Analysis of Global Sustainability and Resilience

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Abstract. This paper analyzes the circular economy framework within the European Union, focusing on its contribution to global sustainability and resilience during 2023. Using the entropy method, the study examines convergence and divergence among EU member states based on three key indicators: consumption footprint, greenhouse gas emissions, and material import dependency. The results show convergence in terms of consumption footprint, while material import dependency exhibits the greatest divergence. The analysis highlights the uneven implementation of circular economy principles across EU countries, offering insights relevant for future sustainable development policies.
Keywords: *circular economy, sustainability, resilience, European Union, convergence, entropy method*

Introduction

Through the launch of the Roadmap to a Resource Efficient Europe (European Commission, 2011) and the EU Action Plan for the Circular Economy (European Commission, 2015), the European Commission has demonstrated a strong commitment to improving resource efficiency and accelerating the transition from a linear to a circular economic model (Domenech & Bahn-Walkowiak, 2019). These policy initiatives emphasize the need to decouple economic growth from resource use and environmental degradation, thereby promoting a more sustainable and resilient economic system (MacArthur, 2013; Kirchherr et al., 2017).

Against this policy background, this paper examines differences in the implementation of circular economy (CE) principles across EU member states. The main objective is to assess and compare the level of circular economy performance among EU countries using an entropy methodological approach, with the aim of identifying disparities related to global sustainability and resilience.

By applying entropy analysis to selected circular economy indicators for the most recent available year, this study provides an contemporary and comparative assessment of CE performance in Europe. Particular attention is given to key indicators within the global sustainability and resilience pillar, including consumption footprint, greenhouse gas emissions and material import dependency. Unlike earlier studies that primarily rely on static or single country analyses, this research offers a cross-

country comparative perspective, contributing new empirical insights into the current state of the circular economy in the EU (Smol et al., 2020).

The structure of this paper is organized into five main sections. The first part, Introduction outlines the research context. The Theoretical Framework presents key concepts related to the circular economy, sustainability, and resilience, with a focus on EU policy development. The Methodology section explains the use of the entropy method and the selection of data for analysis. The Results and Discussion section presents the findings on convergence and divergence among EU member states, followed by an interpretation of their implications for policy and practice. Finally, the Conclusion part summarizes the main findings, research limitations, and suggests directions for future research.

Theoretical background

Transition towards a resource efficient circular economy in Europe

The term "circular economy" (CE), is gaining popularity, particularly in the European Union, and it encourages the prudent and periodic use of resources, which may support sustainable growth. CE is a general term that encompasses many meanings. Some authors such as Webster (2015) said that CE present "a systemic change… with idea is to create a regenerative system where products, components and materials are maintained at their highest value for as long as possible and resources can be productively recovered and reintegrated in the economy or provide nutrients to natural systems".

Some authors highlight that CE refers to an economic system aimed at minimizing waste and maximizing the use of resources through closed-loop material cycles (Geissdoerfer et al., 2017). Kirchherr et al.., (2017), in their review of over 100 definitions, propose that CE is "an economic system that replaces the 'end-of-life' concept with reducing, reusing, recycling, and recovering materials in production, distribution, and consumption processes." Similarly, the Ellen MacArthur Foundation (2013) defines CE as "a restorative and regenerative system" that aims to maintain the value of products, materials, and resources for as long as possible, emphasizing design, systems thinking, and innovation.

From an industrial ecology view, CE aligns with resource efficiency, eco-design, and industrial symbiosis (Stahel, 2010; McDonough & Braungart, 2002). In policy terms, such as the EU's Circular Economy Action Plan, it focuses on goals like reducing landfill, boosting recycling, and decoupling growth from resource use (European Commission, 2015). Recent perspectives broaden CE to include social, ecological, and governance dimensions, linking it to sustainability, innovation, and equity (Schröder et al., 2019; Korhonen et al., 2018).

On the basis of a detailed insight into the literature, we can highlight that several schools and opinions of CE existed in the past period. The concept and explanations are presented in Table 1.

Table 1. Schools of Thought on the Circular Economy – Explanation, Principles and Focus Areas

Concept	Explanation of CE	Key principles	Authors
Industrial Ecology "cradle to cradle" concept	CE as a system for efficiency and closed loops via technology and innovation	Recycling, resource loops, industrial symbiosis, eco-design	Stahel (2010), McDonough & Braungart (2002)
Ecological Economics	CE as a pathway to reduced material throughput and post-growth economies	Sufficiency, limits to growth, localism, minimal resource extraction	Kallis et al. (2018), Jackson (2016), Raworth (2017)
Social Justice / Just Transition	CE as a vehicle for equity and inclusion, not just material efficiency	Labor rights, community participation, global justice, informal sector	Valenzuela & Böhm (2017), Schröder et al. (2019)
Market-Driven	CE as a business opportunity for innovation, value creation, and growth	Profitability, new markets, servitization, value retention	Lacy & Rutqvist (2015)
Blue Economy	CE as a regenerative system inspired by nature, fostering local solutions and zero waste	Use what you have, zero emissions, cascading use of resources, biodiversity	Pauli (2010)

Source: Author

The EU's shift toward a resource-efficient circular economy is guided by key policy frameworks, including the Europe 2020 Strategy, the Resource Efficient Europe Initiative and Roadmap, and the Circular Economy Action Plan (European Commission, 2010, 2011, 2015). Together, these policies build on traditional environmental pillars like waste management and energy efficiency, integrating circular principles across sectors and governance levels.

Table 2. Circular Economy in the EU – Policy Instruments and Their Main Purposes

Policy Instrument	Year	Main Purpose
Europe 2020 Strategy	2010	Promote smart, sustainable, and inclusive growth; integrate resource efficiency in EU growth strategy.
Flagship Initiative: Resource Efficient Europe	2011	Decouple economic growth from resource use; encourage sustainable production and consumption.
Circular Economy Action Plan	2015	Support transition to a circular economy; increase recycling rates; reduce landfill; promote eco-design and innovation.

Source: Author, based on European Commission strategies

Another more recent directive is the Proposal for a Regulation establishing a framework for setting ecodesign requirements for sustainable products (European Commission, 2022). It is focused on energy-related products and ecological requirements for products sold in the EU. This directive proposed in 2022 as part of the EU Green Deal and Circular Economy Action Plan, aims to broaden the directive to cover all physical goods, promoting a circular product policy framework.

Measuring the Circular Economy: Insights from Existing Conceptual Frameworks

The CE helps reduce environmental pressures and promote long-term economic and social well-being (Korhonen et al., 2018). Resilience, the ability of systems to absorb shocks and adapt while maintaining key functions (Folke, 2006), has become increasingly important in the EU amid crises like COVID-19 and geopolitical disruptions. As global challenges such as resource scarcity, climate change, and waste grow, interest in circular strategies is rising across micro (products, firms), meso (industrial symbiosis), and macro (cities, regions, nations) levels (Ghisellini et al., 2016).

Despite the growing academic and policy focus on CE, measuring its implementation and outcomes remains a significant challenge. The complexity of CE, which encompasses environmental, economic, and social dimensions, has led to a proliferation of conceptual frameworks and indicator systems aimed at capturing its performance. However, these frameworks vary widely in scope, methodology, and practical applicability, making it difficult to compare results across contexts or to establish a standardized measurement approach (Moraga et al., 2019; Saidani et al., 2019).

Traditional econometric models (for ex. input–output analysis and material flow accounting) offer useful insights but often overlook the dynamic, multidimensional nature of circular economy transitions. To address this, the entropy method has emerged as a robust tool for objectively weighting indicators and analyzing system variability (Siddique et al., 2022). Based on information theory, it quantifies data dispersion, highlighting the most informative variables and reducing subjective bias. This makes it particularly effective for constructing composite indices in CE assessments, as it assigns greater weight to indicators with higher discriminative power (Busu & Busu, 2018). Considering that some authors came to the conclusion that, despite the unified policy vision, substantial disparities persist across EU member states in terms of circular economy performance (Friant et al., 2020), this paper will measure these disparities.

Methodology

The methodology part consists of three main components: study area, The indicators and data sources and The tools and techniques. This approach enables a structured analysis of sustainability performance across the EU.

Selection of study area

This study focuses on the member states of the European Union (EU) for which relevant data on circular economy indicators were available for the year 2023. A total of 27 EU countries are included

in the analysis: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden. These countries represent a diverse group in terms of economic development, resource dependency, and environmental policies, making them a suitable sample for assessing convergence and divergence in the implementation of circular economy principles within the EU.

Indicators and Data Source

This study relies on three core indicators from the Eurostat Circular Economy Monitoring Framework, specifically under the dimension of Global Sustainability and Resilience. The selected indicators capture different aspects of resource efficiency, environmental pressure, and dependency on external materials. All data were retrieved from the official Eurostat database for the year 2023.

Table 3. List of indicators

	Dimension	Unit of measure	Code	Code in Eurostat
CIRCULAR ECONOMY: Global sustainability and resilience	Consumption footprint	Index, 2010=100	CF	Consumption footprint [cei_gsr010__custom_18183049]
	Greenhouse gases (CO_2, N_2O in CO_2 equivalent, CH_4 in CO_2 equivalent, HFC in CO_2 equivalent, PFC in CO_2 equivalent, SF_6 in CO_2 equivalent, NF_3 in CO_2 equivalent)	Kilograms per capita	GHG	Greenhouse gases emissions from production activities [cei_gsr011__custom_18183086]
	Material import dependency	Percentage	MID	Material import dependency [cei_gsr030__custom_18183113]

Source: Author

These indicators are particularly relevant for assessing convergence and divergence among EU countries, as they reflect both environmental impacts and structural dependencies within national economies.

Tools and techniques

In this paper, the entropy approach was used to assess differences among EU member states, in accordance with Czyz & Hauke (2015). Entropy-based methods are particularly suitable for comparative regional analysis, as they allow the measurement of how evenly or unevenly a given indicator is distributed across spatial units, such as countries or regions.

The concept of entropy originates from information theory and was formalized by Shannon (1948). In this context, entropy reflects the degree of uncertainty or diversity in a distribution: indicators that are similarly distributed across countries contain less information about differences, while indicators with large cross-country disparities provide more information. This property makes entropy a useful tool for evaluating spatial inequalities and convergence or divergence patterns among regions. In regional and spatial studies, entropy is commonly interpreted as a probabilistic concept describing the outcome of a stochastic process, where higher entropy values correspond to more heterogeneous spatial structures (Nijkamp and Paelinck, 1974; Fedajev et al., 2020). Applied to circular economy indicators, entropy captures how uniformly EU member states perform with respect to a given indicator. Based on Shannon's entropy measure, the Shannon Entropy Index is calculated to quantify inequality among EU countries for each selected indicator. If entropy values are high (close to 1), the indicator values differ substantially across countries, indicating high variability or divergence. Conversely, low entropy values (close to 0) indicate that countries exhibit similar performance levels, suggesting convergence.

This measure of inequality is particularly useful for analyzing spatial disparities among countries or regions and can be expressed by the following equation:

$$I(x) = H(x)_{max} - H(x) = \log_2 n - \sum_{i=1}^{n} p(x_i) \log_2 \frac{1}{p(x_i)}$$

$$= \sum_{i=1}^{n} p(x_i) \log_2 [n\, p(x_i)]$$

$$\text{for } 0 \leq I(x) \leq \log_2 n$$

where I(x) = 0 indicates the absence of inequality (or uniform distribution), while I(x) = log2 n indicates the maximum non-uniformity of the selected parameters x.

In our case if entropy is high (close to 1) values vary greatly across countries and it indicates high variability or divergence. If entropy values are low (close to 0) it indicate that values are very similar across countries and explain low variability or convergence between countries.

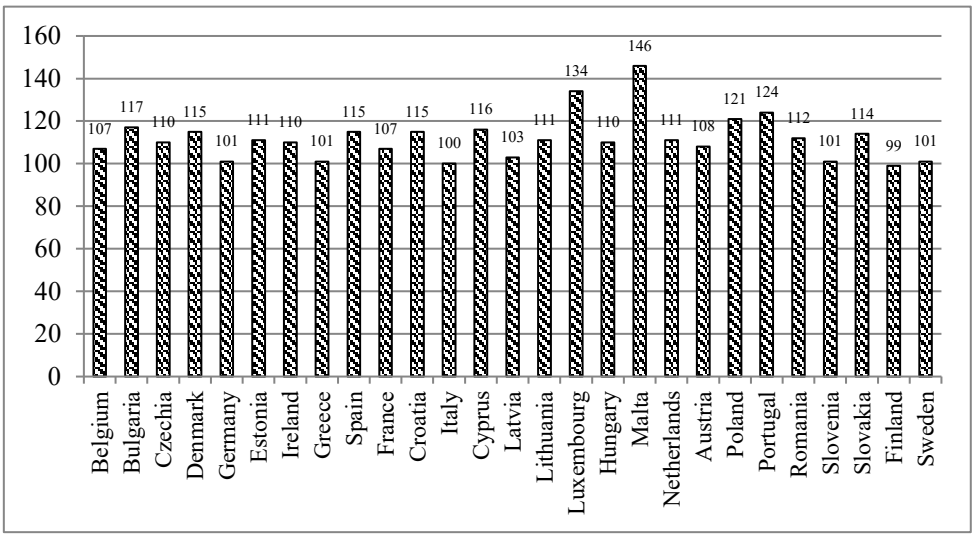
In this context, the entropy approach, or objective weighting, is applied to determine the relative importance of each indicator, by assigning greater weight to criteria that show greater differences between countries, while assigning less weight to those where the situations between countries are more similar.

Results and Discussions

Consumption footprint

The data on consumption footprint reveals notable disparities among EU countries, reflecting differences in resource use intensity and the implementation of circular economy principles.

Figure 1: Index of Consumption footprint in EU, 2023 (Index, 2010=100)



Source: Author

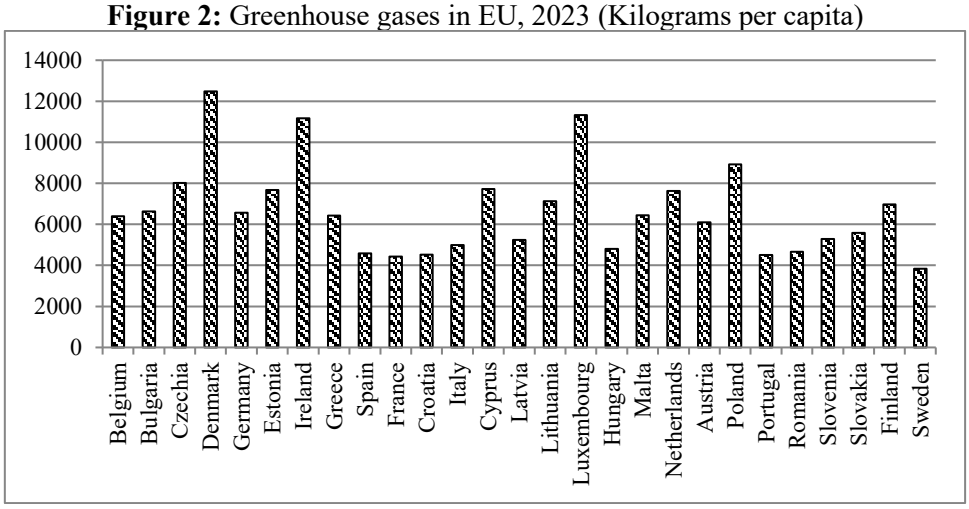
As presented on Figure 1, Malta (146) and Luxembourg (134) stand out with the highest index of consumption footprints, indicating a significant environmental pressure associated with domestic consumption patterns. Such high values may stem from high-income lifestyles, resource-intensive imports, or limited circularity practices (Frendo, 2023). These countries could benefit from stronger policies promoting sustainable consumption and circular production systems.

In contrast, Finland (99) and Italy (100) register the lowest index of footprints, suggesting relatively lower material intensity or higher efficiency in resource use. However, these values could also reflect lower levels of industrial activity or consumption, which must be interpreted carefully in the context of economic structure. The middle-performing group includes countries like France (107), Austria (108), and Belgium (107), which likely have established some circular policies but still exhibit moderate consumption pressures. Interestingly, Baltic countries show variation: Latvia (103) has a low footprint, while the same values are in Estonia and Lithuania (111), suggesting some differences in energy sources, industrial mix, or levels of domestic extraction.

Greenhouse gases

The analysis of greenhouse gas (GHG) emissions across EU member states reveals significant disparities in environmental performance, with implications for circular economy and climate policy alignment. Countries such as Denmark (12481.46461 Kilograms per capita), Luxembourg (11332.23173 Kilograms per capita), and Ireland (11176.06661 Kilograms per capita) exhibit the highest levels of emissions, suggesting greater carbon intensity in their economic activities or slower progress in energy transition. For example Luxembourg's per capita electricity production is nearly half the world average and considerably lower than that of countries like Norway and Sweden (Oberhausen Krippler, 2023). These elevated values may result from reliance on fossil fuels (Hvelplund et al., 2019), energy-intensive industries (Alcantara &Duarte, 2004), or inefficient transport systems (Domagała& Kadłubek, 2022).

Figure 2: Greenhouse gases in EU, 2023 (Kilograms per capita)



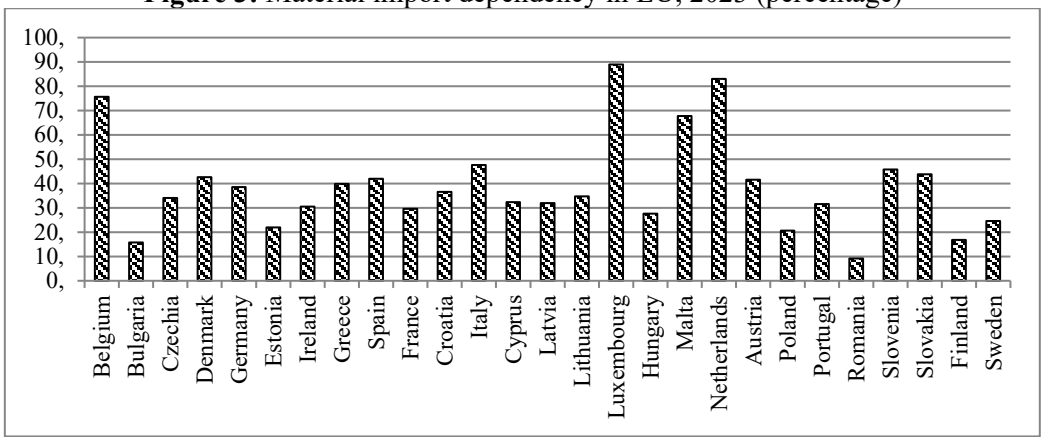
Source: Author

In contrast, Sweden (3,833.55), France (4,424.19) and Spain (4,590.57) demonstrate lower emissions, likely reflecting investments in renewable energy, technological innovation, and stricter environmental regulations. The mid-range group, including countries like Austria and Belgium points to moderate performance that still demands improvement.

Material import dependency

The material import dependency data highlights substantial variation in how EU countries source their raw materials, reflecting differing levels of resource self-sufficiency and exposure to external supply risks. Countries like Luxembourg (89%), Belgium (75.6%), and the Netherlands (83%) exhibit the highest dependency on material imports, indicating a strong reliance on global supply chains (Notteboom, 2009) and limited domestic extraction or recycling capacity (Bandera, 2021) . These high levels underline the urgency of adopting circular practices such as material substitution, reuse, and increased recycling.

Figure 3: Material import dependency in EU, 2023 (percentage)



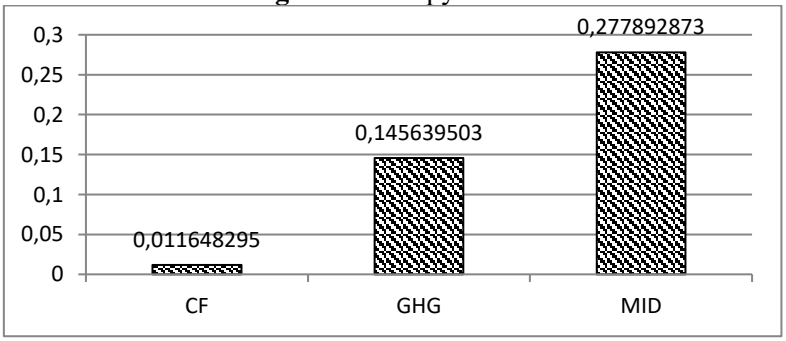
Source: Author

On the other end of the spectrum, Romania (9.2%), Bulgaria (15.8%), and Finland (16.8%) show very low dependency, implying a higher degree of material self-reliance—either due to domestic resource availability or lower industrial import needs. The mid-range countries, including Germany (38.6%), France (29.6%), and Italy (47.6%), balance import reliance with domestic resource management, potentially offering a foundation for building resilient circular systems.

Findings from earlier studies highlighting the varied adoption of circular economy tactics throughout Europe are consistent with the observed differences in material import dependency among EU member states. Numerous studies have noted that structural flaws in resource management and local material cycles, in addition to economic openness, are reflected in high import dependency (Korhonen et al., 2018; Schröder et al., 2019). Countries such as Luxembourg, Belgium, and the Netherlands, with dependency rates exceeding 75%, are exposed to external shocks and geopolitical risks in global supply chains—an issue increasingly highlighted in the post-COVID and post-Ukraine war contexts (European Commission, 2020). Prior work by Kirchherr et al. (2017) stresses that circular economy efforts must move beyond recycling and waste management toward building systemic resilience, particularly through reduced dependency on virgin and imported materials. Conversely, countries like Romania and Finland demonstrate low import reliance, consistent with findings by the Ellen MacArthur Foundation (2013), which promote local loops and material self-sufficiency as key dimensions of an effective circular economy. This suggests that import dependency is not merely a trade statistic but a strategic indicator of a country's circular readiness, vulnerability, and potential for industrial transformation. Therefore, aligning national circular economy strategies with material security considerations is a necessary step toward achieving the EU's broader Green Deal and climate neutrality targets.

After presenting the data, we calculate the entropy for each of the observed indicators.

Figure 4: Entopy results



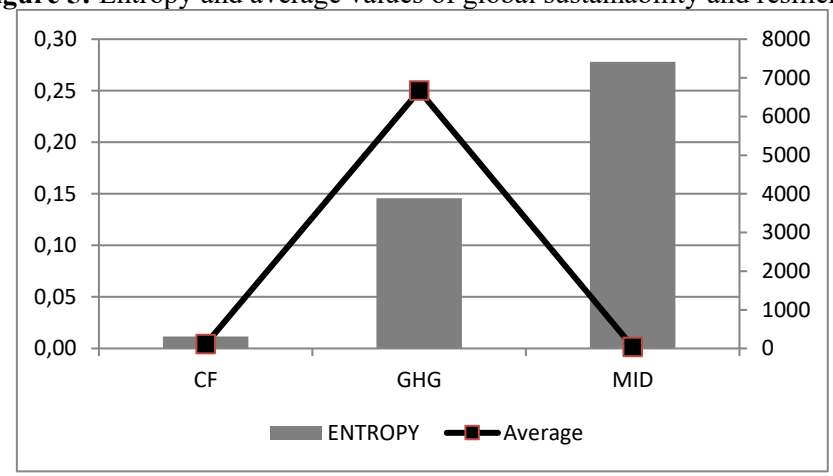
Source: Author

In our study, entropy values close to 1 indicate high variability or divergence among countries, meaning that indicator values differ greatly across EU member states. Conversely, entropy values close to 0 suggest low variability or convergence, where countries show similar performance levels for the given indicator. The entropy values obtained for the three indicators — Consumption Footprint (0.0116), Greenhouse Gases (0.1456), and Material Import Dependency (0.2779) — reflect varying degrees of divergence and convergence among EU countries. Specifically, the very low entropy value for Consumption Footprint indicates a significant convergence in consumption patterns across member states, suggesting that disparities in this area are decreasing. This aligns with the findings of Geissdoerfer et al. (2017), who emphasize that coordinated EU level policies are essential for harmonizing sustainability efforts and reducing differences among countries.

On the contrary, higher entropy values for greenhouse gas emissions and especially for material dependence indicate the existence of a significant divergence. These differences may be the result of different economic structures, industrial policies and access to resources, which is supported by Korhonen et al. (2018) who point out that "divergent development paths and resource bases of countries require tailored policies for an effective transition to a circular economy".

Furthermore, the entropy approach, as reported by Siddique et al. (2022), "enables the objective quantification of differences among variables, thus facilitating the identification of areas in need of further harmonization and focused intervention". This is key to understanding and addressing the problem of divergence that can threaten the EU's common goals for climate neutrality and sustainability (European Commission, 2020). This entropy analysis confirms that there is progress in harmonizing some dimensions of the circular economy (convergence in the consumer footprint), significant differences remain in other areas (emissions and material dependency) that require differentiated but coordinated policies to achieve a sustainable and more resilient European economy (Kirchherr et al., 2017).

Figure 5: Entropy and average values of global sustainability and resilience



Source: Author

Figure 5 shows the results of entropy and average values for the three observed indicators. The dashed line shows the entropy results (primary axis-left side, Clustered Column diagram) which range from 0-1 on the left side of the y-axis. On the secondary axis (values on the y-axis to the right) they show average values. Author include average scores for global sustainability and resilience indicators to provide understanding of both the degree of variability (divergence/convergence) and the central tendency (overall performance) among EU member states.

The Consumption Footprint indicator displays the lowest entropy value (0.0116) and an average of 111.85, suggesting a high degree of convergence among EU countries. This implies relatively uniform performance and possibly a shared baseline in consumer behaviour or environmental impact per

capita. However, the low entropy also means this indicator contributes less to distinguishing between countries in composite assessments, despite reflecting a moderate overall footprint.
In contrast, GHG emissions have higher entropy (0.1456) and an average value of 6,668.24, indicating moderate convergence and pointing to a small difference in countries' contributions to climate change. The relatively high average underscores the need for more ambitious decarbonisation policies across the region, particularly in high-emitting member states.

Table 4. Summary table

	Entropy	Average	Interpretation
CF	0.0116483	111.8519	High convergence
GHG	0.1456395	6668.241	Moderate convergence
MID	0.2778929	39.06296	The relatively high Divergence

Source: Author

Among the observed indicators, material import dependency (MID) exhibits the highest entropy value, indicating that this indicator shows the greatest variability across EU member states. In other words, differences between countries are more pronounced for material import dependency than for the other indicators considered. Although the average MID value at the EU level remains relatively moderate (39.06%), given that the index ranges up to 100%, the elevated entropy value suggests a lack of convergence among countries rather than a uniformly high level of dependency. This implies that while some EU member states have reduced their reliance on imported materials, others remain highly dependent, resulting in a divergent pattern.

Such variability reflects differing levels of strategic autonomy and resource self-sufficiency across EU countries, which is consistent with previous studies emphasizing the role of domestic material loops in strengthening circular economy resilience (Korhonen et al., 2018; Schröder et al., 2019). At the same time, the moderate average level of MID indicates that a substantial share of EU countries still relies heavily on imported materials, potentially increasing their exposure to external supply disruptions and geopolitical shocks.

Conclusion

This study applied the entropy method to assess disparities among EU member states in the implementation of circular economy principles, with a specific focus on the global sustainability and resilience dimension through three key indicators: consumption footprint, greenhouse gas emissions, and material import dependency. The results reveal a nuanced landscape. Consumption footprint shows a high level of convergence (low entropy), suggesting relatively similar consumption related environmental pressures across EU countries. In contrast, greenhouse gas emissions and material import dependency display lower levels of convergence, with material import dependency exhibiting the highest entropy value. This indicates persistent structural differences among member states in terms of decarbonisation pathways and resource self-sufficiency, both of which are critical for strengthening a resilient and circular European economy.

Overall, the findings suggest that while EU countries are progressing toward harmonisation in certain circular economy dimensions, particularly consumption-related impacts, other areas require stronger and more differentiated policy efforts to foster convergence. In particular, emissions reduction and material dependency remain key challenges that may widen disparities if not addressed through coordinated EU-level and national strategies. A longer-term observation of these indicators is necessary to determine whether the observed patterns represent temporary fluctuations or persistent trends of convergence or divergence.

The results of this study are particularly relevant for EU policymakers, national governments, and regional planners, as they provide a comparative and data driven basis for identifying priority areas where policy intervention is most needed. By highlighting which dimensions of the circular economy

are converging and which are diverging, the findings can support more targeted resource allocation, the design of differentiated policy instruments, and the monitoring of progress toward EU sustainability objectives. In addition, sustainability analysts and researchers may use the entropy framework as a diagnostic tool for cross country benchmarking of circular economy performance.

Despite its contributions, this study has several limitations. First, the analysis is constrained by the selection and availability of indicators, which represent only a subset of the circular economy framework and do not fully capture other important dimensions such as waste management, secondary raw materials, competitiveness, innovation and production side dynamics. Also, the focus on a single year (2023) limits the ability to assess dynamic changes or long-term convergence trends.

Future research should therefore expand the indicator set to include both quantitative and qualitative measures, apply longitudinal analyses to capture temporal dynamics, and combine entropy analysis with complementary approaches such as multi-criteria decision-making (MCDM) or econometric methods. Extending comparative analyses beyond the EU and examining the determinants of divergence would further enhance the understanding of circular economy transitions and support the development of more inclusive and effective policy frameworks.

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The theories of lessons learned-comparative trends between economic and military powers with Romania forced structures

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Abstract. The lessons learned are a concept with universal and national fundamental value. Societal, economic and political architecture is built on the teachings of the past and the challenges of the future for a realistic and sustainable present. The protagonists come from all areas of activity, create procedures, face obstacles, identify lessons and adapt by specific methods project portfolios for sustainable development. The purpose of the article was to highlight the differences in the field approach the field of lessons learned by comparing attempts between the military perception of defense of NATO and other economic powers, with reference to the importance of the concept and the degree of implementation in Romania, is one of the topics analyzed. The natural flow, after all, maybe sometimes bold in diversity, continues with the presentation of lessons learned as they were assumed in the field of the Shengen information system, the economic and banking spectrum in Romania, the impact of personal data protection, accidents at work and last but not least, applicability in the area of public order and safety. The conclusions will bear the majority mark of the recommendations from the point of view of the performance indicators from a generalist perspective related to the essential findings of the article, in order to sustainably develop the promotion of the importance of implementing the lessons learned seen as a policy of societal and human innovation in the institutional protection of the state.

Keywords: ***comparative trends between economic and military powers with Romania****, fields of application of lessons learned,*

1. Introduction

Following the documentation on the study of the literature in the field, the need to develop trends that integrate the portfolio of lessons learned from both universal and national spectra has emerged. Determining the needs in Romania regarding the conceptualization of the dysfunctions in various fields of activity, had as starting point the method of comparison with the economic and military powers from the highly developed states that have put an unquestionable emphasis on capitalizing the syncope and transforming them into rules to follow. Through the mechanisms of comparison with international force systems, such as NATO, the authors will show improvement needs regarding the whole process of approaching the lessons learned at Romania level.

Thus, various bibliographic sources were consulted for the formation of sound, scientific and well-grounded hypotheses that provide the interested reader with landmarks in addressing the issue.

The article also presents the lessons that resulted from the findings in various key areas of the societal architecture, such as security and information crises, vulnerabilities of excess formalism in the field of public and private administrations, banking risks in recent years in Romania with affecting operations

that lead to decisive decisions for the business environment in order to strengthen the position on the labor market knowledge gaps in the field of personal data protection, occupational safety and environmental preservation, but also from the perspective of public order and safety with force impact in the Romanian society.

The reasons for which the lessons learned are not applied in certain sectors of activity, the obstacles, the general principles of lessons learned for all methods, will be another topic of discussion in the article, based on the study of recent literature, but also the expertise of authors at managerial level in areas of state force, namely public order and safety and economy.

Performance indicators will take the form of authors' assessments following the essential findings in the article. Thus, they target intercollected recommendations, the message of which contributes to the prevention of similar precedents. Of course, in the generalist sense, account will be taken of the scale over time, of the managerial structures, of the changes in technology and of the cognitive perceptions adapted to each case.

A recommendation to be presented at the end, will focus on the existence of a national database, accessible to interested natural and legal persons, at any level, so that it can respond as effectively as possible to the needs and interests of the target groups.

Promoting awareness activities to prevent errors in key areas of society is the basis of the article. To remain relevant, the lessons learned must be based on practical experience and regularly analysed. The information provided shall be transparent in order to know the potential outcome of the lessons learned among the beneficiaries.

2. Methodology

The article has as scientific basis the qualitative method of the study of the literature corroborated with the analysis of normative acts specific to the field of valorization of the lessons learned. By the method of comparing the processes of lessons learned NATO versus the force structure of Romania, the authors will use the regulatory mechanisms that confer authenticity to the study case.

At the same time, through the method of analysis and observation, in conjunction with the professional expertise of the authors in the professional fields of public policy and national security, respectively economy, relevant findings were issued and highlighted the recommendations formulated in the article.

3. Theoretical aspects of the concept of lessons learned

The practice of organizational knowledge management (KM) continues to be of critical importance for organizations of all sizes and sectors in the face of continued technological, economic, and societal disruptions that have complicated the operating landscape. In support of processes and mechanisms that enable the socialization, externalization, creation, and internalization of knowledge. [1]

This systematic literature review focuses on lessons learned systems (LLS), a class of knowledge management systems (KMS) designed to capture experiential knowledge on the context, actions, and outcomes gained from carrying out various organizational processes and procedures that may help ensure success or prevent failure, or increase efficiency. [2]

Given the importance and value of experientially derived knowledge on organization processes, the design of lessons learned system is of significant interest to practitioners and academics alike. [3]

Lessons learned (LL) are defined [4] as true and valid experiential knowledge on the positive or negative outcome of some activity that can inform design, future processes, and decision-making to induce or prevent some outcome. Lessons learned are distinct from other forms of experiential knowledge as they don’t describe a complete process, track both success and failure, and are oriented towards organizations rather than industries. [5] To find efficiency and organizational outcomes [6], many organizations have implemented lessons learned systems (LLS) to facilitate the collection, verification, storage, dissemination, and reuse of knowledge. [7]

Knowledge is commonly conceptualized as being valid relationships between concepts, often about procedures, facts, or ideas that can help guide future action. [8] The specificity of knowledge also varies. While general knowledge is broadly held, contextually and technically specific knowledge is relevant only to certain locations, situations, or specialized areas of practice. [9]

For activities that rely more on tacit know-how knowledge, collaboration, training, and apprenticeships are commonly employed mechanisms to ensure that members of the organization have the requisite knowledge to execute tasks [10], while the development of procedures, routines, and direction of work may be suitable for tasks relying more on explicit knowledge.

At the level of the Ministry of Internal Affairs, the activity of lessons learned is regulated by Order of the Ministry [11], [12], approving the working methodology on capitalising on the results of operational activities carried out at the level of the line ministry, defining the concept as a process that consists as a whole, activities organised and carried out in stages in accordance with the provisions of head/commander of the interested unit.

The NLLP workshop was held for the first time in 2019, collocated with the Conference of the North American Association of Computational Linguistics (NAACL). The first edition consisted of 12 original papers, 9 of which are archived in the workshop proceedings. The NLLP community aims to bring together researchers and practitioners from Natural Language Processing (NLP) and the legal domain who work on methods and applications of Natural Language Processing by focusing on legal text and text with legal significance. [13]

Through the Center for Army Lessons Learned and the eight Centers of Excellence, the Combined Arms Center creates a knowledge sharing culture within the Army in which every Soldier and Army Civilian Corps employee is a discoverer and user of information, with the intent of driving continuous collection and sharing of observations from every unit level. The lessons learned program provides a system in which discovered lessons and best practices are validated and corrective actions are implemented into doctrine, training, education, leader development and operations. This is accomplished through a network of commands, units, and organizations continuously collaborating on observations to facilitate the integration and sharing of lessons and best practices. The program further improves the implementation of recommended changes to determine effectiveness in addressing identified issues. [14]

3.1. Particularities in the field of public order and safety

According to the above regulation, the stages of the process of lessons learnedis: preparation for observation and collection of data and information; observation and collection of data and information; analysis of data and information; endorsement of the information note; implementation and monitoring of lessons identified; validation of lessons identified; exploitation and dissemination of lessons learned. [11]

Performance improvement aims at correcting the malfunctions that have arisen in the organization, planning, management, execution, resources necessary to carry out specific activities, including the professional training of the participating personnel with an emphasis on interactive and qualitative training sessions.

3.2. Cases of applicability of lessons learned in diversified societal areas

Insufficient time causes employees not to value identifying solutions for the future so that performance can be improved precisely from the syncope of honesty.

The studied literature shows, following the selection of authors, some examples from different fields of activity, so as to point out the importance of the lessons for preventing the registration of precedents when it was not acted properly. As a general perception, leaders should also take into account the training of employees who were not personally involved in the events or projects from which the lessons learned are drawn. The direct consequence is that they tend to forget and not to make their own recommendations, which could lead to ways of action similar to the corrected case.

Knowledge-based organizations have as primary objective the organizational processes of learning lessons. The term lessons learned is generally used to describe people, things, and activities related to the act of learning from experience in order to achieve improvement of any kind. The idea of lessons learned in an organization is that through a formal approach to learning, both individuals and the organization can reduce the risk of repetitions of previous mistakes and increase the chances of repeated successes. [15]

3.2.1. Project management and lessons learned

From the point of view of project management, the process of the lessons learned are essential for their operability. Factors such as the organization of data collection and their faithful registration are

prerequisites for the implementation and execution of a project, also helping to more easy monitoring mechanisms.

The main purpose of data collection is to support both management and employees to ease the execution of the project and, most importantly, to prevent the dysfunctions that initially led to the rejection of applicability.

For evidence, the lessons learned are recorded in a special document intended for this action, which can be in physical or online format, with the obligation to be kept regardless of the form. Archiving the data would not help without refreshing the recommendations and without conducting periodic training sessions. The dynamics of human resources being volatile, the need for open discussions based on what has been directed according to punctual cases, demonstrates art in the managerial process. [16]

3.2.2. Schengen Information System and lessons learned

The initial Schengen Information System (SIS 1) was developed under a France-led intergovernmental mental project and became operational in 1995. This functioned, being administered by France, until May 2013, the date on which it was replaced by SIS II. Consider the differences in culture, organization and functionality of the member states that led to inaccuracies in the operationalization of the system due to the lack of adequate communication or common regulatory procedures, as shown by the main specialized studies.

Thus, the Council decided to develop SIS II on the basis of a feasibility study carried out in 1998 and held a series of consultations between member states culminating in the Belgian Swedish initiative which formed the basis for the first legal basis of SIS II. The Council decision established as the date of the salt mine end of 2006. The Commission has not played any formal role in the legislative process. In addition to the fact that since 2001 the Commission has presented in each annual activity report the progress and main difficulties of the project, it has drawn the attention of the Member States, in the 2001 and 2003 communications, to the risks of this deadline and to the assumptions that should have been met if that deadline was maintained.

The Commission drew lessons from the SIS II project which it presented in its 2010 communication and the proposal to set up an agency dedicated to the management and development of large-scale information systems in the policy area. The Commission confirms that it has indeed drawn several key lessons from the development of large-scale information systems and has already implemented them, particularly in the design of the smart borders package.

3.2.3. Chemical work accidents, lessons learned

Contracted workers are usually persons involved in installation or maintenance work on equipment and systems within the unit, but are not employees working in the hazardous building. They usually perform periodic/occasional maintenance work, which is not part of the usual routine work.

These accidents may also involve significant production losses as well as damage to the environment and property. For example, in one case exposed in this bulletin, more than 50 tons of dangerous substances were removed, but fortunately there were no casualties. Outsourced activities may directly or indirectly create a high risk on a very dangerous site, due to insufficient attention to the interaction of contracted workers and contracted activity with plant processes and storage. Maintenance, high-temperature work and housework tasks such as cleaning and painting are frequently outsourced activities.

In the debate in the article studied, it is shown thatit is very important for the operator to ensure the identification and control of all risks in the area, as well as those associated with the work performed by the contracted workers. In addition, as with its own employees and normal workflow, every effort should be made to maintain a high level of awareness of the danger and to control the risks associated with a particular activity. Standard control measures include appropriate training, wearing appropriate protective equipment, controlling access to processing areas, and applying good practice in performing manual work, such as authorising high-temperature work, checking site safety before work starts, and regularly supervising work in progress.

Specialists in the field argue that the lessons learned consist of several useful recommendations when two or more tanks of petroleum products are connected to each other, connecting pipes must be provided with insulation valves to prevent the removal of flammable vapors. 'The undertaking shall develop and

implement written procedures and train the work-executor to ensure safe working practices during high temperature work, tank cleaning work and work at height. These measures would have helped workers identify and eliminate hazards before welding works began. Protection equipment must be better designed to minimise human factor errors in normally operated facilities or maintenance (e.g., warning signs, function buttons, valve safety signs, etc.); If an alarm systems exist in the building, these equipment must function properly, and if their functionality is restricted, it is necessary to install a backup system. The Arms must be designed and installed in such a way that they are understood and can initiate measures if necessary. Active alarms must not be delayed, nor must they be disconnected manually or automatically. [18]

3.2.4. Bank patrons, lessons learned

The Council of Banking Employers of Romania presented a study on the activity of banks in the last 10 years by Deloitte, which aims at the correlation between past, present and future. The studio presents ten lessons learned as a result of the moments of crisis through which the banking institutions passed, being of real use for the management in the future of the inaccuracies found with economic and social effects. The authors will write the lesson as stipulated in the study and will explain on the observations and professional expertise, the nunantele to point.

Lesson 1. Transparency helps

The study highlights the importance of transparency to information accessible to customers as a necessity for market regulation in accordance with the European Directives.

Lesson 2. "Universal measure" is not suitable for all

The studio refers to risks and vulnerabilities related to socio-demigraphic categories when adjusting portfolios for quality services. Differentiated approaches according to economic, demographic and geographic potentials require targeted adaptations of banking services to meet customer needs, but also to avoid counterproductive risks on the labor market.

Lesson 3. Shape does not create substance – not immediately

The study argues that formally harmonized laws, regulations and institutions do not guarantee an efficient business infrastructure. From this we understand the effects of the economic crisis of 2008 that led to the slowdown of development efforts. The lack of market maturity at that time had to be covered with efficient financing allocations. The negative factors that led to the perpetuation of the economic crisis were the growth of the underground economy, cases of corporate abuses, and a level of fiscal predictability. The lessons learned led to the revitalization of investments, the restructuring of the capital market, coherent policies to the benefit of customers and banks.

Lesson 4. Consolidation is the key to sustainability

In the absence of scale and growth, consolidation and reduction of investments are essential to ensure profitability and an efficient allocation of capital. The bank's austere decisions on collateral investments are defining to strengthen sustainability.

Lesson 5. Fast debt restructuring and recovery are prerequisites for development and profitability.

Specialists believe that immediate profitability is related to the identification of money recovery mechanisms.

Lesson 6. Lend your business, not your guarantee

The main objective of the lack of performance was the unproductive vision of the principle that collateral guarantees are a safe replacement for business plans. Hence, there have been situations of non-credit coverage and deterioration of the global financial position.

Lesson 7. Once you enter the hall, you have to play

The domestic capital suffered as a result of the unconsolidated investments.As a result of the effect of the combination between the lower number of viable projects and the better evaluations of projects, the efficiency of the fund allocation process has improved significantly, with the direct effect of increasing the support of sectors with higher growth prospects. However, eligible projects are rare and multiplier factors are still low, with banks continuing to be required to finance low-performing projects in their portfolios under the risk-reduction strategy.

Lesson 8. External financing: Accelerates growth but creates dependence

Although essential for growth, in the absence of domestic economies and sufficient capital formation,

excessive dependence on external financing creates a significant local imbalance and excessive dependence on foreign markets.

Lesson 9. Credit report – deposits less mean more .sustainable.

From the client's view, a balance between the income obtained and the periodic repayment of the debts due to the credits concluded, is a lesson learned bivalent, in the sense that the bank takes measures to secure the beneficiary's portfolio, but also the debtor becomes mature in the choices made. Economic sustainability is precisely in this balance.

Lesson 10. Currency loans – Do we keep calm and continue?

Over exposure to foreign currency loans is one of the factors generating high levels of non-performing loans and market turbulence. After five years of accelerated growth and efforts to sustain convergence until 2008, mainly based on foreign direct investments that fueled domestic consumption and imports, the five years of economic adjustment and stabilization that followed, forced individuals, companies and active banks in Romania to reevaluate their spending practices, including business and finance models and identify healthier and more sustainable options in the long run. In order to cope with this changing environment, banks and their customers had to restructure, resize and reposition themselves according to new levels of economic activity and significantly lower availability of funds and capital at international level. However, the strong reliance on external financing in the growing years remains a legacy with negative long-term consequences for both banks and the client, the article said. [19]

3.2.5. GDPiR, lessons learned

Studies have shown that the GDPiR project has seen a fairly low level of knowledge of representatives of the manufacturing sector about data protection. Workers' representatives at all levels are of the opinion that there are gaps in knowledge of the General Data Protection Regulation (GDPR) and national data protection legislation - the most common experience with data management being the introduction of job-specific systems while new monitoring technologies (such as artificial intelligence-based tools) are still unexplored. Some training sessions on this subject addressed to workers' representatives took place in most of the countries covered by the project, largely during the period when European and national data protection legislation was first adopted.

It is recommended to promote awareness, training and capacity-building activities addressed to workers representatives on the protection of personal data. Those training sessions should highlight the importance of understanding GDPR regulations for preventing violations.

It is recommended to schedule regular updates and training sessions on data protection laws and relevant labor regulations for all workers' representatives so that they can keep up with legal and technological changes.[24]

3.3. Obstacles in implementation and grounds for refusing to identify lessons learned

Over time, from known practice, several possible causes have been identified for which leaders do not give due importance to the dissemination of lessons learned. Some authors consider that they are:

Lessons learned are often addressed at the end of a project, but there is no formal process for capturing, sharing, or integrating these lessons into future projects.

The time pressure

The multitude of tasks to be accomplished in a very short term often leads to the impossibility of allocating time to evaluate errors and capitalizing on tips, lessons learned. From the point of view of the structural organization, the lack of specialized personnel on this line of work in all aspects of approach, from identification of the cause to dissemination in the institutional community, leads to superficial perception of the problem.

Changing the resistance

Comfort at work, habit with current requirements bring inefficiency, counterproductivity and poor performance. The new through the correct assumption of the old brings comfort through safety. This principle must overcome the barriers rooted in the conventional, under the power of the law.

Lack of responsibility

For lessons to become a priority mechanism, it takes courage, initiative and responsibility, that is, ownership. Clarifying the lesson message has its substance in the leader's science and training specialists to convert error into opportunity.

Insufficient communication
Even when the lessons learned are documented, they are not always well communicated to the team or organization. This can happen if lessons are left in a report without actively sharing or discussing them.[25]

4. Case study. *comparative trends between economic and military powers with Romania force structures*

"Intuitive versus analytical? That's a foolish choice. It's foolish, just like trying to choose between being realistic or idealistic. You need both in life." — Mae Jemison, American engineer, physician, and NASA astronaut

4.1. Aim

Experience teaches you! The purpose of the case study is to highlight by the analysis and comparison method, the mechanisms for implementing lessons learned at NATO versus Romania level, precisely to observe the development needs in this field in order to capitalize on the results of operational activities in diversified spectra. The partnership principle contributes to the overall increase in capacity of institutional authorities. As a result, good practices and the transfer of international know-how contribute to the identification of solutions for constructive measures for the implementation of the lessons learned.

4.2. Hypothesise Verifiable statements

a) The stages of valuing the lessons learned.
b) Ways to capitalize on the lessons learned.
c) Mechanisms for implementing the lessons learned.
d) Stream of dissemination of lessons learned.

Table 1. The stages of valuing the lessons learned.

NATO	ROMANIA
• Clarify the Requirement • Design the Analysis • Collect and Analyse • Develop Findings • Draft the Report • Improve the Draft	• Preparing for observation and collection of data and information • Observing and collecting data and information • Analysis of data and information • Information note; • Implementation and monitoring • Validation of lessons identified • Valorisation and dissemination

Source: https://nllpw.org/about/ and System procedure regarding the process of lessons learned in the Ministry of Internal Affairs, code PS-MAI-DGMO-57, [22]- [12]

Table 2. Ways to capitalize on the lessons learned.

Each of these steps of activities requires different types of thinking and answers different questions	
NATO	**ROMANIA**
❖ Clarifying the analysis requirement ❖ Designing the analysis approach ❖ Collecting and structuring data ❖ Analysing data ❖ Exploring ❖ Interpreting ❖ Investigating ❖ Drafting a report ❖ Developing recommendations ❖ Self review	❖ Storage of information collected ❖ Setting objectives based on beneficiary requirements ❖ preparing the analysis ❖ Performing the analysis ❖ Drafting the information note ❖ The value of the lesson that must match the beneficiary's requirements ❖ Objectivity, based on actual findings, careful study and investigation ❖ Interoperability indicators ❖ Recommendations and proposals ❖ The endorsed information note acquires the identified lesson value

Source: https://nllpw.org/about/ and System procedure regarding the process of lessons learned in the Ministry of Internal Affairs, code PS-MAI-DGMO-57, [22]- [12]

Table 3. Mechanisms for implementing the lessons learned.

NATO	ROMANIA
➢ JALLC Analyst Training Modules: JALLC internal training that covers the content in this handbook and the How to guides. ➢ JALLC Analytical Writing Course: JALLC internal training that covers the content of Chapters 6 and 7 of this handbook in more detail, from a communications perspective. • ➢ NATO Alternative Analysis Course: Facilitation skills and structured thinking techniques training that covers content in the NATO Alternative Analysis Handbook ➢ NATO Lessons Learned Online Course: Joint Advanced Distributed Learning (JADL) course ADL-138, which covers basic NATO LL-specific concepts and terminology. ➢ NATO Lessons Learned Staff Officer Course: NATO LL Process training that covers content in the NATO LL Handbook (Reference 2), including how to implement the Analysis Phase of the NATO LL Process	The implementation and monitoring of the identified lessons is done by the specialized staff, which aims to fulfill the measures and recommendations. The measures and recommendations are what must be done to achieve a positive result or to avoid repeating a mistake. When implementing and monitoring the identified lessons are considered: a) the interested unit implementing and monitoring the lesson b) the stage of the identified lesson: in the process of implementation, endorsed, validated, establishing measures, learned c) the field of activity to which the identified lesson relates; d) the level of classification e) the responsible structure The use of the lessons learned responds to the needs of preparation, planning and organization of specific activities and is achieved by integrating the results obtained in working documents, manuals, regulations, instructions, orders or publications M.A.I. The lessons learned can be implemented in internal rules only at the level of the interested units and remain in the documentary bases, specifying the form of their exploitation. Lessons learned that are not introduced into internal rules are kept in documentary bases and, depending on the situation, can be implemented during/after the execution of specific activities. The lessons learned are published in the Information Bulletin of the M.A.I. on the lessons learned or in other specialized publications and are disseminated to the structures of the MA, depending on their field of competence.

Source: https://nllpw.org/about/ and System procedure regarding the process of lessons learned in the Ministry of Internal Affairs, code PS-MAI-DGMO-57, [22]- [12]

d). Flow of dissemination of lessons learned

NATO	ROMANIA
➢ The NATO website (www.nato.int). ➢ The NLLP NATO ➢ Official NATO publications and terminology. These include policies, concepts, plans, doctrines, and directives, among many others. Reviewing these will help build the analyst's topic-specific vocabulary and basic understanding of organizations, tools, and processes in NATO associated with the topic. ➢ JALLC Reports. The JALLC has been producing analysis reports on various topics in NATO since 2002.	The dissemination of the lessons learned has the role of facilitating the exchange of information, in order to improve the performance of specific activities, within the scope of application and is carried out by the specialized staff of the Ministry of Internal Affairs.

Source: https://nllpw.org/about/ and System procedure regarding the process of lessons learned in the Ministry of Internal Affairs, code PS-MAI-DGMO-57, [22]- [12]

4.3. Results

NATO's learned lesson port is centered on the NATO Learning Hub, managed by Joint Analysis and Lessons Learned Centre's JALLC.

NATO partners can submit relevant documents in the portal and on this occasion contribute to the enhancement of the lessons delivered.

In 2013 NNLP was founded, being valid in two versions, respectively for the unclassified network accessible on the internet, but also for an internal network accessible exclusively for NATO cadres.

NNLP is managed by managers under the coordination of the Supreme United Command of NATO. The managerial tasks are divided into important stages, such as the management of NNLP content, the counseling of the learned lesson actions, as well as the administrative area.

The lesson portal is divided into two fields, namely the Analysis and implementation process and the Portal itself.

JALLC achieves its mission through the process of collecting, analysing and disseminating the lessons learned. This Center dedicated to the field is the quintessence of trust in the institutional effectiveness of the lessons learned. From exploration, interpretation, investigation, drafting of a report, developing recommendations and final report, all these tasks lead to the effectiveness of implementing a way of working considered professionally correct.

The system analyses areas from different areas, such as documents, activities, exercises, operational systems, assessed at minimum, average or high levels of complexity.

Conjugated to the used digital systems, NNLC experts emphasize human judgment in association with critical thinking based on the professional experience of the evaluators correlated with the procedural regulation of activities. [21]

At the force structures in Romania, the conceptualization of the lessons learned exists, but the mechanisms of implementation by selective methods with the support of bidual technology/critical thinking are at the beginning of the road.

At the same time, although there is a database where the lessons learned are implemented, until now outsourcing comprising a common institutional spectrum has not yet been identified.

4.4. Some useful recommendations for the subject of lessons learned in Romania

Working group members as well as leaders should be encouraged to exchange best practices through scheduled meetings for international know-how transfer, actions that would increase compliance with the capacity of the authorities.

Experienced project leaders in areas of societal impact, not refrained to a specific resort.

Outsourcing the mechanism of lessons learned from a field of applicability to all important sectors of activity in our society.

Development of digital platforms to provide accessibility to interested groups on levels of competence.

Training sessions through dedicated modules and subsequently implemented in institutional practice.

Formation of human resource capabilities exclusively for the stages of valorization of the lessons learned.

Mechanisms for monitoring the degree of implementation, feedback and interest, through case analysis to indicate the increase of performance level due to the non-repetability of errors from which a lesson learned was outlined.

Establishing a compartment dedicated to lessons learned within the Romanian force structures, consisting of experienced specialists and professional expertise regarding skills from all areas of competence.

The exchange of experience with states where the field of lessons is developed, so that the transfer of knowledge increases the interest in development.

Managerial opposability, understanding by this term the feedback obligation of the beneficiaries.

The permanent adaptability of the implemented lessons, so as to represent a realistic guarantor of a faithful, legal and transparent way of working.

4.5. Limitations and Future Studies

The specialized literature, vast in the field, could not be included as much as possible by the authors, certainly the interest to deepen the subject remains in the attention of the authors. Moreover, following the evolution of the field of lessons learned in Romania compared to other states or high level organizations, will be a target of scientific progress and complementing the findings of the article. The discussions with key factors in the public administration will aim to present the syncope and indicate the reasons for progress in the field.

Changes in vision in current institutional activities lead to the readjustment of lessons previously learned as a result of managing a situation. This recital determines interest in re-evaluation so as to highlight the causes that generate excess formalism, bureaucratization, comfort, lack of risk management. The benefits of collaborative and team learning create strategies through social functions to disseminate results either through shared platforms or through scripted documents that can take multiple forms.

5. Conclusions

The findings of the case study, as well as the exposures of the specialists from the consulted literature, lead to the majority opinion that the lessons learned represent a productive field at national and international level for people in general, and for target groups in particular. History has proved that the lessons learned are still valid today. See the great philosophers, literary critics, historians whose assumptions assumed in writing were based on errors in the management of an action, emotion or case. Human nature in its essence does not change, but only, depending on the age and context, some traits temporarily gain more weight than others, such as tools, new technologies and the scope of their societal impact.

Referring to the differences highlighted in the case study, it is outlined the hypothesis that in Romania the system of lessons learned is not fully developed. The structure that has shown interest in collecting relevant data following the recorded precedents and transforming it into identified lessons, later learned is the Ministry of Internal Affairs. Limitations were noticed on the background of the lack of a common national strategy to include in the key areas the lessons from errors. From here, a whole carousel of factors that consist of existing specialized skills, planning training sessions, assessing lessons learned, response of beneficiaries, readjustment to the actuality and how much it helps for institutional performance.

To appreciate the effort of the other institutions to locally identify certain situations that generate dysfunctionalities and are not constrained in lessons learned, but without implementation in an assumed and regulated system, the efforts may not always reach the desired destination.

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From compliance to performance: How ESG contributes to the sustainable growth of companies

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Abstract. Corporate sustainability has evolved from a simple compliance requirement to an essential factor in supporting the medium and long-term performance of companies. In the context of the global transition to a greener and more responsible economy, organizations face significant challenges in assessing and communicating sustainable performance. International standards, such as GRI, SASB and the ESG framework, impose increased requirements for transparency and accuracy in reporting environmental and social impacts.
This research adopts an applied case study, using a mixed approach, combining qualitative and quantitative analysis. In the first stage, a theoretical documentation was carried out on the concept of corporate sustainability, the regulatory framework and the main international reporting standards. In the second stage, the analysis was applied to OMV Petrom, based on the data published in the sustainability report for 2023. Financial, environmental and social indicators were extracted and organized in synthetic tables and schemes, to highlight both the performance on each ESG dimension and the interdependencies between them.
The main objective of the study is to assess how the implementation of an ESG strategy contributes to sustainable corporate performance, including operational efficiency, investor relations and organizational transparency. The novelty of the research lies in the development of a unified analytical framework, applied to a reference company in Romania, which provides an empirical perspective on the impact of ESG strategies on financial and non-financial performance. The results suggest that the adoption of ESG principles can lead to the optimization of operational processes, strengthening credibility with investors and facilitating access to sustainable financing. The conclusions are relevant not only for the management of the analyzed company, but also for investors, academia and other users interested in the assessment of sustainable corporate performance.

Keywords:*performance; ESG; sustainable growth; sustainability; international standards.*

Introduction

In recent decades, corporate sustainability has become a central element of companies' strategies, going beyond a simple compliance obligation. Organizations are increasingly under pressure to assess their impact on the environment, society and corporate governance, as investors, authorities and the public place increasing importance on social responsibility and sustainable performance. International reporting standards, such as GRI, SASB or the ESG framework, impose strict requirements for transparency and consistency of information, but their adoption in practice can be difficult, especially for companies in regions with limited experience in integrated reporting.

In this context, this study addresses an important issue: how the implementation of an ESG strategy influences corporate performance and business decisions. The research focuses on OMV Petrom, a leader in the Romanian energy sector, and aims to identify both the challenges and opportunities generated by the adoption of an integrated sustainability policy. This approach allows highlighting the added value of ESG for the company and for other users of the information, such as investors, academia or local communities.

Amind the tightening of European sustainability regulations and growing demands from investors, ESG (Environmental, Social, Governance) disclosure and the incorporation of sustainable practices have become critical for major corporations. The European Union (EU) has establishedrigorous obligations for non-financial reporting, most notably through the European Sustainability Reporting Standards (ESRS) introduced under the Corporate Sustainability Reporting Directive (CSRD)(Directive EU 2022/2464).

This study adds value and originality by integrating ESG indicators into an analysis of a major company. Although there is a lot of such research, the application of sustainability is still limited. The novelty is the construction of a unified perspective, which combines financial, social and environmental indicators in a comparable framework, with an emphasis on their practical relevance for integrated reporting. Also, the study proposes a critical interpretation of the company's alignment with international standards, thus providing a useful benchmark for researchers and practitioners.

The main objective of this paper is to assess the sustainable corporate performance of the OMV company through a structured set of indicators and to highlight how these are reflected in the company's integrated reporting.

Sustainable performance refers to an organization’s capacity to generate long-term value through the incorporation of environmental, social, and governance dimensions within its business strategy. ESG metrics serve as tools for evaluating a firm’s environmental footprint, its relationships with employees and communities, as well as its governance structures. The concept of integrated reporting represents a contemporary practice that unites financial and non-financial disclosures, offering a comprehensive perspective on overall organizational performance.Recent studies(Vezeteu, 2024) highlight the positive correlation between ESG transparency and investor attractiveness, making sustainability reporting not just a legal obligation but a strategic opportunity.

In my opinion, an organization can be considered high-performing if it is productive,but performance is not ensured only by productivity. All elements must be combined for an organization to be performing, namely: the financial side, the social side, the environmental side, as well as other elements (shortening production times for example or rapid adaptation to market requirements and innovation). Sustainable reporting ensures the sustainable development of the company's activity and should be used by all organizations because entities that approach non-financial reporting receive more attention from stakeholders.

Grosu and Tanasă (2019) believe that integrated reporting brings a new vision of performance and increases the degree of transparency, credibility, quality and connectivity of information, which contributes to ensuring business sustainability. Integrated reporting, through the concept of integrated thinking within an organization, highlights business sustainability.

Developing an independent, stand-alone report to provide a holistic picture of the entity's ability to create value over time and to connect published reports will lead to increased comparability. Integrated reporting is not limited to producing the report but focuses on substantiating integrated thinking, leading to organizational changes, focusing on reducing polluting factors, actions to manage climate change and social policies (Dănescu and Matei, 2020).

Integrated quality reports that are provided to stakeholders help improve the company's reputation leading to attracting potential investors (Lawal, 2024).

Sustainability is no longer just about efficient consumption of resources, such as energy, recycling and environmental protection. It also involves measures that must be implemented for the well-being of the community. From this point of view, companies, considered as the engines of economic development, have a major impact on social and ecological aspects in the long term.

The elements concerning the profit of companies, the preservation of the environment and the well-being of people must be joined in an innovative business model, which must be permanently improved and which must take into account the entire value chain of the company, both in the short, medium and long term (Emelian, 2023).

For the implemented sustainability practices to be successful, they must be part of the organizational culture and not be used only to benefit from an improvement in the market image (Kam and Kim, 2022). The quality of financial reporting can be considered as a continuum, which varies from the highest, containing relevant, correct, complete and unbiased information, to the lowest, containing information that is not only biased or incomplete, but can also be fabricated (Bahnean et al., 2023).

Sustainable corporate performance brings together all three dimensions of performance, namely: financial performance, social performance and environmental performance. Companies no longer focus on maximizing profit. They have reoriented themselves towards sustainable corporate performance which brings together the three types of performance and which is measured through financial indicators, but especially through non-financial ones that refer to the environment, safety and employees of the organization.

Global performance or sustainable performance is made up of three types of performance:

- financial performance;
- environmental performance;
- social performance.

To say that an entity is performing, a comparison will be made between a specific result and a reference criterion: past situations, competition, as well as the objectives proposed for the future.

The system of indicators developed within the G4 – GRI standard (Global Reporting Initiative) can be associated with economic, social and environmental performance and is presented as follows:

- economic performance indicators – these refer to the entity's impact on the economic conditions of stakeholders and on economic systems;
- environmental performance indicators – refer to the entity's impact on the environment;
- social performance indicators – are grouped into four categories: indicators that refer to labor practices, indicators that refer to human rights, indicators regarding society and indicators regarding the responsibility of products and services offered to customers.

In the current context, there is a need to adopt actions to make the activities of organizations more transparent, and the quality of the information presented and published by them has become over time the decisive factor in terms of building and maintaining a competitive position in the market.

The increasing orientation of entities towards social, environmental and sustainability responsibility has led to the emergence of new performance standards that go beyond the financial dimension. These must be integrated into the activities of organizations to ensure business sustainability and achieve the desired level of overall performance (Velte et al, 2017).

In recent times, the reporting method of companies has undergone changes, and in addition to financial reporting, there has been an increasing emphasis on sustainable corporate reporting. The ability of an entity to create value for itself depends significantly on the interactions and relationships with the external environment and with other forms of capital than financial capital.

Sustainable development is closely linked to the volume of capital that covers economic, environmental and social needs, and in the current context there is a need to move from traditional indicators of economic activity, such as productivity, profit, profitability, cash flow, which reflect the satisfaction of the entity's objectives, to the management of factors that form trust in the entity in the long term from all stakeholders (Ungureanu, 2023).

Business sustainability has become an accepted concept in the economic environment over time, both from the perspective of entities and from the perspectives of stakeholders and interested parties. In recent times, interested parties have increasingly focused on communicating information regarding the sustainability of companies, but at the same time, many questions have been raised about the credibility of the reported information. In this regard, a very important step is the adoption of internal reporting.

In a global context marked by accelerated transformations in the field of sustainability, companies are forced to redefine their business models, taking into account not only economic objectives, but also the impact on the environment and society. Corporate sustainability is not only an ethical option, it represents a strategic necessity for long-term survival and competitiveness. In this context, integrated reporting is an essential tool for credibility, transparency, but also for effective stakeholder engagement.

Work methodology

This research adopts a qualitative approach, based on the case study of OMV Petrom. OMV Petrom is the largest integrated energy company in Romania and one of the important players in South-East Europe. Its activity fully covers the entire energy chain, from the exploitation and production of crude oil and natural gas, to refining, fuel distribution and electricity supply (https://www.omvpetrom.com/ro).The main source of data is the 2023 Annual Report, which also includes the ESRS Sustainability Statement. To complement the data, I also analyzed the sustainability reports published in previous years (2021 and 2022), as well as the relevant GRI and ESRS standards. The analysis was based on the assessment and interpretation of ESG indicators, their interconnection with the company's strategic objectives and the identification of the impact on overall corporate performance.

The research methodology assumed a qualitative analysis, based on the OMV Petrom case study, using as the main sources and sustainability reports of the companies. The approach through the documentary analysis of integrated reports and ESG indicators is validated in the specialized literature, which highlights the relevance of these methods for the evaluation of corporate performance and organizational transparency (Bahnean et al, 2023; Grosu and Tanase, 2019).

At the same time, recent studies show that integrated global reporting provides an adequate framework for correlating strategic objectives with the growth achieved, facilitating the development of the impact of sustainability on the performance of companies (Dănescu and Matei, 2020; Hamad et al, 2020).

In the first stage of the analysis, I identified the relevant indicators for the evaluation of sustainable performance through the theoretical documentation on the concept of sustainable corporate performance, the normative framework and international reporting standards, such as GRI (Global Reporting Initiative) and Refinitiv recommendations. Subsequently, financial, environmental and social indicators were extracted and grouped according to the three major dimensions of the ESG model. In the final stage, we made a comparative and critical interpretation of the results, with the aim of highlighting the company's transparency and involvement in integrating sustainability into its business model. This analysis was supplemented with observations on international trends in the field of integrated reporting, in order to underline the degree of alignment of the company with global standards.

For this analysis, I chose OMV Petrom, which publishes a comprehensive ESG report and is an example of integrated reporting, being the most robust option in Romania. I chose this company because it publishes an annual sustainability report with clear environmental, social and governance indicators, has an ESG strategy until 2030, including decarbonization and energy transition targets, includes integrated reporting and has firm commitments to net-zero emissions.

To carry out the analysis, I identified the main environmental, social and corporate governance indicators from the annual sustainability report. Regarding environmental indicators, I referred to emissions, renewable energy capacity and waste recycling rate. From a social point of view, I analyzed the total rate of recordable incidents, training hours/employee/year, as well as the percentage of employees trained in human rights. The last category of indicators analyzed refers to corporate governance indicators, such as: the percentage of investments aligned with the EU taxonomy, diversity and independent members on the board of directors, the application of ethics and compliance policies, as well as the degree of reporting according to the ESRS. The applied case study allows for an in-depth investigation of the relationship between ESG and corporate performance in a real context, with concrete empirical data. The mixed approach offers the advantage of combining quantitative rigor with the depth

of qualitative analysis, facilitating a complete interpretation of the effects of sustainability strategies on company performance.

This methodology offers both practical value, through recommendations and lessons applicable to management and investors, and academic value, through the contribution to the literature on the integration of ESG into corporate performance in the context of companies in Romania.

Results and discussions

According to the company's website, OMV Petrom is active across the entire energy value chain, from oil and gas exploration and production, refining and distribution to power generation, as well as the trading of natural gas and electricity.

In 2021, the "OMV Petrom Strategy 2030" was launched, through which the company commits to transforming the future into one with lower carbon dioxide emissions. The strategy sets out how the company intends to develop by adding new low-carbon business activities and setting the path to net zero in operations by 2050. Sustainability is fully integrated into the business strategy, with a focus on the transition to low-carbon businesses, conducting responsible operations, innovation and digitalization, and promoting people and communities.

The OMV Petrom Group Sustainability Report 2023 presents the impact of our activities on the economy, the environment and society, as well as how we managed these impacts to strengthen our performance and ensure long-term sustainable development.

From the annual sustainability report, I have extracted key data for analysis presented in table 1 and the main integrated ESG achievements, as follows:

- 30% of the company's CAPEX (Capital Expenditures) is eligible and aligned with the EU Taxonomy – reflecting the transition to sustainable investments;
- 2.4 GW renewable portfolio (wind and solar energy) through acquisitions and partnerships;
- 900 charging points for electric vehicles in Romania – signifying a contribution to green mobility;
- 3,23 billion EUR paid in taxes and dividends to the Romanian budget.

Table 1. GRI sustainable performance indicators

Indicator	**Value 2023**	**Target 2025/2030**
↓ Scope 1[1]+ Scope 2[2] emissions vs. 2019	- 25%	-
TRIR rate	1.37 per million hours	1,0 (2025) and< 1,0 (2030)
Workplace fatalities	1	0 by 2030
Waste recycling rate	74%	continuous growth
Training hours/year	~ 30h	≥ 30h by 2030
Employees trained in human rights	71%	100% by 2025
Suppliers with climate targets	71%	80% (2025), 100% (2030)

Source: Own processing based on data from the annual sustainability report

In Table 1, I have summarized the main sustainable performance indicators according to GRI and based on which I have conducted the extended analysis, below.

Analysis of ESG indicators at OMV Petrom

To substantiate the analysis carried out, it is necessary to present concrete data reflecting the sustainable performance of OMV Petrom. The following table summarizes the most relevant ESG indicators reported for 2023. They provide a clear picture of how the organization has aligned its activity with the strategic sustainability objectives and current requirements, such as ESRS standards or the European Union taxonomy. The inclusion of this data allows for a deeper understanding of the progress made and the integrated dimension of corporate performance.

[1]Direct emissions from the company's activities

[2]Indirect emissions associated with the electricity and thermal energy purchased and consumed by the company

Table 2. ESG indicators according to the 2023 Annual Report

Field	Indicator	Reported value 2023	Observations
Environment	Scope 1 and 2 GHG emissions	- 25% compared to 2019	Goal: Net Zero by 2050
	Planned renewable energy capacity	2.4 GW of solar and wind in development	Aligned with EU taxonomy
	Electric vehicle charging points	Over 900 units	Sustainable mobility infrastructure
	Waste recycling rate	74%	Up from the previous year
Social	Total Recordable Incident Rate (TRIR)	1,37	Target: below 1 by 2030
	Training hours /employee/year	> 30	Continuous staff training
	Percentage of employees trained in human rights	70%	Active social responsibility policy
Governance	Percentage of investments aligned with EU taxonomy	30% from CAPEX	According to ESRS standards
	Diversity and independent members on the board of directors	Yes	Compliance with good practices
	Enforcement of ethics and compliance policies	Confirmed	Internal and external audit
	Degree of transparency in reporting according to ESRS	Complete – ESRS Statement included in the report	Alignment with the CSRD Directive

Source: Own processing based on data from the annual sustainability report

Analysis of environmental indicators

The GRI regulatory framework considers that the main indicators for measuring environmental performance include: materials, energy, water and interaction with water sources, biodiversity, emissions, waste, as well as environmental impact providers.

A classification of environmental indicators is also provided by the Refinitiv database[3], as follows: greenhouse gas emissions (direct and indirect emissions), energy use, water use, waste management, biodiversity impact, resource management, compliance with environmental regulations, and environmental programs and certifications.

The European Commission has proposed the integrated environmental system for the EU Member states of the European Union as a way to report online. All economic operators must provide information on waste generated, packaging waste, used or fresh oils, electronic and electrical equipment, accumulators and batteries, end-of-life vehicles, damaged tires, waste management, wastewater, chemicals and solvent balance, according to the legislation in force and the National Agency for Environmental Protection (ANPM)(Law 211/2011 Waste Regime).

Environmental reporting is very important for employee well-being, improving health and safety conditions at work and leads to employee productivity and satisfaction and preventing legal problems.

By engaging in environmental reporting and complying with its requirements, organizations can enhance their environmental efficiency.OMV Petrom demonstrated, in its annual report published for 2023, a constant concern for reducing its environmental impact, gradually aligning itself with European climate objectives. One of the most significant advances is the reduction of greenhouse gas emissions in the Scope 1 and Scope 2 categories, which have decreased by 25% compared to previous years. OMV set 2019 as its reference year. At that time, the total level of direct and indirect emissions amounted to approximately 13.7 million tons of CO2. By 2023 this value has dropped to 10.3 MT, which shows a downward trend of about 25% officially mentioned by the company.This reduction reflects the

[3]Refinitiv is one of the largest global platforms for providing financial data and analytics. It provides access to a varied volume of information on capital markets, companies, transactions and sustainability indicators, being used by investors, analysts, financial institutions and companies to make strategic decisions.

company's systematic efforts to improve energy efficiency, modernize facilities and transition to low-carbon energy sources.

Simultaneously, the company has advanced in expanding its renewable energy capacity, presenting a growing portfolio of nearly 2.4 GW in solar and wind projects. These initiatives support both the diversification of the energy mix and the growth of taxonomy-aligned investments under EU regulations, thereby reinforcing the firm's overall sustainability profile.At the same time, OMV Petrom has invested significantly in green mobility infrastructure, implementing over 900 charging points for electric vehicles throughout the national network. This initiative facilitates the transition to less polluting transport and supports the European agenda on the decarbonization of the transport sector.

From a circular economy perspective, the company reported a waste recovery rate of 74%, indicating an increasingly efficient management of resources and a responsible approach to reducing its environmental footprint. This progress highlights the strategic orientation towards operational sustainability, strengthening OMV Petrom's position as a regional leader in the field of responsible energy transition.

Amid the challenges generated by the energy transition at European level, the environmental component has become a strategic pillar in OMV Petrom's business model. The company has focused its efforts not only on reducing emissions, but also on transforming traditional operations into a cleaner, more efficient and sustainable system. The adopted environmental strategy reflects both regulatory pressures and a voluntary assumption of responsibility for the impact on natural ecosystems. In addition, the company continued to implement concrete measures regarding energy efficiency in industrial processes. These include the modernization of equipment, the optimization of extraction and refining processes, but also the digitalization of operating flows, which led to a more judicious use of resources and the reduction of indirect consumption.

The company also emphasized the transparency of environmental data in its report, publishing detailed and comparable indicators that allow for the assessment of performance over time. This openness towards stakeholders increases investor confidence and strengthens the company's positioning as a responsible actor in the energy sector in Central and Eastern Europe. The company's approach to environmental sustainability is not reactive, but proactive, based on significant investments, strategic adaptation and a long-term vision. This orientation confirms OMV Petrom's commitment to playing a key role in the country's energy transition.

Analysis of social indicators

Corporate social responsibility is one of the general issues of sustainability of an entity. It is a field of research that investigates solutions and processes that ensure a strategic balance between types of performance, both at the international, national, local and enterprise levels (Tienc et al., 2020).

The indicators for measuring social performance according to GRI are divided into various categories as follows:

- labor practices and decent work: employees and social commitments, health and safety at work, training and education.
- human rights: human rights in operations, diversity and equal opportunities.
- community impact.
- product responsibility: consumer health and safety.
- fundamental rights and freedoms: freedom of association and collective bargaining.

Social performance indicators are used by stakeholders and investors to assess the social impact of companies and cover various key areas.

The social dimension of corporate sustainability is an essential element within the integrated strategy of the company under review, with the company paying increased attention to occupational safety, employee development, social equity and responsibility towards the community. In a context where stakeholder expectations are continuously increasing, the company has consolidated its position as a responsible employer and active partner in the economic and social life of the country.

A key performance indicator in this area is the total recordable incident rate (TRIR), which stood at 1.37 for 2023 (in 2022 it was 1.54). This result indicates a moderate level of risk in the activities carried out, and the company aims to improve this indicator until reaching a sub-unit threshold by 2030. To this end, OMV Petrom has intensified safety training measures,such as practical sessions for accident prevention, introduced technological solutions for real-time monitoring of operational risks and promoted a prevention-oriented organizational culture[4].

In terms of professional development, the company maintained a high level of investment in employee training. On average, each employee received over 30 hours of training annually, covering both technical aspects specific to the activity, as well as topics of ethics, leadership and diversity. These initiatives contribute to maintaining a high level of competence and adaptability in the face of technological and regulatory changes in the sector in which the company under review operates.

An essential component of the company's social policy is the protection and promotion of human rights, embedded within the organizational culture and reinforced through internal regulations. In 2023, nearly 70% of employees took part in training programs on this topic, reflecting a structured and preventive strategy for managing social risks. Furthermore, the company oversees its supply chain, urging business partners to adhere to the same ethical principles.Externally, OMV Petrom continued its active involvement in the communities in which it operates, through corporate social responsibility programs focused on education, health and sustainable development. Initiatives such as the modernization of school infrastructure or the support of environmental projects contribute to increasing the quality of life and strengthening the relationship with local actors.

The company also promotes equity and inclusion in the workplace, supporting gender, age and skills diversity in the decision-making process. These principles are integrated into recruitment, development and promotion policies, reflecting a modern vision of human resources management.

Overall, the social performance of the analyzed company reflects a strategic approach, oriented towards creating long-term value not only for the company, but also for society. By investing in people, safety and sustainable partnerships, the company demonstrates that social sustainability is an active component of corporate responsibility.

Analysis of corporate governance indicators

Corporate governance is a set of mechanisms and principles through which companies are managed and controlled, playing a key role in creating long-term value and also in protecting the interests of shareholders and other stakeholders. The literature on corporate governance has evolved considerably, addressing issues such as board structure, shareholder rights, transparency and business ethics.

The OECD (2015) emphasizes that corporate governance principles should provide a framework that supports economic efficiency, market stability and investor confidence.

La Porta et al (2000) consider that corporate governance is essential for reducing the risks of corruption and abusive practices, and Gompers (2003) considers that it is essential for improving the financial performance and sustainability of companies.

Corporate governance has a very important role in ensuring the long-term sustainability of the company, and OMV Petrom has demonstrated through its actions and policies a firm orientation towards integrity, transparency and responsibility in decision-making. In a context in which ESG requirements are becoming increasingly rigorous, the company structures its governance in such a way as to respond, in addition to legal obligations, to the expectations of investors, the general public and the authorities.

An important aspect in this direction is the alignment with European requirements on sustainability reporting, in particular with the new ESRS standards implemented through the CSRD directive. OMV Petrom has integrated these aspects in the 2023 report, through a structuring of the ESG section, placing great emphasis on the connection between economic performance and the impact it has on society and

[4]Prevention-oriented organizational culture refers to a proactive approach to safety, where every employee is actively involved in reducing risks and protecting colleagues. This involves identifying hazards in time and promoting a safe and healthy work environment.

the environment. The company is among those that capitalize on integrated reporting as a strategic communication and governance tool.

The investment allocation represented 30% of capital expenditure (CAPEX), being redirected to eligible projects according to the EU taxonomy. This percentage highlights the commitment that the analyzed company has to directing financial resources towards sustainable activities, such as renewable energy, power generation or green mobility. Governance is not limited to compliance for OMV, but almost perfectly integrates the strategic dimensions that contribute to the transformation of the business model.

Another equally important indicator is organizational ethics. In 2023, OMV Petrom strengthened the implementation of the code of conduct and the ethical warning mechanisms available to external partners and employees. If complaints are received, they are analyzed by a specialized internal structure, and the results of the analysis are reported and monitored in a transparent and responsibly executed annual report.

Next, I approachedthe topic of ESG risk management, the company creating, for this purpose, an integrated framework for assessing and managing risks related to environmental regulations, climate, reputation, as well as relations with stakeholders. These risks are analyzed both at the operational and strategic levels, being always included in investment decisions, but also in the company's development plans.

Within OMV Petrom, corporate governance represents an active source of value creation, not being seen as a set of formal and mandatory rules. The company manages to support the sustainable transformation of its business model through a solid system of control, transparency and strategic involvement, while consolidating its position as a responsible leader in the Romanian energy sector.

According to the international survey conducted by KPMG in 2017, corporate governance is achieved as a result of the pressure that companies feel in terms of voluntary publications. According to Velte and Stawinoga (2017), the corporate governance structure of a company has a significant impact on voluntary disclosure and the adoption of integrated reporting.

The adoption of integrated reporting can lead to increased transparency and reduced information asymmetries (Hamad, 2020).

According to the previously analyzed studies, the common concepts used in both corporate governance reports and integrated reports lead to an increase in companies' transparency and, at the same time, to an increase in their long-term value.

Conclusions and further developments

Through this article, I analyzed the interdependence between ESG performance, corporate sustainability and effective governance, emphasizing the role of specific indicators in shaping the strategic decisions of the analyzed Romanian integrated oil company: OMV Petrom. This case study represents, in my opinion, an example of the integration of these principles in a sector traditionally perceived as polluting and resistant to change. Based on the analysis carried out on sustainable performance indicators, I can conclude that the analyzed entity has taken important steps towards the transition to a more responsible business model aligned with the principles of sustainable development. In terms of the environmental dimension OMV Petrom has made progress in terms of carbon emissions, in promoting renewable energy, but also in improving energy efficiency. The results are supported by transparent reporting and monitoring mechanisms, as well as by strategic investments.

On a social level, OMV Petrom has maintained a solid commitment to employee safety, workforce diversity and community involvement. The analyzed indicators, such as the TRIR rate, training hours per employee, as well as the degree of coverage in human rights education, demonstrate the constant concern for human capital and for establishing sustainable relationships with external and internal stakeholders.

Regarding corporate governance, OMV Petrom has integrated the principles of corporate responsibility into the decision-making structure and internal policies. The high level of compliance

with EU regulations, as well as ethical control mechanisms, lead to mature governance, capable of preventing risks, but also of capitalizing on opportunities related to sustainability.

As a general conclusion of the article, I can state that OMV Petrom is making progress and aligning itself with EU and international developments in terms of integrated reporting, social and environmental responsibility, and corporate sustainability. The strategic direction assumed is very clear and very well supported by measurable indicators and sustainable actions.

The results of the analysis also validate the hypothesis that companies that correctly implement ESG strategies have an improved reputation and a real competitive advantage in a business environment that is becoming increasingly demanding and oriented towards social and environmental responsibility.

The study is based on public data from the OMV Petrom 2023 sustainability report and GRI and Refinitiv standards, which may limit access to detailed internal information. The analysis focuses on a single case study, which reduces the generalizability of the results. The indicators used, although relevant, do not cover all ESG aspects, and the observed correlations between sustainable and financial performance do not imply direct causal relationships. The results also reflect the specific context of the company and the Romanian market, without capturing all external global or political influences.

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Mapping the evolution of ESG in the insurance sector: An empirical bibliometric analysis of conceptual structures and regulatory-driven research dynamics

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Abstract. This study examines how the concept of sustainability, expressed through ESG (Environmental, Social and Governance) principles, is reflected in academic research focused on the insurance sector. The study is based on a bibliometric analysis of 88 articles published between 2011 and 2024, using the Web of Science database and VOSviewer software. The results highlight a notable increase in academic interest after 2020, closely aligned with recent European sustainability regulations (CSRD, ESRS, EU Taxonomy, Solvency II, Omnibus I). The analysis identifies four main research directions: social responsibility, financial performance, corporate governance and risk management. The findings demonstrate that ESG has become a key analytical framework for understanding structural transformations in insurance, being increasingly used in assessing performance, regulatory compliance and long-term value. The study provides an empirical perspective on the mutual influence between academic research and public policies and highlights the need for interdisciplinary approaches to support the transition to a more sustainable financial system.
Keywords: *ESG, insurance, bibliometric analysis, VOSviewer, governance, sustainability, risk, regulation*

Introduction

Existing studies analyze ESG in finance broadly but rarele isolate how insurance specific regulator transformations have influenced scholarly domain. This study contributes to the specialized literature by mapping and analyzing the conceptual networks surrounding the theme of ESG in the insurance industry, an endeavor that can also be understood as *tracing the development of ESG insurance* that is, following the process of formation and consolidation of this interdisciplinary research field. In the context of the climate crisis, increasing social expectations, and stricter governance standards, insurance companies stand at the intersection of risk and responsibility: they not only manage risks but also act as pivotal agents in the transition towards sustainability. The integration of ESG (Environmental, Social, and Governance) principles into insurance is no longer a symbolic or rhetorical commitment, but a strategic imperative requiring the reassessment of investment policies, underwriting processes, and

disclosure practices. Yet, the conceptualization and consolidation of the "ESG insurance" field remain relatively recent and marked by fragmentation, reflecting the ongoing institutional transformations across the European regulatory landscape.

The consolidation of sustainability and ESG principles within the insurance sector is deeply rooted in both the international and European regulatory evolution. Globally, the 1987 Brundtland Report [1] and the 2015 United Nations 2030 Agenda for Sustainable Development [2] provided the normative foundation for integrating economic growth, social equity, and environmental protection into a unified development model. The Sustainable Development Goals (SDGs) [3], particularly Goals 8 (Decent Work and Economic Growth) [4], 12 (Responsible Consumption and Production) [5], and 13 (Climate Action) [6], directly link sustainable finance and risk management to systemic resilience and long-term value creation objectives in which the insurance sector plays a central role.

At the European level, this vision gradually materialized through a series of strategic and legislative milestones. The first legal foundation emerged with the Treaty of Rome (1957), which introduced the Common Agricultural Policy (CAP) under *Part Two – Bases of the Community, Title II – Agriculture, Articles 38–47* [7], establishing the principle of collective responsibility for resource management and economic stability an early precursor to modern sustainability governance. Over time, this foundation evolved toward a comprehensive sustainability agenda, culminating in the Common Agricultural Policy Strategic Plan Regulation (EU) 2021/2115 [8], which integrated environmental performance, eco-schemes, and rural development into a unified policy framework. These developments converged with the European Green Deal [9], launched in December 2019 (*COM(2019) 640 final*), the Union's strategic roadmap for achieving climate neutrality by 2050 and embedding sustainability across all economic sectors.

The Green Deal triggered a cascade of legislative instruments that collectively redefined the governance of sustainability. Among them, the Corporate Sustainability Reporting Directive (Directive (EU) 2022/2464 – CSRD) [10] expanded corporate reporting obligations and introduced the European Sustainability Reporting Standards (ESRS), legally adopted through Delegated Regulation (EU) 2023/2772 [11], to ensure transparency, comparability, and accountability in sustainability disclosures. The Taxonomy Regulation (EU) 2020/852 [12] established a unified classification for sustainable economic activities, reducing the risk of greenwashing and fostering coherence between financial and environmental objectives. In the insurance field, Delegated Regulation (EU) 2021/1256 [13] amended the *Solvency II* framework to incorporate sustainability risks into governance and risk management processes, reinforced by EIOPA's 2024 guidelines on the prudential treatment of sustainability risks [14][15]. More recently, the Omnibus I package (COM/2025/80 final) [16][17] simplified and harmonized ESG reporting and due diligence requirements, aiming to alleviate administrative burdens while strengthening cross-sectoral consistency.

Within this evolving context, the interplay between regulation, sustainability, and insurance practice has become a focal point for both academic and policy-oriented research. The progressive institutionalization of ESG principles has influenced how risk, performance, and corporate legitimacy are conceptualized and measured in the insurance domain. Consequently, this paper seeks to investigate how these regulatory shifts are mirrored in academic discourse by examining the bibliometric evolution of ESG-related research in insurance between 2011 and 2024. Specifically, it explores (1) the growth and thematic diversification of publications, (2) the dominant conceptual clusters defining the field, and (3) the extent to which major EU frameworks, including the Green Deal, CSRD, ESRS, EU Taxonomy, Solvency II, and Omnibus I, have shaped the trajectory of scholarly attention.

The purpose of this study is to trace the *bibliometric evolution of the ESG insurance field* using VOSviewer software, identifying emerging conceptual structures, thematic linkages, and research gaps. The analysis is based on data extracted from the Web of Science Core Collection, rigorously filtered for thematic relevance and document type (articles and reviews in English). Beyond mapping the scientific trajectory of ESG insurance, this study provides insights into how institutional regulation, transparency requirements, and market expectations jointly shape

research and practice in sustainable finance and insurance governance. In this sense, ESG insurance research is no longer a descriptive endeavor but an analytical framework for understanding the structural transformation of the European insurance sector amid the global sustainability transition and the implementation of the 2030 Agenda for Sustainable Development.

Literature review

The integration of Environmental, Social, and Governance (ESG) principles into the insurance sector has become a major axis of research in sustainability governance and financial regulation. The literature demonstrates a steady evolution from fragmented descriptive analyses toward increasingly systematic and theory-driven approaches. Three core thematic strands can be identified: (1) the conceptual and empirical evolution of ESG in insurance, (2) the bibliometric and methodological consolidation of ESG research, and (3) the institutional and industrial operationalization of ESG standards in practice and policy.

1. The conceptual and empirical evolution of ESG in insurance has been marked by a gradual transition from normative considerations of corporate ethics to strategic dimensions of performance and accountability. Early studies approached ESG as an extension of corporate social responsibility and environmental risk management. Johannsdottir and Cook (2019) [23] examined systemic risks associated with Arctic oil spills, illustrating insurers' dual motivations, ethical accountability and pragmatic liability control. Pfeifer and Langen (2021) [22] aligned the insurance business with the UN Sustainable Development Goals (SDGs), conceptualizing insurers as both enablers and beneficiaries of sustainability transitions. Wang et al. (2023) [21] later demonstrated that digital transformation enhances ESG performance primarily through transparency and investor trust. These findings indicate that ESG has evolved from a normative ideal into a measurable strategic dimension influencing both performance and reputation. Martí et al. (2024) [18] and Aburto-Barrera and Wagner (2023) [19] extended this discussion through systematic reviews, showing that while environmental aspects dominate, the social and governance dimensions remain underexplored.

2. The methodological and bibliometric consolidation of ESG research represents a second axis of inquiry, reflecting the analytical maturation of the field through bibliometric mapping and quantitative synthesis. Nobanee et al. (2023) [24] identified seven dominant themes in sustainable insurance research, revealing conceptual fragmentation but methodological convergence around visualization and co-citation analysis. These approaches build upon the foundational work of Van Eck and Waltman (2014) [20], whose VOSviewer and CitNetExplorer tools shaped the methodological architecture of knowledge mapping. Chytis et al. (2024) [25] and Khaw et al. (2024) [26] expanded bibliometric investigations to ESG governance-performance linkages, while Ye et al. (2020) [27] confirmed that corporate governance and social responsibility persist as conceptual anchors across sustainability studies. Beyond the insurance sector, Kiflee et al. (2024) [28] and Contreras and Abid (2022) [29] associated ESG with SDG advancement and the social dimension of corporate sustainability, respectively. This cluster of studies highlights the progressive formalization of ESG as a research field supported by advanced bibliometric evidence.

3. The institutional and practical operationalization of ESG constitutes the third thematic trajectory, emphasizing the application of ESG frameworks within governance, regulation, and industry practices. Recent scholarship and industry reports converge in recognizing ESG as a core determinant of strategic resilience, competitiveness, and compliance. Sood and Özen (2024) [30] demonstrated that ESG integration drives investment, product innovation, and risk management. Martí, Bastida-Vialcanet, and Marimon (2025) [31] analyzed disclosure quality, showing persistent inconsistencies in ESG key performance indicators (KPIs), while Bressan (2023) [32] explored fiscal trade-offs between sustainability commitments and profitability. Parallel to academia, consultancy and institutional publications, such as PwC (2022, 2023) [33][34], KPMG (2025) [35], and Deloitte (2023) [36], have underscored the need to strengthen climate risk governance and harmonize sustainability-related disclosures. At the policy level, The Geneva Association (2022) [37] defined insurance as a driver of social inclusion and resilience, while UNEP FI (2021, 2022) [38][39] provided specialized guidance for

managing ESG risks and aligning underwriting practices with climate transition objectives. Corporate evidence, exemplified by the *Sustainability Report 2023* (Vienna Insurance Group, 2023) [40] and Groupama's *ESG Climate Report 2022* [41], demonstrates that ESG has become integral to governance frameworks, regulatory compliance, and long-term corporate strategy.

Taken together, these three thematic trajectories reveal the interconnected evolution of ESG in the insurance sector, linking conceptual foundations, methodological consolidation, and institutional implementation into a coherent framework of sustainable governance. The reviewed literature confirms that ESG in insurance has evolved from an ethical commitment into a structural pillar of corporate governance and financial strategy. The transition from descriptive analyses to clustered, methodologically grounded frameworks illustrates the consolidation of ESG as an interdisciplinary domain linking environmental risk, governance efficiency, and social responsibility. The convergence between academic, regulatory, and industry narratives reinforces the notion that ESG in insurance is not a transient trend but a durable architecture of sustainable finance and institutional transformation.

Materials and Methods

The Web of Science Core Collection, recognized for its rigorous peer-review standards, robust indexing process, and broad multidisciplinary coverage, was selected as the data source for this study to ensure the reliability, consistency, and relevance of the analyzed data, as well as compatibility with citation-mapping and bibliometric visualization tools. The database was queried with the combined terms *"*ESG insurance*"* (without quotation marks) in the *"*Topic*"* category to identify the relevant body of literature.

The acronym *ESG* referring to *Environmental, Social, and Governance* criteria is widely used in both academic and policy literature to denote the multidimensional framework guiding corporate sustainability practices. Its combination with *insurance* captures a consolidated and conceptually recognized research area that links sustainability, financial performance, and risk governance within the insurance sector. Following the initial search, which generated 141 records, a set of systematic filters was applied to adjust the dataset. Based on the *"*Final Publication Year*"* field, records from 2025 were excluded, as this year corresponds to an ongoing publication and indexing cycle. Within the *"*Document Types*"* category, only *Article* and *Review Article* were retained, while *Proceedings Papers* and *Letters* were not considered. This selection ensured a homogeneous and analytically coherent dataset, enhancing the precision of bibliometric results and the interpretability of conceptual clusters. Additionally, only English-language publications were included to maintain terminological consistency, comparability, and replicability of the analysis. These criteria were applied to guarantee the quality, comparability, and analytical consistency of the dataset. After applying these filters, the resulting period, 2011–2024, was established as the analysis interval, corresponding to the first documented occurrence of the selected terminology and the most recent fully indexed year available.

After implementing these selection criteria, the final dataset comprised 88 publications. These records were exported in plain text format (*Full Record and Cited References*) to be processed through the bibliometric analysis software VOSviewer (version 1.6.20). The dataset was analyzed using a co-occurrence approach, with *"*All Keywords*"* as the unit of analysis and the *"*Full Counting*"* method. This analytical configuration was selected because keyword co-occurrence mapping provides a reliable indicator of conceptual connectivity within a scientific field, revealing how topics evolve and interact across disciplinary boundaries. The *"*Full Counting*"* method was preferred to *"*Fractional Counting*"* since it ensures that each occurrence of a keyword contributes equally to the network, thereby improving the representation of interdisciplinary linkages and emerging thematic intersections within the ESG insurance domain.

Out of 519 terms initially identified, a minimum occurrence threshold of five was applied to exclude isolated or low-frequency terms that could introduce noise and distort cluster interpretation. This threshold was determined after exploratory testing with alternative values, which confirmed that a cut-off of five occurrences provided the best balance between conceptual inclusiveness and analytical precision. As a result, 26 representative keywords were retained, forming the core of the network and capturing the conceptual essence of the field. The bibliometric visualization generated by VOSviewer

revealed the conceptual structure and internal organization of the ESG insurance research field, delineating major thematic clusters that reflect its intellectual consolidation, diversification, and progressive maturation over time.

Limitations of the study

This study is subject to several methodological and technical constraints that should be acknowledged when interpreting the results. The exclusive reliance on the Web of Science Core Collection, although justified by its rigorous peer-review standards, robust indexing, and compatibility with bibliometric visualization tools, may restrict the scope of coverage by omitting relevant studies indexed in other databases such as Scopus or Google Scholar. Likewise, the inclusion of English-language publications only intended to ensure terminological consistency and analytical comparability introduces a potential linguistic bias, limiting the inclusion of research published in other languages.

The exclusion of records from 2025, due to the ongoing indexing process, and the focus on specific document types (Article and Review Article) were methodological decisions aimed at improving data reliability and analytical coherence. However, these restrictions inevitably reduce the ability to capture the most recent scientific developments and non-traditional scholarly outputs. Additionally, the search string "ESG insurance", while thematically precise, may not encompass all relevant studies employing alternative expressions or related terminological variations.

From a technical standpoint, the use of the "Final Publication Year" field instead of "Publication Year" could result in minor discrepancies in temporal distribution. Furthermore, the analytical configuration applied in VOSviewer a co-occurrence analysis using "All Keywords" and the "Full Counting" method may emphasize frequently recurring terms while underrepresenting emerging or low-frequency concepts. The adoption of a five-occurrence threshold, established after exploratory testing, enhanced interpretative clarity but also excluded marginal topics that could reflect early conceptual developments.

Finally, while VOSviewer ensures transparency and replicability, its analytical capacity is limited compared to integrated or algorithmically advanced bibliometric platforms capable of cross-database comparisons. These methodological and analytical limitations highlight that the present study offers a structured but partial mapping of the ESG insurance research field, providing a foundation for future studies to expand and refine the results through complementary databases and analytical techniques.

Results and discussion

The analysis demonstrates that research on "ESG insurance" has expanded rapidly after 2020, driven by the consolidation of the European sustainability framework, and this evolution is consistently reflected across all five analytical dimensions. (1) The temporal evolution and conceptual maturation highlight a marked post-2020 increase directly associated with major European regulatory reforms. (2) The citation impact and influential contributions confirm the consolidation of ESG as a central analytical instrument for assessing performance and risk. (3) The thematic cluster and conceptual integration reveal a structurally coherent domain aligned with EU priorities on social responsibility, economic performance, managerial integration, and climate-related risk. (4) The evolutionary dynamics and conceptual progression indicate a shift from normative debates to the full operationalization of ESG as reporting and risk-management obligations intensified. (5) The density structure and emerging trajectories confirm the centrality of ESG within the field and point to underexplored directions, such as the interaction between financial markets and sustainable insurance products or the prudential implications of green investments.

1. Temporal evolution and conceptual maturation

Figure 1 illustrates the evolution of research on the topic of "ESG insurance" between 2011 and 2024, highlighting an accelerated growth after 2020. During the 2011–2018 period, scientific activity remained limited, with only two publications in 2011 and one in 2016, indicating a marginal interest in the field. In 2020 and 2021, five papers were published each year, coinciding with the adoption of the

European legislative framework for sustainable investment (Regulation (EU) 2020/852 the EU Taxonomy). The year 2022 marks a sharp increase, reaching 18 publications, parallel to the enactment of Directive (EU) 2022/2464 on corporate sustainability reporting (CSRD). The upward trend continues in 2023, with 19 publications, driven by the introduction of the European Sustainability Reporting Standards (ESRS - Regulation (EU) 2023/2772), while the peak in 2024, with 34 publications, reflects the consolidation of the field following the release of EIOPA's reports on the prudential treatment of sustainability risks in the insurance sector. Figure 1 thus demonstrates a clear correlation between the intensification of scientific production and the advancement of European regulatory initiatives in sustainable finance.

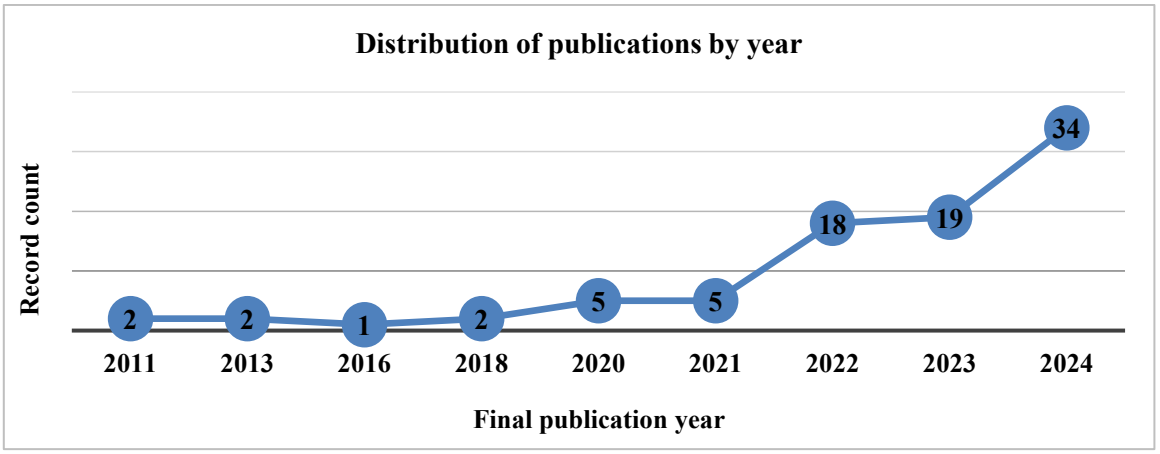

Figure 1. Distribution of publications by year on "ESG insurance" (2011-2024)

Source: Authors' own research results.

2. Citation impact and influential contributions

Table 1 summarizes the most cited works shaping the field of "ESG insurance" (2011–2024). "Market Interest in Nonfinancial Information" (Eccles, Serafeim, and Krzus, 2011; 286 citations) [42] demonstrates investors' growing demand for ESG-related data. "Stock market reactions to adverse ESG disclosure via media channels" (Wong and Zhang, 2022; 222 citations) [43] confirms that negative ESG news significantly reduces firm valuation. "Economic policy uncertainty, stakeholder engagement, and environmental, social, and governance practices: The moderating effect of competition" (Vural-Yavaş, 2021; 137 citations) [44] shows that companies intensify ESG efforts during periods of high uncertainty as a risk-mitigation strategy. The remaining leading contributors, Landi et al. (2022) [45], de la Fuente et al. (2022) [46], Zhou et al. (2024) [47], Lu et al. (2022) [48], Lin and Dong (2018) [49], Li et al. (2022) [49], and Breitenstein et al. (2021) [50], expanded the field through diverse empirical and conceptual approaches addressing sustainability integration, financial performance, innovation, and risk management. Collectively, these studies underscore the consolidation of ESG insurance as a mature and dynamically evolving area of scholarly inquiry within the broader sustainability and finance research landscape.

Table 1. Top 10 most-cited articles in the "ESG insurance" dataset (2011–2024)

No.	Title	Authors	Publication Year	Total Citations	Average per Year
1	Market Interest in Nonfinancial Information	Eccles, Robert G.; Serafeim, George; Krzus, Michael P.	2011	286	19,07
2	Stock market reactions to adverse ESG disclosure via media channels	Wong, Jin Boon; Zhang, Qin	2022	222	55,5

No.	Title	Authors	Publication Year	Total Citations	Average per Year
3	Economic policy uncertainty, stakeholder engagement, and environmental, social, and governance practices: The moderating effect of competition	Vural-Yavas, Cigdem	2021	137	22,83
4	Embedding sustainability in risk management: The impact of environmental, social, and governance ratings on corporate financial risk	Landi, Giovanni Catello; Iandolo, Francesca; Renzi, Antonio; Rey, Andrea	2022	111	27,75
5	The value of a firm's engagement in ESG practices: Are we looking at the right side?	de la Fuente, Gabriel; Ortiz, Margarita; Velasco, Pilar	2022	82	20,5
6	ESG rating divergence and corporate green innovation	Zhou, Jian; Lei, Xiaodong; Yu, Jianglong	2024	72	24
7	Are firms with better sustainability performance more resilient during crises?	Lu, Jing; Rodenburg, Kathleen; Foti, Lianne; Pegoraro, Ann	2022	71	17,75
8	Corporate social responsibility engagement of financially distressed firms and their bankruptcy likelihood	Lin, K. C.; Dong, Xiaobo	2018	67	8,38
9	ESG performance and stock prices: evidence from the COVID-19 outbreak in China	Li, Zengfu; Feng, Liuhua; Pan, Zheng; Sohail, Hafiz M.	2022	49	12,25
10	Environmental hazards and risk management in the financial sector: a systematic literature review	Breitenstein, Miriam; Nguyen, Duc Khuong; Walther, Thomas	2021	47	9,4

Source: Authors' own research results.

3. Thematic clusters and conceptual integration

The bibliometric analysis of the literature dedicated to the concept of "ESG insurance", illustrated in Figure 2[1], reveals a complex thematic network structured into four main clusters, each representing a distinct dimension. The numbers indicate the frequency of term occurrences. The visualization produced with VOSviewer demonstrates that the integration of ESG principles into the insurance sector unfolds along four major directions: social responsibility, corporate governance, financial performance, and climate risk management, highlighting a conceptual coherence between the scientific literature and the European regulatory framework.

Representing the normative dimension of ESG, the red cluster focuses on corporate social responsibility and transparency, thereby reinforcing companies' institutional legitimacy. It is defined by terms such as "corporate social responsibility" (6), "csr" (9), "disclosure" (9), "environmental" (9), "responsibility" (12), "market" (7), "reputation" (6), and "social" (6), which illustrate concerns for organizational ethics and sustainable reporting in line with the CSRD, ESRS, and SDG 12.

[1] The analysis was based on normalization by "association strength", with standard layout parameters (attraction = 2, repulsion = 0), a clustering resolution of 1.00, and the minimum cluster size set to 1, while the "Merge small clusters" option was enabled to avoid fragmentation. The visualization was generated using "occurrences" (size = 0.89) as the weighting variable, with labels displayed as "frames" (font "Open Sans", size 0.50, maximum 35 characters). Lines were color-coded by cluster, with a minimum strength threshold of 0 and a maximum of 1000 connections, while the "size variation" parameter was set to 1.00.

Reflecting the economic dimension of ESG, the green cluster demonstrates the connection between sustainable performance, governance, and corporate financial value. It includes "corporate social-responsibility" (19), "esg performance" (5), "financial performance" (13), "firm value" (5), "governance" (16), "social-responsibility" (8), and "impact" (20), emphasizing how sustainability contributes to corporate performance and competitiveness, consistent with the EU Taxonomy and SDG 8. Emphasizing the managerial dimension of ESG, the blue cluster centers on the integration of sustainability principles into corporate and investment strategies. It comprises "esg" (35), "firm" (5), "insurance companies" (5), "investment" (7), "management" (11), and "sustainability" (11), demonstrating the application of ESG within decision-making processes and corporate development strategies. This framework is regulated under Solvency II, which requires the inclusion of sustainability risks in governance, and is reinforced by the European Green Deal (2019).

Illustrating the climatic and prudential dimension of ESG, the yellow cluster underscores the essential role of insurance companies in managing climate risks and maintaining financial stability. It focuses on "climate" (5), "insurance" (18), "performance" (19), "risk" (15), and "stakeholder theory" (5), emphasizing the importance of environmental risk assessment and prudential performance in accordance with SDG 13 and the 2024 EIOPA Reports.

Overall, these four clusters define a coherent structure of the ESG field within the insurance sector, demonstrating its evolution from social responsibility and transparency (red), to economic performance (green), investment strategy (blue), and climate risk management (yellow), thereby confirming the integrated and regulated nature of corporate sustainability in this industry.

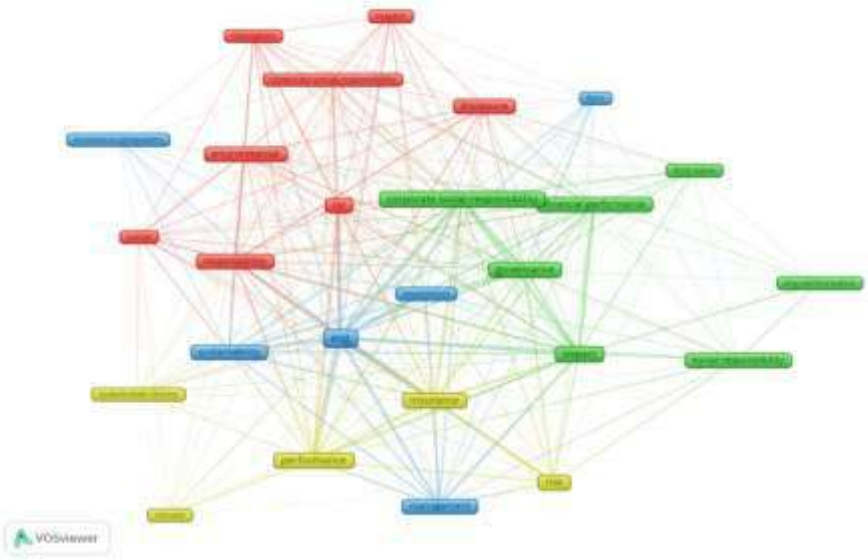

Figura 2. Network visualization of thematic mapping in VOSviewer based on keyword analysis of "ESG insurance"

Source: Authors' own research results.

4. Evolutionary dynamics and conceptual progression

Figure 3[2] illustrates the evolutionary development of ESG insurance research between 2020 and 2024, as depicted through the overlay visualization generated in VOSviewer. The image reveals a densely

[2] The analysis was performed using normalization by "association strength", with standard layout parameters (attraction = 2, repulsion = 0), a clustering resolution of 1.00, and the minimum cluster size set to 1, while the "Merge small clusters" option was enabled to prevent fragmentation. The visualization was generated using "occurrences" (size = 0.89) as the weighting variable, with labels displayed as frames (font "Open Sans", size 0.50, maximum 35 characters). The score dimension was set to "average publication year", which enabled the temporal distribution of terms within the network. Colors were assigned according to the "Spectral" overlay scheme, with a minimum strength threshold of 0 and a maximum of 1000 connections, while the "size variation" parameter was fixed at 1.00.

interconnected network of keywords whose spatial proximity and chromatic gradation capture the chronological and conceptual progression of the field. The color spectrum, ranging from blue (2020) to red (2024), encodes the average publication year, allowing for a clear interpretation of the evolutionary trajectory of ESG research within the insurance domain. The network, characterized by strong cohesion, is structured around central terms such as "ESG", "CSR", "corporate social responsibility", "financial performance" and "governance" which together form the conceptual core of the scientific field. Their strong interconnectivity confirms that ESG has become an integrative framework uniting the ethical, managerial, financial, and climatic dimensions of insurance research.

Terms such as "market" and "CSR" (2021) reflect the early theoretical foundations of ESG, rooted in corporate social responsibility theory and concerns regarding market legitimacy. The transition toward the yellow and orange tones corresponding to 2022–2023 indicates a thematic expansion toward governance (governance, management, investment, performance) and operationalization (insurance, financial performance, risk). This stage coincides with the institutional consolidation of ESG, driven by European regulatory frameworks (CSRD, ESRS), which extended the principles previously established within the normative structure of Solvency II.

Between 2023 and 2024, the emergence of orange and red nodes such as "disclosure", "ESG performance", "stakeholder theory" and "insurance companies" marks the transition of ESG insurance research toward a stage of empirical validation, reporting standardization, and stakeholder integration, defining the process of ESG institutionalization within the insurance sector.

Conceptually, this visualization confirms that ESG insurance research has evolved from descriptive and ethically oriented debates to an advanced, multidimensional framework addressing performance, governance, and risk. The structural density and even distribution of connections indicate that no isolated subfields persist, reflecting a consolidated and interdisciplinary research domain. The chromatic progression further suggests a phase of increasing thematic coherence, with the figure capturing the dominant co-occurrence dynamics that shape contemporary ESG insurance research. Overall, the visualization illustrates a field influenced by regulatory developments, strengthened expectations for organizational responsibility, and a sustained orientation toward sustainability and long-term resilience.

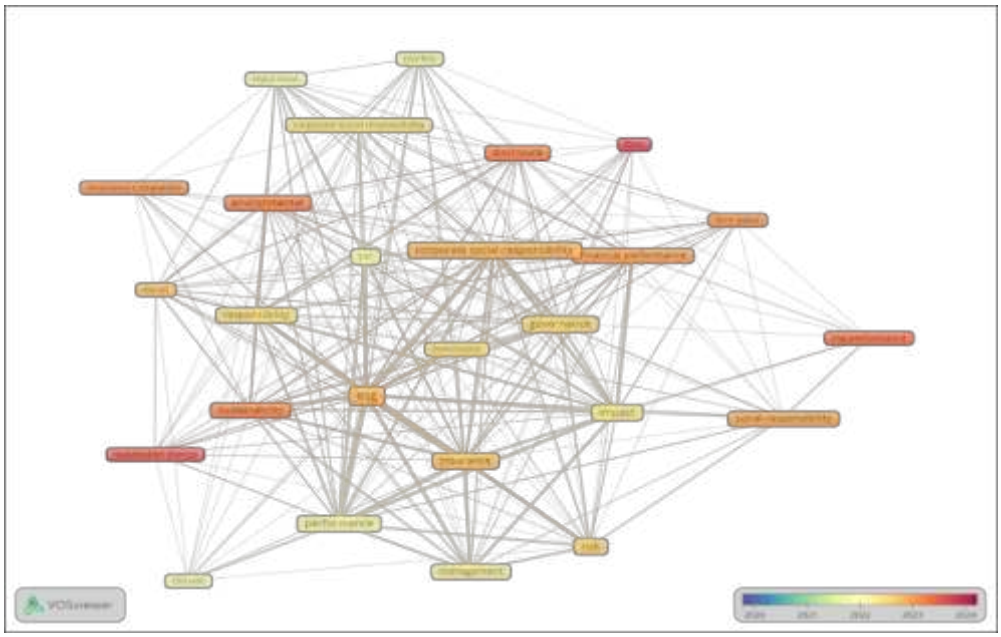

Figure 3. Overlay visualization of thematic mapping in VOSviewer for "ESG insurance" (2020–2024).

Source: Authors' own research results.

5. Density structure and emerging trajectories

Figure 4[3] the density visualization for the thematic domain of ESG insurance reveals that the literature is structured around the central concept of "ESG" which constitutes the conceptual core of the research field. This term appears in direct connection with "insurance", "performance", "corporate social-responsibility", "governance" and "impact" illustrating the integration of ESG principles into governance strategies and organizational performance assessment. This convergence confirms that, in recent years, the reporting and transparency standards imposed through CSRD and ESRS have strengthened ESG as an operational instrument within insurance company governance.

A complementary set of concepts "sustainability", "responsibility", "risk", "management", and "financial performance" captures the managerial dimension of the field, where ethical responsibility, financial objectives, and risk management processes are addressed in an integrated manner. These themes align with the classification requirements and consistency mechanisms established by the EU Taxonomy, as well as with the incorporation of sustainability risks into the prudential framework defined by Solvency II. On the social and reputational level, the literature highlights the importance of terms such as "stakeholder theory", "social", "reputation" and "corporate social responsibility" indicating that organizational legitimacy and alignment with stakeholder expectations constitute essential components of ESG evaluation. The consolidation of a coherent reporting system is reflected by the presence of concepts such as "disclosure", "firm value", "esg performance", and "social-responsibility" marking the transition from voluntary reporting practices to a standardized system based on comparable and verifiable assessments. At the emergent level, terms such as "market", "environmental", "investment", "insurance companies" and "climate" signal a growing interest in the integration of ESG into financial markets, investment strategies, and the insurance industry's management of climate-related risks. These developments reflect the strategic influence of the European Green Deal and are reinforced by recent legislative adjustments introduced through Omnibus I, which aim to harmonize sustainability obligations and streamline reporting requirements.

Overall, the density map illustrates a stratified evolution of the field: the central core encompasses the integration of ESG into governance and performance; the intermediate layer brings together social responsibility and managerial sustainability; and the peripheral area reflects emerging directions related to climate, markets, and investments. This structure confirms the maturation of an interdisciplinary domain strongly shaped by European legislative transformations and by the growing emphasis on sustainability within the insurance sector.

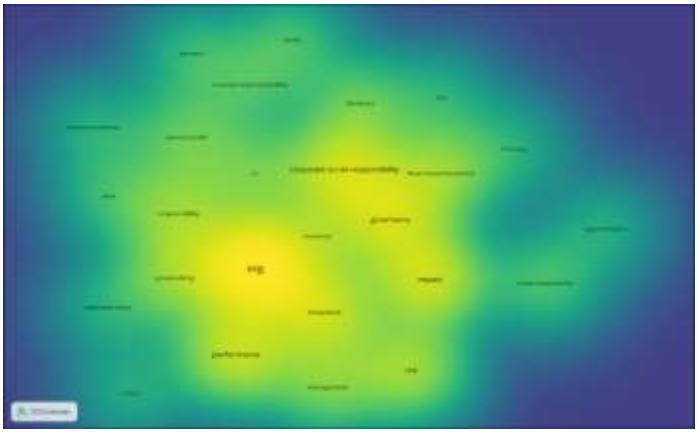

Figure 4. Density visualization of thematic mapping in VOSviewer for "ESG insurance".
Source: Authors' own research results.

[3] The analysis was performed using normalization by "association strength", with standard layout parameters (attraction = 2, repulsion = 0), a clustering resolution of 1.00, and the minimum cluster size set to 1, while the option "Merge small clusters" was enabled to prevent fragmentation. The visualization was generated using "occurrences" (scale = 0.77) as the weighting variable, with labels displayed in the "Open Sans" font (maximum 35 characters). The density kernel width was set to 2.30, and the visualization mode was configured to "item density." Colors were assigned according to the "Viridis" density color scheme.

Conclusion

A bibliometric analysis of ESG research trends in the insurance sector for the period 2011-2024 highlights accelerated development, deeply influenced by major changes in the European regulatory framework on sustainability. The substantial increase in scientific output after 2020 confirms the decisive role of legislative instruments, such as the revisions of the EU taxonomy, CSRD, ESRS, and Solvency II, in redirecting academic interest toward topics such as reporting, transparency, risk management, and sustainable performance. Thus, the answer to the first research question, concerning the evolution and diversification of the field, indicates a transition from a narrow thematic core to a broad, articulated, and methodologically coherent field.

Thematic mapping has identified four major groups: social responsibility, governance and financial performance, managerial integration of ESG principles, and climate risks, which outline the conceptual architecture of the field and provide the answer to the second research question. The coherence of these groups shows that ESG in insurance is no longer treated as a simple ethical benchmark, but as an integrated analytical tool, necessary both for shaping performance and for informing strategic decisions and reporting obligations.

The influence of the European legislative framework, investigated through the third research question, is clearly reflected in the reconfiguration of academic priorities. The Green Deal, CSRD, ESRS, EU Taxonomy, Solvency II, and Omnibus I have redefined not only institutional expectations regarding sustainability reporting, but also the directions of scientific research, favoring studies focused on transparency, climate risk integration, the consequences of sustainable investments, and alignment with green transition objectives. The results suggest that academia is responding directly to legislative changes, producing the knowledge needed for the insurance sector to adapt to new sustainability requirements.

At the same time, the analysis highlights the need to strengthen ESG reporting tools, develop common methodologies for integrating climate risks, and deepen the relationship between sustainable investments and the financial stability of insurance companies. It also emphasizes the need for increased interdisciplinary collaboration between environmental sciences, finance, economics, and data sciences, so that models for assessing sustainable performance and systemic risks are based on rigorous foundations.

An important contribution of this study is the methodological model used, a replicable procedure for data selection, bibliometric analysis, and conceptual mapping using VOSviewer, which can also be applied in other areas of sustainable finance or corporate governance. In addition, the results highlight emerging areas that require further investigation, such as the integration of ESG standards into solvency models, the effectiveness of green investments in reducing financial risks, and the impact of regulatory pressure on the quality of corporate reporting.

Overall, ESG in the insurance sector is emerging as a mature field, essential for understanding the profound transformations generated by the European transition to sustainability. The development of climate risk research, ESG data infrastructures, and sustainable performance assessment models are priority areas for progress, with the potential to guide public policy, funding agendas, and institutional strategies. The study thus contributes to strengthening the dialogue between academia and the legislative environment, providing a solid basis for future analytical investments dedicated to a more resilient and sustainable financial system.

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