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A Fuzzy Cognitive Map and PESTEL-Based Approach to Mitigate CO_2 Urban Mobility: The Case of Larissa, Greece

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Abstract: The CO_2 reduction promise must be widely adopted if governments are to decrease future emissions and alter the trajectory of urban mobility. However, from a long-term perspective, the strategic vision of CO_2 mitigation is driven by inherent uncertainty and unanticipated volatility. As these issues emerge, they have a considerable impact on the future trends produced by a number of exogenous and endogenous factors, including Political, Economic, Social, Technological, Environmental, and Legal aspects (PESTEL). This study's goal is to identify, categorize, and analyze major PESTEL factors that have an impact on the dynamics of urban mobility in a rapidly changing environment. For the example scenario of the city of Larissa, Greece, a Fuzzy Cognitive Map (FCM) approach was employed to examine the dynamic interactions and behaviors of the connected criteria from the previous PESTEL categories. An integrative strategy that evaluates the interaction of linguistic evaluations in the FCM is used to include all stakeholders in the creation of a Decision Support System (DSS). The methodology eliminates the uncertainty brought on by a dearth of quantitative data. The scenarios in the study strands highlight how urbanization's effects on sustainable urban transportation and the emergence of urban PESTEL actors impact on CO_2 reduction decision-making. We focus on the use case of Larissa, Greece (the city of the CIVITAS program), which began putting its sustainable urban development plan into practice in 2015. The proposed decision-making tool uses analytics and optimization algorithms to point responsible authorities and decision-makers in the direction of Larissa's sustainable urban mobility and eventually the decarbonization of the urban and suburban regions.

Keywords: FCM; CO_2; mitigation; scenario; analysis; urban; mobility; DSS

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1. Introduction

The European Commission (EC) has produced policies for Net Zero Emissions (NZE) that have been verified by the International Energy Agency (2021) in order to uphold their goal of a carbon-neutral economy by the year 2050. These policies aim to reduce greenhouse gas emissions and promote sustainability across various sectors. One of the flagship policies is the European Green Deal, which was introduced in December 2019 and is a comprehensive roadmap that outlines the EU's commitment to becoming the world's first climate-neutral continent by 2050 [1]. To support the European Green Deal and other climate-related initiatives, the European Commission has proposed several legislative measures. For example, the "Fit for 55" package, introduced in July 2021, includes numerous legislative proposals aimed at reducing emissions by at least 55% by 2030 compared to 1990 levels [2]. Another policy of equal significance is the European Union Emissions Trading System (EU ETS), which puts a price on carbon emissions and helps incentivize businesses to reduce their carbon footprint [3]. Given these tendencies in decarbonization, it is essential to put the right policies in place for a low-carbon economy while simultaneously promoting energy independence in terms of price and viability as a business. Low-carbon fuels and electricity are intended to take the place of currently used fossil fuels, requiring little effort to upgrade transmission and distribution infrastructure.

At the same time, economic activity and automobile mobility are expanding quickly in modern cities, but this rapid growth has come at an unparalleled cost in terms of raising the environmental burden and lowering the quality of life [4]. This emphasizes how important it is to create sustainable transportation systems in metropolitan areas to avoid risks in transportation [5], so that citizens can have a healthy environment and social lives in addition to achieving all mobility sustainability goals [6]. The following key features must govern any sustainable urban mobility system: (a) make it possible to address the basic requirements of people and society in a way that is safe and compatible with environmental health and human equity; (b) encourage the use of affordable and effective transportation options in order to foster economic growth; and (c) impose emission and waste restrictions in order to diminish the consumption of non-renewable resources and reduce land use while increasing recycling at all levels [7].

Nowadays, there are numerous efforts in numerous European urban and municipal regions aimed at mitigating CO_2-producing mobility, such as car and ride sharing, intensification of all types of public transportation, biking and walking designated pathways, electrification of vehicles, spatiotemporal interoperation, synchronization of transportation services, and so on. Indicative projects include the Sustainable Urban Mobility for Trabzon project (Europa Funding and Tenders Proj. Code: NEAR/ANK/2022/EA-RP/0037), the Düzce Sustainable Urban Mobility Plan (Europa Funding and Tenders Proj. Code: NEAR/ANK/2022/EA-RP/0058), and the Regional Electric Car-Sharing System: The SAUVér Project in ten Quebec municipalities in Canada (https://greenmunicipalfund.ca/ (accessed on 4 June 2023)). Simultaneously, there are several negative activities that undercut the aforementioned initiatives (the effect of inclement weather and working zones, residents' economic position, technological improvements, various politics and regulations, and so on).

The goal of this study is to better understand the future of transportation induced sustainable urban mobility in Greece by examining these outside variables. More specifically, we concentrate on a specific city, which is the center of Greece and has the potential to become a significant transportation hub for central Greece and elsewhere. The study underlines that rather than individual determinants of individuals' adoption behavior, policy decisions such as competent authorities' regulations and incentives have a substantial impact on transportation, mobility, and other relevant macro factors. Contributing reasons include the low level of public education and awareness, the high cost of implementing environmentally friendly transportation technology, and the limited behavioral control of drivers [4]. As a result, we recognize in this study that a high degree of modeling methodology should be employed and that the Greek government should aggressively encourage sustainable urban mobility. In order to provide a DSS for competent authorities that tracks the direction and momentum toward sustainable urban transportation, previous initiatives must be carefully evaluated, taking into account all pertinent parties and available data.

When dealing with complicated issues in unstable situations where less specific notions have holistic and non-linear relationships, the Fuzzy Cognitive Map (FCM) is beneficial. It is simple to use, flexible for higher-level policy research, and can include macroelements without necessitating precise empirical data. This approach is simple for policymakers to use, but it is also effective at capturing high-level abstractions of challenging issues. FCM works well for dealing with domains where there are inherent uncertainties when combined with descriptive tools. According to [8–11], FCM has been applied in a variety of sectors, including energy, management, climate change, medicine, engineering, and social studies. In this study, transportation scenarios that support both quantitative and qualitative aspects of sustainable urban mobility are evaluated using FCM. All probable scenarios are based on the changing behaviors of key players and sector-wide uncertainty. Investigating future sustainable urban mobility, particularly when it is concentrated in a particular region, is an underappreciated field of study. Due to this, this study implements a detailed PESTEL analysis and focuses on sustainable urban mobility on a strategic level, taking into consideration the most recent political changes in Greece. In order for the offered DDS to be a valuable tool for responsible authorities and important stakeholders, it is important to provide current, sound decisions and successful policies. The organization of this study is as follows: Section 2 introduces the FCM, its development process, key concepts, and scenario analysis. Section 3 lists the traits of the concepts and the simulation results of the FCM after providing a complete PESTEL analysis of the current problem. The discussion and summary of the findings are the critical topics of Section 5.

2. Materials and Methods

2.1. Case Study: The City of Larissa, Greece

In the middle of Greece, and specifically in the biggest Thessalian city of Larissa, both the population and the urban mobility landscape are changing. A variety of means of transportation and infrastructure are included in the city's urban mobility features to make it simpler for citizens to get around. Larissa, which is connected by road and rail to the port of Volos and the cities of Thessaloniki and Athens, is the geographical and administrative center of the Thessaly area as well as a significant agricultural, regional, transportation, and financial hub of central Greece. According to the most recent census, the city and its surrounding suburban and peri-urban areas have ~200,000 residents, according to the 2021 latest population census (https://en.wikipedia.org/wiki/Larissa_(regional_unit) (accessed on 4 June 2023)) making Larissa Greece's fourth most populous area. The majority of the area is used for residential and agricultural purposes, with a small portion designated for industrial use on the outskirts of the city. The high building density of up to 7-story buildings, which likely exceeds the average for Greek cities, is a prominent feature of the urban structure. As a result, there is a high population density in the inner-city areas, which leads to a busy/congested transportation system with parked cars lining the streets and a steady low-speed vehicle flow. According to municipality figures, the average number of vehicles traveling throughout a typical business day is anticipated to reach 350,000 (increased incoming traffic into the city) [12]. Although private vehicles make up the majority of transportation (60%), it is also thought that 30% of all transportation involves freight (medium-sized trucks), and the remaining 10% is made up of public transportation vehicles. The majority of the system for public transportation consists of buses. The bus system is run by the Larissa Urban Transport Organization (LATO), which offers regular services across the city and its surroundings. The bus routes go through vital areas and link residential neighborhoods with important destinations, including business hubs, schools, and other landmarks. There are now 22 routes, including those for peri-urban areas, since the public bus fleet has recently begun to be modernized and upgraded. Larissa has made improvements to its bike and pedestrian infrastructure recently. A snapshot of Google Maps for Larissa is presented in Figure 1. The city has created designated bicycle lanes along some roadways to promote environmentally friendly means of transportation and ease traffic. Additionally, pedestrian-friendly sidewalks and crossings have been created to encourage safer walking conditions. At the same time, car-sharing services are becoming increasingly popular since they give locals and visitors the option of having a private vehicle. These services enable customers to rent cars for brief durations, encouraging the effective and cost-effective usage of automobiles. For individuals who want door-to-door service, traditional taxi services are also available, offering convenient transportation options. To increase the effectiveness of transportation, Larissa has been aggressively developing smart mobility initiatives. It is the competent authorities' significant goal to enhance traffic flow and give commuters reliable trip information through intelligent transportation technologies such as traffic management systems and real-time information systems. These programs, when implemented, will seek to shorten travel times, improve safety, and ease traffic congestion.

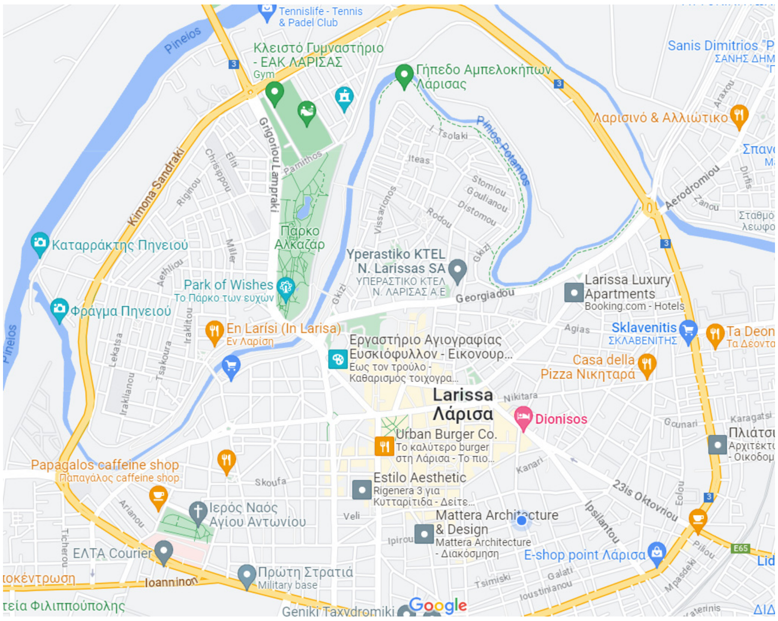


Figure 1. A map of the Larissa, Greece, center (www.maps.google.com (accessed on 4 June 2023)).

However, at this time, Larissa has implemented park-and-ride facilities to reduce traffic and encourage the use of public transportation. Commuters can park their cars at these thoughtfully placed locations on the outskirts of the city and continue their trips by taking public transportation. This strategy lessens city center traffic congestion and promotes environmentally friendly transportation options. We must say that Larissa is constantly improving the infrastructure for urban transportation with the expansion of the bicycle network and the installation of EV charging sites. At the same time, the city of Larissa wants to follow the example of the nearby city of Trikala, which uses unmanned vehicles for public transportation. The ultimate goal is to create an integrated transportation ecosystem that is environmentally friendly and functional.

2.2. FCM Fundamentals

FCMs are visual representations of systems that show the causal connections between various concepts and enable us to characterize their behavior in a straightforward and symbolic manner [13]. Constructivist psychology can be used to derive the nodes in an FCM, which represent concepts, and the arcs, which reflect the perceived relationships between them [14–17]. These connections are made logically necessary by establishing directed linkages that demonstrate the causality between the notions [16]. Additionally, users can modify the weights of the ideal interconnections by training FCMs with learning strategies and methods taken from Fuzzy Logic and Neural Networks.

Experts' knowledge, which is used to choose the concepts that should be incorporated into the system, forms the foundation of FCMs. Before knowledge is retrieved, stakeholders' feedback is considered. After the knowledge is de-fuzzified, this information is converted into numerical values, yielding a collection of concepts designated as $C_i (i = 1, 2, \ldots n)$ (graph nodes) and their interrelations denoted as w_i (graph directed edges). According to [18–20], each notion is given a value in the [0, 1] or [−1, 1] range, and weights are given values in the [−1, 1] range to account for both positive and negative causality [19–21].

With a positive weight, an increase or decrease in the value of one concept will lead to an increase or decrease, respectively, in the value of the connected concept, whereas with a negative weight, a decrease or increase in the value of one concept will lead to an increase or decrease, respectively, in the value of the connected concept. A weight of 0 indicates that there is no connection between the two concepts. The relationships between any two concepts C_i and C_j given above are summed up as follows:

(a) $R_{ij} > 0$: positive causality, where C_i casually increases C_j,
(b) $R_{ij} < 0$: negative causality, where C_i casually decreases C_j and
(c) $R_{ij} = 0$: meaning that no causality exists between C_i and C_j.

Figure 1 illustrates an example of an FCM model with its adjacency matrix.

An adjacency matrix can be created using the inter-causalities w_{ij} to represent all the data collectively. Additionally, the de-fuzzified value A_i from the previously described defuzzification procedure is applied to each concept C_i. Every time the FCM is turned on, A_i is updated to represent the impact of all connected nodes with incoming causalities to C_i. One of the following common rules governs simulation (also known as inference in the context of neural networking). The three equations below illustrate (a) Kosko's inference, (b) Modified Kosko's inference, and (c) Rescaled inference:

$$A_i(k+1) = f\left(\sum_{j=1, j\neq i}^{N} w_{ji} \times A_j(k)\right) \quad (1)$$

$$A_i(k+1) = f\left(A_i(k) + \sum_{j=1,\ j\neq i}^{N} w_{ji} \times A_j(k)\right) \quad (2)$$

$$A_i(k+1) = f\left((2 \times A_i(k) - 1) + \sum_{j=1,\ j\neq i}^{N} w_{ji} \times (2 \times A_j(k) - 1)\right) \quad (3)$$

Additionally, we denote as $f(.)$ the threshold (transformation) function, which can be: (a) bivalent, (b) trivalent, (c) sigmoid, or (d) hyperbolic according to Equations (4)–(7), respectively:

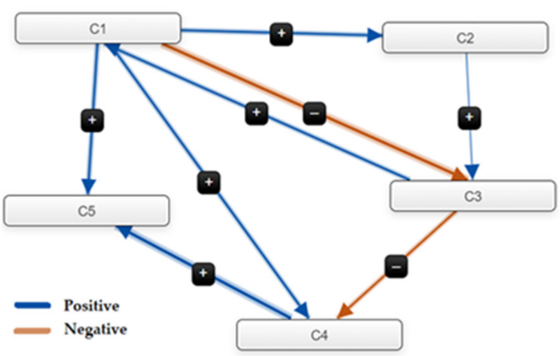
$$f(x) = \begin{cases} 1 & x > 0 \\ 0 & x \leq 0 \end{cases} \quad (4)$$

$$f(x) = \begin{cases} 1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} \quad (5)$$

$$f(x) = \frac{1}{1 + e^{-\lambda x}} \quad (6)$$

$$f(x) = tanh(\lambda \times x) \quad (7)$$

with $(\lambda > 0)$ to be real number determining the steepness of the continuous function f and x to be the equilibrium point value $A_i(k)$ (i.e., the last step of the simulation). Note that Equation (6) ensures that values A_i are within the interval [0, 1]. A typical example of an FCM is shown in Figure 2:



	C_1	C_2	C_3	C_4	C_5
C_1	0	1	−1	1	1
C_2	0	0	1	0	0
C_3	1	0	0	−1	0
C_4	0	0	0	0	1
C_5	0	0	0	0	0

Figure 2. Graphical and adjacency matrix representations of an FCM model.

2.3. FCM Development Using Expert Knowledge

We first identify the involving concepts and then find the causal linkages between any concept pair in order to create an FCM with the help of experts in the specific field for which the FCM is intended. Their knowledge enables them to precisely set the weight of the model arcs, providing a numeric value between [−1, 1] or a fuzzy (categorical or linguistic value) representation of this relationship. In Likert scale form, these values typically accommodate the conceptual ranges in between. The FCM's structure must also be reevaluated using fuzzy conditional statements or fuzzy rules in order to obtain the corresponding numerical values in the aforementioned range. Various algorithms might be utilized for this meta-learning process [22,23]. The most well-known, however, is the one by [18,24,25], which is as follows:

Step 1: All concepts C_i that constitute the decision support system (DSS) are first identified and evaluated by experts.

Step 2: Each expert independently determines the causal relationship between any concept pair.

Step 3: The average of all expert values is the final numerical value of the link between any two concepts.

The absolute value of a concept pair's numerical causal relationship, w_{ij}, determines how much impact each has. The following rule is used to determine each concept's value during the simulation:

$$A_i(k) = f\left(k_1 A_i(k-1) + \sum_{j=1,\ j\neq i}^{N} w_{ji} \times A_j(k-1)\right) \quad (8)$$

2.4. Development of a DSS for the Transition to CO_2-Minimized Urban Mobility Using FCM

To promote sustainable urban mobility solutions and clarify the meaning of sustainability for urban planning, fuzzy cognitive methodology is used. The method is built on concept-keywords that are found and organized using dialog-based processes with the experts and the regional stakeholders. The method can also be used to transition between emphasizing cross-sectoral factors like sustainable transportation and energy efficiency and sectorial factors like territorial management and urban planning. In order to determine what they actually need to decide and the main obstacles to the adoption of current urban sustainability measures, this study proposes a decision support system (DSS) to make the procedure for deciding on policy for a region's transition to CO_2 mitigation in urban mobility easier. We built the system for a specific area in Thessaly, Greece, emphasizing the structured interaction with decision-makers at the national, regional, and local levels.

We consider, pick, and set up transitional modes for sustainable urban mobility. The next stage is to do a detailed literature review to identify the factors that influence this transition to sustainable mobility, taking into consideration various standards, innovations, regulations, and global conditions. In order to identify the significant exogenous and endogenous elements, including Political, Economic, Social, Technological, Environmental, and Legal aspects that affect this sustainable transition in this particular Greek region, a complete PESTEL analysis was then carried out. The details of the following analysis serve as the foundation for building the FCM. An expert group of professionals in the field of urban mobility, along with various tightly interested stakeholders representing associations, agencies, companies, and research institutions, was assembled. According to [22,26,27], the number of specialists may vary depending on the specific renewable energy transition occurring at the time. However, according to studies on how fuzzy cognitive mapping (FCM) learning is structured, a minimum of seven experts are needed [28–31].

Five academic specialists, one from the transportation sector of Civil Engineering Depts., two from the regional competent authorities in Thessaly, Greece, and two members from the private transportation sector in Larissa, Greece, made up the group in our case. Using focus groups and questionnaires, the FCM was developed as a synthesis of expert and public opinion. It is based on a detailed PESTEL analysis that is shown and documented in the upcoming Table 1. To closely align with the expert viewpoints, the questionnaires were developed based on the results of the PESTEL analysis. The final design of the FCM incorporates every suggestion made by the experts, with the weights of the edges determining the pairwise causalities of the concepts involved. The FCM learning method utilized hebbian-based, population-based, and hybrid techniques [32,33].

Specific FCM features such as density, centrality, and hierarchy index are going to determine the most important factors influencing near-zero CO_2 urban mobility. The aim is to support decision-making in the transition to such sustainable urban mobility, considering technological, economic, social, and environmental variables. The public's assessment of the potential effects of future FCM policies is highlighted, with the threshold for acceptability varying based on regional factors. The effects of these policies are evaluated retrospectively in terms of socioeconomic, environmental, and political aspects. Research studies indicate that initially supported policies may have unintended consequences when implemented. Policies that lack public support are modified, and sensitivity analysis and stakeholder rearrangement are used to improve the FCM design [34]. Furthermore, to achieve greater precision, we perform a sensitivity analysis, which corrects the initial design and, in the majority of urban mobility transitions, rearranges stakeholder groups to create an improved version of the FCM.

The recommended DSS also provides flexibility in two crucial areas, namely methodological and technical. When analyzing the impact analysis findings from a methodological perspective, the qualitative component of the FCM methodology is considered. Considering that FCMs are typically used to identify trends or momentum towards an increase or reduction in a receiver concept based on changes in drivers, they are advantageous in substituting qualitative systems modeling and associated assessments. Accepting the FCM conclusions and backing the imposed policies are crucial factors to consider when making such crucial decisions for a regional economic and social diversion. Figure 3 demonstrates the design and evaluation of the decision support system when urban mobility transitions are imposed on a region using a dynamic and recursive structure.

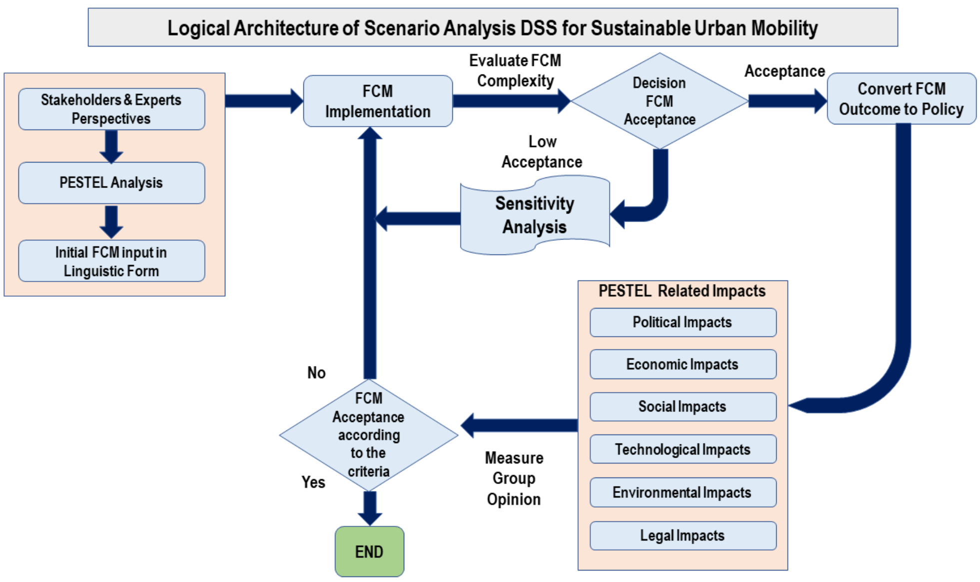


Figure 3. Visualization of the decision support system for sustainable urban mobility.

2.5. PESTEL Analysis Specifics

PESTEL Analysis is a strategic management method to assess the external macroenvironmental factors that could impact urban mobility sustainability. PESTEL stands for Political, Economic, Social, Technological, Environmental, and Legal. The analysis involves identifying and analyzing important external elements to develop a strategic plan. The breakdown of PESTEL analysis includes:

- **Political factors**: Laws and regulations in relation to political stability and government involvement that may affect sustainable urban mobility in Greece. These may include making decisions to adopt and enforce tighter car emissions restrictions, promoting electric and hybrid vehicles and offering financial incentives to encourage their use, or increasing financing and support for the creation of effective and sustainable public transportation networks, including those for buses and trains.
- **Economic factors**: Economic conditions, production costs, economic growth, investments, and interest rates. These may include (i) tax incentives, such as providing financial and tax breaks to encourage the purchase of electric vehicles (EVs) and the development of EV charging stations; (ii) subsidies and grants, which give cash assistance to groups and individuals to promote the use of low-emission vehicles and other forms of transportation; and (iii) a range of pricing strategies, like the use of tolls or congestion pricing to discourage the use of private vehicles and encourage public transportation.
- **Social factors**: Public perception, cultural attitudes, technological acceptance, education, awareness, and social equity that influence sustainable urban mobility. These may include: (i) public awareness efforts to inform people about the advantages of sustainable transportation choices and the negative effects of CO_2 emissions on the environment; and/or (ii) recognition and responding to the shifting requirements and preferences of the urban populace by, for example, supporting car-sharing programs and bicycle infrastructure.
- **Technological factors**: Developments in technology, including communication, research and development, and automation, that impact the sustainability level of urban mobility. These factors may include: (i) encouraging the creation and use of electric vehicles by investing in the infrastructure needed for charging, promoting research and development; and (ii) improving traffic flow via intelligent transportation systems to ease congestion.
- **Environmental factors**: Physical and ecological components of the operating environment that affect urban mobility. These may include: (i) investments in the creation of efficient and sustainable transportation infrastructure, including green areas, designated bicycle lanes, and pedestrian-friendly areas; and (ii) the promotion of alternative fuels to lower CO_2 emissions from transportation, such as biofuels and hydrogen.
- **Legal factors**: Consumer protection laws, labor regulations, and intellectual property laws related to sustainable urban mobility. These may include: (i) vehicle emission regulations to enforce stringent vehicle emission requirements that are routinely updated to keep up with new technology; and (ii) enacting zoning laws that encourage mixed-use development, thereby lowering the demand for long-distance travel and promoting walkability.

The analysis process involves several steps: scanning, forecasting, association, and interpretation. Scanning involves identifying factors within each macro-environmental segment. Forecasting involves predicting possible changes related to the scanned factors. The association focuses on understanding the connection between factors and the hydrogen energy sector. Finally, interpretation assesses whether the factors represent opportunities or threats. Overall, the PESTEL analysis to achieve sustainable urban mobility while mitigating CO_2 is based on the following pillars, which are clustered according to the aforementioned categories of factors and are depicted in Table 1:

Table 1. PESTEL Pillars for Larissa, Greece, in relation to sustainable urban mobility.

Factors	Pillars	Justification
Political Factors	P1	The Greek government has been promoting policies for stricter emission standards, incentives for electric vehicles, and regulations to increase government funding and support for the development and improvement of sustainable public transportation systems [6,35,36].
	P2	Various urban planning regulations (depending on the region's idiosyncrasies) and traffic management policies to prioritize public transportation have been initiated by the government, along with the introduction of alternative fuel infrastructure [37–39].
	P3	The country has signed international commitments according to EU directives to align with the European Union (EU) to mitigate CO_2 emissions in the transportation sector. This includes complying with regulations such as the EU's Clean Vehicles Directive to achieve the EU's overall emission reduction targets [40,41].
	P4	There are many initiatives in terms of funding and financial support via grants and subsidies for sustainable transportation projects, as well as the European Green Deal or Horizon Europe projects, to support sustainable mobility initiatives and research and development in the field [42–46].
	P5	There are initiatives from the officials to intensify stakeholder engagement through collaboration with industry and NGOs (transportation companies, environmental organizations, and citizen groups) for CO_2 emission reduction in urban mobility and public consultation to involve the public in decision-making processes through public consultations [47–50].
Economic Factors	P6	Financial incentives are promoted, such as tax incentives for the purchase of electric vehicles, the installation of EV charging infrastructure, and the offering of financial assistance to public transportation operators, to encourage the adoption of sustainable transportation options and the development of related infrastructure [51–53].
	P7	The municipalities are processing future scenarios in terms of pricing mechanisms such as the introduction of tolls on certain roads or areas to encourage the use of alternative routes or transportation modes [54].
	P8	The cost of fuel and energy is critical (pricing of fossil fuels and incentives for renewable energy). Overall, there must be monitoring and adjustment of fuel prices to reflect the true environmental costs of carbon emissions and also provision of incentives for the development and use of renewable energy sources to power electric vehicles, such as solar or wind energy [55,56].
	P9	The cost-effectiveness of public transportation must be evaluated to maintain an efficient, reliable, and affordable public transportation network. At the same time, encourage the growth of shared mobility services to maximize cost savings and reduce the number of vehicles on the road [57–59].
	P10	There are some economic development opportunities in relation to the expansion of sustainable transportation infrastructure and various green investments that provide a favorable regulatory environment and financial incentives [60,61].
Sociocultural Factors	P11	Awareness and education via public awareness campaigns for the environmental impact of CO_2 emissions and the integration of environmental education to promote a culture of sustainability and prioritize eco-friendly transportation choices [62,63].
	P12	Shift in mindset in terms of mobility preferences. More specifically, prioritize environmentally friendly modes of transportation, such as walking, cycling, and public transportation; also develop and enhance infrastructure for pedestrians and cyclists, such as bike lanes, sidewalks, and bike-sharing programs, to encourage active mobility options [64,65].
	P13	A turn to lifestyle and work culture by telecommuting and making flexible work arrangements, as well as promoting the development of mixed-use neighborhoods that offer easy access to amenities and services [66].
	P14	Accessibility and social inclusion by creating a universal design to ensure that transportation infrastructure and services are accessible to people of all ages and abilities, and at the same time address social inequalities in transportation access by prioritizing underserved areas and populations [67–69].

Table 1. *Cont.*

Factors	Pillars	Justification
Technological Factors	P15	Use of electric vehicles and charging infrastructure by offering incentives, subsidies, and tax breaks and also investing in the development of a widespread and efficient charging infrastructure network [70–73].
	P16	Creation of intelligent transportation systems for traffic management and navigation apps and platforms to provide real-time traffic information, alternative route suggestions, and multimodal transportation options to optimize travel routes and reduce travel time and emissions [74–76].
	P17	Data-driven solutions in the form of data collection and analysis and also in the form of predictive analytics to anticipate traffic congestion, optimize public transportation schedules, and improve the efficiency of transportation networks [77,78].
	P18	Shared Mobility Services, either in the form of car-sharing and ride-sharing platforms or in the form of Mobility-as-a-Service (MaaS), integrate multiple modes of transportation to reduce the number of private vehicles on the road, minimize traffic congestion, and decrease overall CO_2 emissions [79–81].
	P19	The use of alternative fuels and energy sources by promoting the integration of use of biofuels and hydrogen while also promoting the renewable energy into transportation infrastructure [51,82].
Environmental Factors	P20	Air quality and health by mitigating CO_2 emissions in urban mobility and promoting sustainable transportation options such as walking, cycling, and electric vehicles that can have positive impacts on public health [81,83,84].
	P21	The increase of green spaces and biodiversity via urban green infrastructures and the protection of regional ecosystems [85–87].
	P22	Climate change mitigation through local and global carbon footprint reduction, management of greenhouse gas emissions, and the overall carbon footprint of transportation systems. At the same time, there is a need to promote sustainable transportation options that can help cities by reducing vulnerability and enhancing resilience [88–90].
	P23	Efficient use of resources by promoting sustainable transportation options and optimizing transportation systems to contribute to this efficiency, including energy and materials, reducing overall resource consumption and waste generation [91,92].
Legal Factors	P24	Emission standards and regulations to enforce strict emission standards for vehicles align with the European Union and comply with EU directives related to CO_2 emissions reduction in the transportation sector, such as the EU's Clean Vehicles Directive [93–95].
	P25	Permitting and Licensing (vehicle registration and incentives for green fleet management) of low-emission and electric vehicles makes it easier for individuals and businesses to adopt sustainable transportation options [96,97].
	P26	Enforcement and compliance by implementing monitoring in relation to emission standards, traffic regulations, and other sustainability-related transportation laws. At the same time, impose penalties and fines for violations, encouraging compliance and accountability in the transportation sector [54,98].

2.6. FCM Development

Following are the steps we've used to gradually guide the development of the FCM: First, concepts were found through a review of the literature. This literature assessment was centered on concepts that have an impact on the Greek cities' sustainable mobility. All participating concepts belong to the aforementioned six PESTEL categories and were given to academia and professional practice experts for further classification. Weights of importance were selected, and a thorough Fuzzy Analytical Hierarchy Process was undertaken to rank all concepts according to their views of crucial significance. In the second phase, a set of questionnaires was given out to a broader audience of professionals, competent authority members, and university students (relevant to the subject at hand). The total number of participants in this process was 32. The scope of the questionnaire was to rate the significance of the concepts developed and rank them accordingly among the new set of stakeholders. Further recommendations were taken into consideration to make the FCM manageable and concise. After this inclusion process, all concepts were filtered by academia and professional practice to make the final collection. The final number of concepts was 27, of which 26 were either drivers or ordinary, and only one was named "Sustainable Urban Mobility". In the last step, experts were asked to define the causal relationship between any of the concepts after they indicated if there was a causal link between them or not. Their causal relationship valuation was initially categorical and then defuzzified to numerical with values within the range of [−1, 1]. The model ended up with 167 links on the 27 concepts and was completed for further steady-state analysis and other scenario analysis. Figure 4 shows the final FCM made using the MentalModeler program (http://www.mentalmodeler.com, (accessed on 4 June 2023)). According to the process, experts were asked to define the causal relationships (positive or negative) using fuzzy measurements that spanned from "extremely inverse/negative effect" to "extremely analogous/positive effect". Their responses were defuzzified to values ranging between −1 and 1, respectively. For undefined relations between any two concepts, no arc in the FCM was created (causal relation = 0).

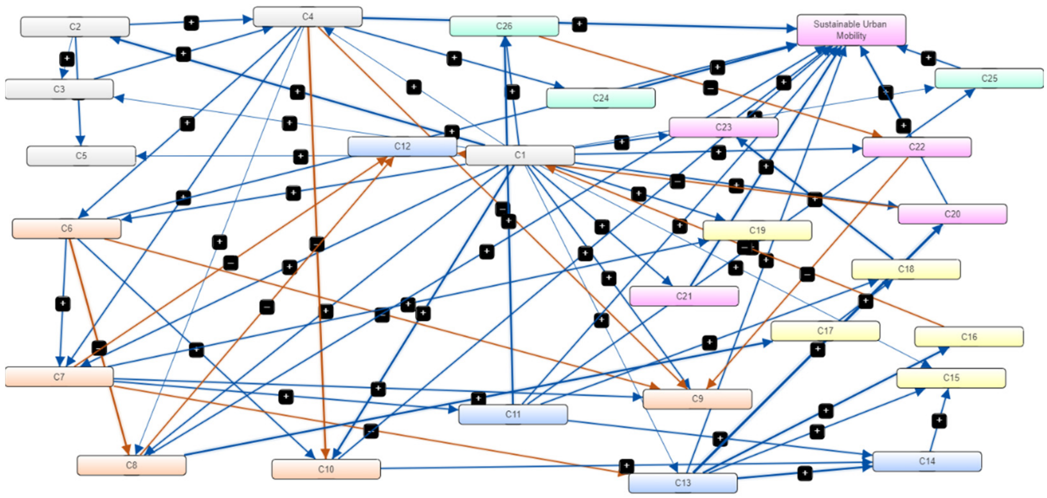


Figure 4. Integrated FCM from the experts' knowledge.

The steady state analysis of the resulting FCM is shown in Table 2, which also contains the in-degree, out-degree, centrality, and type of each concept (driver = not ingoing arcs but only outgoing, receiver = not outgoing arcs by only ingoing, ordinary = both ingoing and outgoing arcs). The first two demonstrate how dependent (driving) or influential (receiving) a concept is.

According to [99,100], a concept's centrality—which is calculated by summing the related absolute indegree and outdegree causal link weights—determines its relative relevance inside the FCM structure. A summary of these derived indices and the concepts mentioned earlier can be seen in Table 2. More specifically, in Table 2, we highlight the concepts that are either drivers or have the greatest centrality in their PESTEL group.

Table 2. Overview of all concept indices of the FCM.

Category	Concept Name	Concepts	In-Degree	Out-Degree	Centrality	Type
Political	C1	Emission-related policies	0.00	2.80	5.20	driver
	C2	Urban planning regulations	1.60	2.10	3.15	ordinary
	C3	International commitments	1.10	2.20	3.10	ordinary
	C4	National and international funding	1.70	1.25	2.10	ordinary
	C5	Stakeholder engagement	1.40	2.50	2.90	ordinary

Table 2. *Cont.*

Category	Concept Name	Concepts	In-Degree	Out-Degree	Centrality	Type
Economic	C6	Financial/tax incentives	1.30	2.30	2.30	ordinary
	C7	Tolls/pricing mechanisms	1.85	3.35	2.80	ordinary
	C8	Cost of fuel and energy	0.00	2.15	2.90	driver
	C9	The cost-effectiveness of public transportation	1.55	2.90	3.40	ordinary
	C10	Sustainable transportation infrastructure and green investments	1.20	4.20	6.20	ordinary
Social	C11	Public awareness of the impact of CO_2 emissions	1.90	3.90	5.20	ordinary
	C12	Shift in mobility preferences	1.50	1.75	2.75	ordinary
	C13	A turn to lifestyle and work culture through telecommuting	2.80	3.25	4.15	ordinary
	C14	Accessibility and social inclusion for the public transportation infrastructure	1.05	1.30	2.15	ordinary
Technological	C15	Use of electric vehicles and charging infrastructure	0.00	2.40	2.40	driver
	C16	Creation of intelligent transportation systems	0.95	1.15	1.40	ordinary
	C17	Data-driven solutions and predictive analytics	2.20	3.60	3.10	ordinary
	C18	Shared Mobility Services	0.80	2.25	4.90	ordinary
	C19	Alternative fuels and energy sources	1.10	3.20	3.80	ordinary
Environmental	C20	Air quality and health by mitigating CO_2 emissions	1.80	3.25	5.45	ordinary
	C21	Urban green infrastructures	1.40	2.15	3.30	ordinary
	C22	Carbon footprint reduction	1.20	1.90	2.40	ordinary
	C23	Efficient use of resources by promoting sustainable transportation	1.20	1.70	2.90	ordinary
Legal	C24	Emission standards and regulations	1.30	2.30	3.75	ordinary
	C25	Permitting and Licensing	1.30	1.90	2.85	ordinary
	C26	Enforcement and compliance	1.35	2.30	2.80	ordinary
	C27	Sustainable Urban Mobility	3.35	0.00	4.15	receiver

3. Reduction of the FCM—Sensitivity Analysis and Scenario Creation

3.1. Reduction of the FCM via Experts' Knowledge

The FCM model's efficiency can be raised, results can be better understood, and the risk of overfitting can be decreased by lowering the number of concepts in the model. Numerous studies have demonstrated this increase in efficiency, three of which are [28,30,101]. Reduced models retain the model's predictive power while being more dependable, thorough, and efficient. The concepts of greatest significance in an FCM can be found using a variety of strategies, including: (a) concept centrality evaluation; (b) sensitivity analysis; (c) expert judgments; and (d) other data-driven approaches. The most widely used techniques are (a) and (b). Degree centrality, betweenness centrality, and proximity centrality are all parts of concept centrality studies. Degree centrality measures how closely related each concept is to every other concept in the FCM; betweenness centrality measures how often a concept acts as a link between other concepts; and proximity centrality measures the connections between concepts. Contrarily, in sensitivity analysis, the FCM's concept values are repeatedly altered, and the system's behavior is observed as a result. In our case, the most critical concepts are those that have the most effects on the way the system behaves as a whole. That is how these concepts behave in relation to the set of receiver concepts (in our case, "Sustainable Urban Mobility"). For that matter, we used Table 2 to select concepts from the original map based on (a) concept centrality and (b) fair representation and distribution of concepts from all criteria categories. We excluded from the selection the driver concepts and the receiver concepts since these must be included in the new FCM regardless of the selection methodology used. As Table 2 depicts, C27 (Sustainable Urban Mobility) is the only receiver, but concepts C1 (Emission-related policies), C8 (Cost of fuel and energy), and C15 (Use of electric vehicles and charging infrastructure) are the three driver concepts. For the rest of the concepts, and according to their centrality values, the following concepts are selected from each category (Table 3).

Table 3. Overview of all major concept indices of the FCM.

Category	Concept Name	Concepts	Centrality	Type
Political	C1	Emission-related policies	5.20	driver
	C8	Cost of fuel and energy	2.90	driver
	C10	Sustainable transportation infrastructure and green investments	6.20	ordinary
Social	C11	Public awareness of the impact of CO_2 emissions	5.20	ordinary
Technological	C15	Use of electric vehicles and charging infrastructure	2.40	driver
	C18	Shared Mobility Services	4.90	ordinary
Environmental	C20	Air quality and health by mitigating CO_2 emissions	5.45	ordinary
Legal	C24	Emission standards and regulations	3.75	ordinary
	C27	Sustainable Urban Mobility	4.15	receiver

The creation of the abovementioned table of critical concepts can also be justified by a thorough sensitivity analysis, as presented in Sections 3.1 and 3.2, in order to examine the effect of changes in the input values of the concepts on the output values of the FCM. This selection, however, leads to the creation of decision-making scenarios in terms of how hydrogen production in the area of interest is affected relative to the critical concepts. The concept selection followed the fairness principle in terms of selecting at least one critical concept from each of the major categories; the creation of scenarios follows the same philosophy. Figure 5 displays the concise version of the FCM.

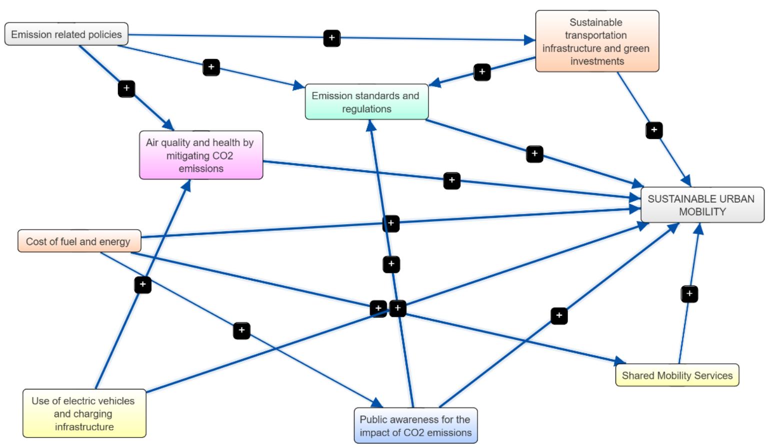


Figure 5. Concise version of the FCM after the reduction of concepts.

3.2. Reduction of the FCM via Sensitivity Analysis of Critical Concepts

Another way to test the system's sensitivity and to discover in a big FCM what the most critical concepts are is to observe the behavior of the receiver concepts as a reaction to the changes of the other concepts. The method relies on the simple idea that "the bigger the change in trend for the receiver concepts, the bigger the influence of the other concepts on them". The values of the receiver concepts and the critical concepts are determined at steady state. The steady state in our system for any test followed was achieved in the worst case in 9 activation repetitions of the FCM. The technique utilized is called "clamping", and it entails setting the values of one or more variables in the FCM model to watch how the other variables react. More specifically, we observe how the system responds to changes in the other variables by clamping the values of a few variables. Any combination is acceptable; however, the inclusion of the driver concepts is apparently significant since they are the ones that affect the state of the model the most. Any ensuing changes can be utilized to spot any potential flaws or restrictions in the system. For the specific task of sensitivity analysis, we employed the Expertise-Driven Semi-Quantitative Analysis for Policy Evaluation instrument (ESQAPE) [102,103]. The use of the free and open-source software ESQAPE is justified since it allows the import of the FCM model from other software types, simplifies updates by incorporating a built-in matrix, and has embedded sensitivity analysis capabilities. The clamping of concepts C1 (Emission-related policies), C8 (Cost of fuel and energy), and C15 (Use of electric vehicles and charging infrastructure) to zero showed the greatest sensitivity of the original FCM. All concepts of the reduced FCM in Table 3 have different levels of change in each activation iteration, which in all cases exceeds 8% from the starting value. As Figure 6 illustrates, the range of convergence is between 0.27 and 0.48. All the significant variations in the activation iterations for the involved concepts are individually discussed in the scenario analysis section upcoming, but the general trend shows the following basic observations, which become the basics for building up the scenarios of study for the DSS:

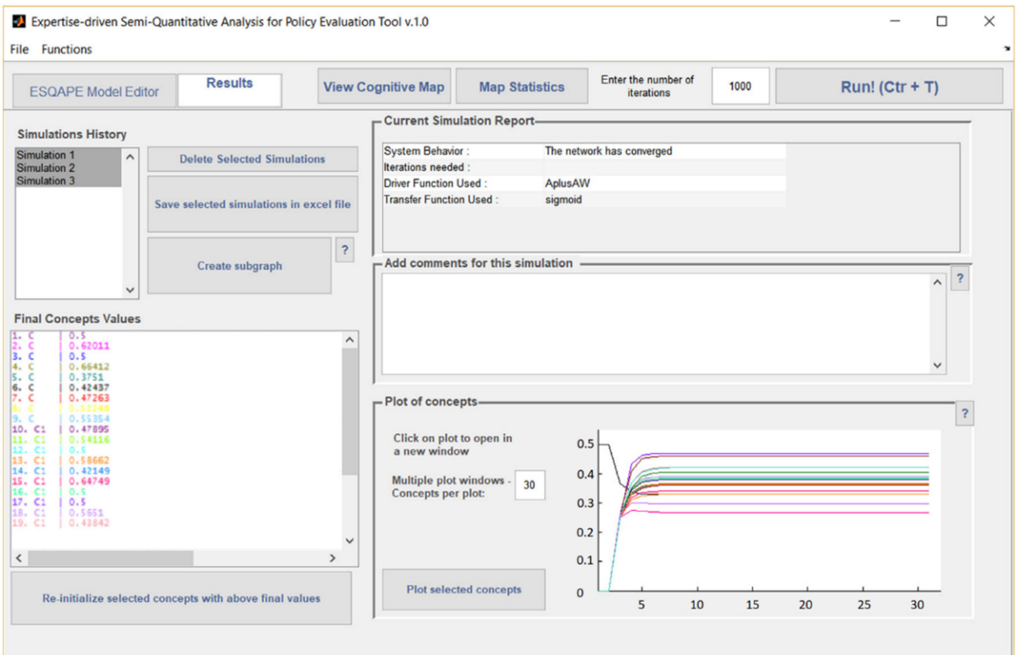


Figure 6. Convergence in nearly nine iterations for all concepts [Sensitivity analysis pane from ESQAPE].

3.3. Scenario Creation

The creation of the abovementioned table of critical concepts can also be justified by a thorough sensitivity analysis, as presented in Sections 3.1 and 3.2, in order to examine the effect of changes in the input values of the concepts on the output values of the FCM. This selection, however, leads to the creation of decision-making scenarios in terms of how hydrogen production in the area of interest is affected relative to the critical concepts. Since then, the concept selection has followed the fairness principle in terms of selecting at least one critical concept from each of the major categories, and the creation of scenarios follows the same philosophy.

In order to investigate the impact of changes in the driver and critical concepts on the receiver concepts of the FCM, we create a set of scenarios that show how sustainable urban mobility can be affected by emission-related policies (C1), the cost of fuel and energy (C8), and the use of electric vehicles and charging infrastructure (C15), mainly. The development of these scenarios adheres to the same philosophy as concept selection, which adheres to the fairness principle by choosing at least one critical concept from each of the key categories. Following is their explanation:

Scenario (S_1)—Energy Crisis: According to this realistic scenario, the effects of the extreme energy crisis that Europe experiences in 2022 will still hold and tremendously affect the overall political and governmental policy-making process in Greece. Favoritism towards the use of shared mobility services and the development of an integrated transportation ecosystem with electric vehicles and charging infrastructures still remains under consideration. The only increase in C8 over the last two years has shown a significant influence on green investments and environmentally friendly transport infrastructure. Affordability issues, shifting financial priorities, increased demand for energy-efficient options, economic ramifications, and regulatory support for sustainable mobility projects are all impacted. There may be a reluctance to accept new technology due to worries about safety, dependability, or cost as car electrification technologies continue to advance in other regions. As a result, this scenario might not change C11 (Public awareness of the impact of CO_2 emissions) at all. In an energy crisis, investing in infrastructure might be very difficult because resources might be in short supply. However, governments and business executives may prioritize infrastructure spending to support either energy security and independence or other sorts of investments; in this case, stability over a rise or decrease in C15 and C18 is preferred. For that reason, neither emission-related policies (C1) nor emission standards and regulations (C24) are expected to be changed.

Scenario (S_2)—Economic stability, but an energy crisis still exists: Policies may prioritize investments in innovative technologies to decrease reliance on fossil fuels and support sustainable urban mobility through a variety of environmentally friendly modes of transportation in a scenario where the energy crisis prevents the Greek economy from expanding to its full potential. To stimulate investments in environmentally friendly transportation, regulations that favor renewable energy sources, such as the electrification of automobiles, are necessary (at least until C15 is stabilized or increased). These regulations may also be aimed at fostering an atmosphere that promotes investment in new technologies and innovation. Furthermore, as the economy grows, there is a potential to fund environmentally friendly transportation infrastructure, such as efficient public transportation systems, specialized bike and pedestrian routes, and innovative mobility solutions (if C10 is stabilized and/or increased). These infrastructure initiatives lessen dependency on fossil fuels and help address the energy problem while assisting the switch to cleaner modes of transportation. People are choosing eco-friendly modes of transportation like walking, biking, carpooling, and public transportation as a result of growing public awareness of CO_2 emissions. Sustainable urban mobility is further enhanced by rising EV usage and the growth of charging infrastructure (C20 remains at prior levels as there is time needed for the new initiatives to take effect). Additionally, shared mobility services provide effective and environmentally friendly substitutes for owning a private vehicle, lowering traffic and carbon emissions while enhancing accessibility (C18 is expected to remain at the same level as the creation of shared mobility services, which is expected to rise after the creation of the necessary transportation infrastructures).

Scenario (S_3)—Economic stability and public awareness after the energy crisis: When Greece's economy expands and people become more aware of CO_2 emissions, a number of elements are critical to maintaining urban mobility and advancing a more environmentally friendly transportation system. First, when economic expansion provides the required resources, investing in environmentally friendly transportation infrastructure becomes viable (C15 and C18 may be increased or at least considered stable). This entails the creation of thoughtfully planned paths for walking and bicycling as well as the incorporation of smart mobility solutions that maximize the effectiveness of transportation. Investments in green infrastructure promote the switch to safer, more environmentally friendly modes of transportation, which lower carbon emissions and improve urban mobility. Along with the expansion of the economy and public knowledge of EVs, the use of EVs and the development of facilities for recharging them have both increased. EVs significantly cut greenhouse gas emissions and air pollution compared to conventional automobiles. The accessibility and convenience of EVs are improved with a well-developed network of charging infrastructure readily available, which further encourages their adoption and supports sustainable urban mobility. Shared mobility services like ride- and car-sharing platforms are essential for maintaining urban mobility. These services encourage effective vehicle use, which lowers the overall number of vehicles on the road. Congestion and carbon emissions can be reduced while enhancing accessibility and affordability for people by promoting shared transportation solutions. Shared mobility services offer adaptable and affordable substitutes for owning a private vehicle, helping to create a more sustainable and effective urban transportation system. The emphasis on environmentally friendly transportation options not only lowers carbon emissions but also significantly improves public health and air quality. Sustainable urban mobility helps to build cleaner, healthier cities by reducing CO_2 emissions from vehicles. This reduces the frequency of respiratory and cardiovascular diseases as a result, making cities more livable and raising the standard of living for residents. Implementing emission standards and regulations is necessary to maintain sustainable urban transportation. Governments play a key role in encouraging environmentally friendly transportation practices by creating and maintaining emission rules and constraints. At the same time there is an open discussion in all political parties in Greece and a well-established common opinion in enacting the necessary legislation that is needed towards: (a) the avoidance of fossil fuels and the increase of other renewable energy sources; (b) the adaptation of new technologies that can achieve considerable amount of energy savings; and (c) the use of ecological and environmentally friendly transportation means via multimodality of electrification energized vehicles to promote sustainable urban mobility and assist in the preservation of the environment as a whole (C24- and C1-related concepts remain stable with a slight tendency to increase as the rest of the concepts and the public awareness increases).

Scenario (S_4)—Full-grown economy and technology with public awareness: Last but not least, if Greece experiences economic growth without the consequences of an energy crisis, along with increased public awareness of CO_2 emissions, a proactive government approach to developing novel regulations and policies for urban sustainability, technological advancements in vehicle electrification, and the establishment of shared mobility services, several favorable outcomes can facilitate the environment toward sustainable urban mobility.

Initially, economic expansion offers a chance to make investments in environmentally friendly transportation infrastructure. This includes creating effective public transportation networks, building specific lanes for cyclists and pedestrians, and putting intelligent mobility solutions into practice. These enhancements to infrastructure promote multimodal mobility, minimize dependency on personal vehicles, and aid in traffic and pollution reduction. EVs will also be a cost-effective and environmentally friendly method of urban transportation. Government initiatives like tax breaks, subsidies, and the construction of charging infrastructure can speed up the adoption of EVs. The goal is to improve the quality of the air by reducing dependence on fossil fuels and emissions. The design and operation of shared mobility services is a way for an economy in growth to prove respect for the environment. New operational platforms can guarantee seamless orchestration of all transport operators to achieve minimal trip delays for residents and freight operators. In addition to that, fewer people will use private vehicles as the reliance on public and shared transportation increases. Traffic conditions will be upgraded, and urban traffic congestion will be diminished. This will automatically promote resource efficiency as well as the provision of ecologically sustainable mobility alternatives. The development of new policies and regulations is made feasible by a proactive governmental approach to urban sustainability. Incentives for eco-friendly transportation, emission requirements, urban planning norms, and assistance with the development of sustainable infrastructure are a few examples of these policies. The government's dedication to fostering an environment that supports sustainable urban transportation spurs development and promotes the adoption of eco-friendly behaviors. A key factor in making the shift easier is raising people's understanding of the effects of CO_2 emissions and the value of sustainable urban mobility. Public relations efforts, awareness programs, and education campaigns can influence attitudes and behavior toward more environmentally friendly modes of transportation. Increased use of shared mobility services such as cycling, walking, and public transportation can result from this, lowering individual carbon footprints and enhancing overall urban mobility. These variables work together to have a large positive impact on the environment. Urban settings become healthier as a result of decreased emissions and better air quality, reducing the detrimental effects of pollution on public health. By offering inhabitants effective, affordable, and environmentally friendly transportation options, sustainable urban mobility increases accessibility, eases congestion, and improves residents' quality of life overall.

All aforementioned scenarios will be explored in the following section to provide realistic decisions for our DSS.

4. Scenario Analysis Results and Discussion

The most crucial stage in our DSS is to analyze the proposed scenarios in Section 3.3 in order to assess the trend of Sustainable Urban Mobility in Larissa, Greece. Based on the presumptions and inputs of the critical concepts of the reduced FCM in Figure 4, the DSS investigates the potential outcomes of scenarios S_1, S_2, S_3, and S_4. Decision-makers can assess prospective consequences, and competent authorities can issue more informed policies by using this process. Based on the scenario analysis, the steady state of the FCM model is used. More specifically, we consider the best and worst cases after clamping the driver concepts and compare the change in the receiver concept relative to its steady-state value. Involved driver concepts are C1 (Emission-related policies), C8 (Cost of fuel and energy), and C15 (Use of electric vehicles and charging infrastructure). The worst case occurs when:

- C1 = 0 (no emission-related policies are created, or they are not beneficial for achieving sustainable urban mobility).
- C8 = 0 (the cost of fuel is at its minimum, thus drivers are not urged to change energy sources for transportation).
- C15 = 0 (the use of electrified vehicles is minimal and there are no charging infrastructures in town).

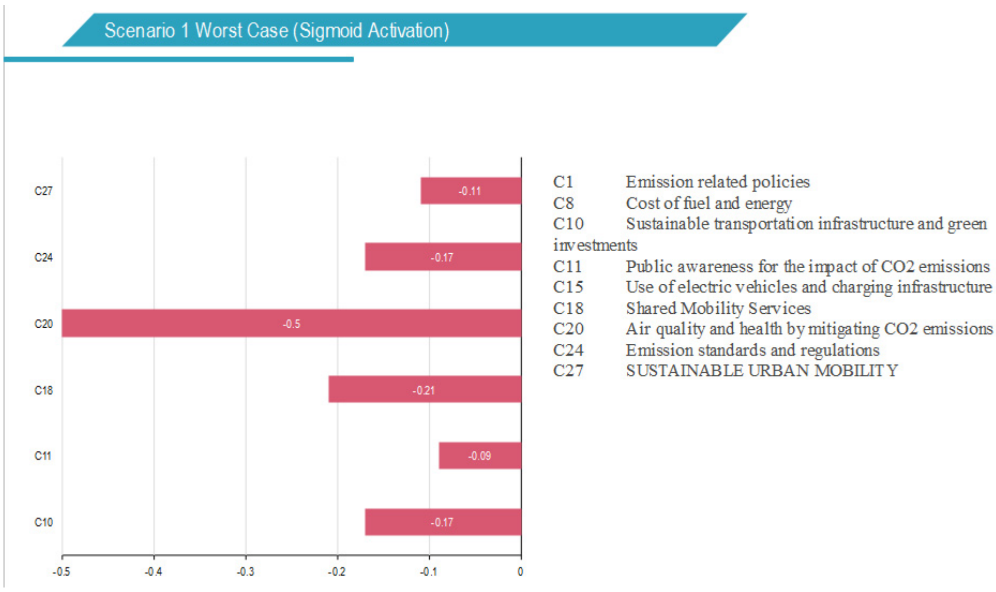
On the other side, the best case occurs when C1 = 1 (enriched emission related policies), C8 = 1 (high cost of fossil fuel energy), and C15 = 1 (high usage of electrified vehicles). Note that the abovementioned use case description holds for each one of the four scenarios illustrated previously, while the other involved concepts are set according to the individual scenario assumptions. Using the MentalModeler online software, we run the best and worst cases for each of the four scenarios, running both sigmoid and hyperbolic tangent activation functions. We discuss each scenario individually.

4.1. Scenario (S_1)—Energy Crisis

As explained in the S1 description, all relevant concepts apart from the drivers are kept unchanged assuming that (a) there is no intention to upgrade the sustainable transportation and mobility regulations; (b) no shared mobility services are created; (c) public awareness for the impact of CO_2 emissions is not promoted; and (d) even though there is knowledge about the critical importance of mitigating CO_2 emissions, there is no social movement towards this target.

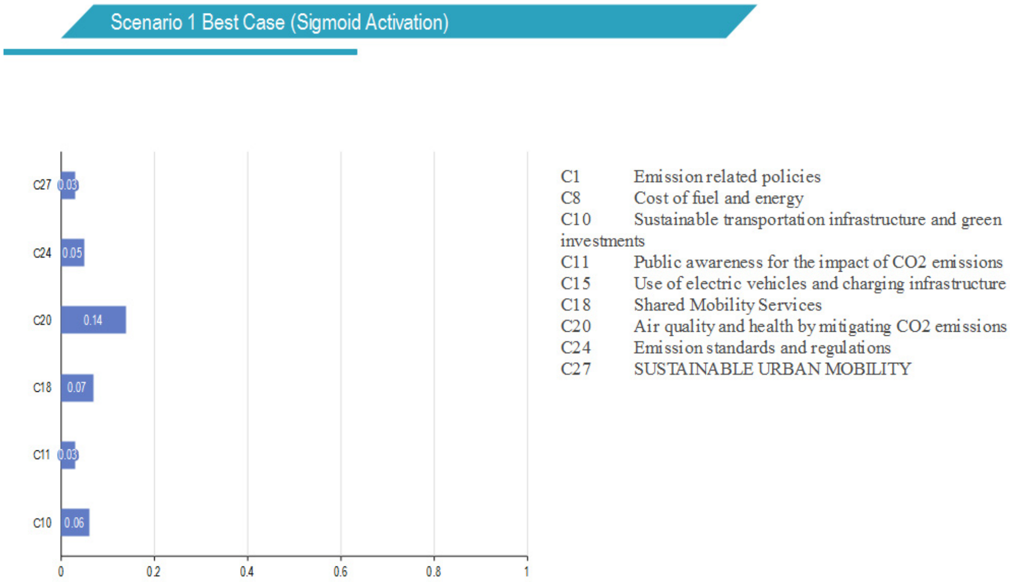
Decoding Figure 7a, we observe a moderate decrease on C10 of 17%, on C11 of 9%, and on the receiver C27 of 11%. However, C18, C20, and C24 are highly affected, with decreases of 21%, 50%, and 17%, respectively. First, the receiver C27 (Sustainable Urban Mobility) presents a decrease in its trend of 11%, which is evaluated as significant but expected if someone considers that these are the worst possible conditions assumed in the middle of the energy crisis. This scenario assumes that no significant political changes have been implemented, neither by the government nor by the competent authorities, towards reaching the global sustainability goals due to the high priority of the energy crisis in the country as a whole. The same is expected to happen when evaluations of other similar European countries/cities are undertaken. For the same reason, there is a decrease in the shared mobility concept, which indicates the degradation of such initiatives. The extraordinary decrease in the C20 is justified by the worst possible input for fossil fuel usage in transportation and the lack of regulations and policies for sustainable and clean air transportation.

On the other hand, the best case for drivers exists when C1 = 1 (enriched emission-related policies), C8 = 1 (high cost of fossil fuel energy), and C15 = 1 (high usage of electrified vehicles). As Figure 7b depicts, we have a rather small increase on C10, C11, C18, C24, and the receiver C27 equal to 6%, 3%, 7%, 5%, and 3%, respectively, and a rather moderate increase on C20 of 14%. The increase in the receiver is rather small, showing that the extremely positive change in emission-related policies, the cost of energy, and the use of electric vehicles is not enough to promote sustainable urban mobility unless the other factors are also changed (C10, C11, C18, and C24). By assuming that these concepts stay unchanged at steady state, they are automatically affected slightly positively but not to the point of giving a significant increase to the receiver trend.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. Worst- and Best-Case analysis results for Scenario S_1. (**a**) Worst-Case Scenario 1 (Sigmoid Activation); (**b**) Best-Case Scenario 1 (Sigmoid Activation).

4.2. Scenario (S_2)—Economic Stability, but an Energy Crisis Still Exists

In this scenario, we assume that there is a strengthening of economic growth, which itself positively affects the stability of various governmental monetary policies and measures. The most critical strategy here is to prioritize investments in cutting-edge technologies (electrification technologies, creation of shared mobility services, Mobility as a Service systems, etc.) in order to reduce the reliance on fossil fuels and encourage sustainable economic growth. At the same time, secondary strategies may be developed, such as stable investments in industries that use green technologies that will help the regional environment. We analyze the best and worst scenarios in regard to the driver concepts using this floor value assumption (the best and worst scenarios are the same for all cases in terms of the values of the driver concepts).

As Figure 8a shows, we observe a rather significant effect in the decrease on C10 as opposed to Scenario 1, since the economic growth with rather moderate positive strategies in terms of the investments shows that it almost zeros the negative effect on the sustainable transportation infrastructures. The decreases on C11 and C18 are comparable with Scenario 1. However, the most critical effect happens in C20, which, when compared to Scenario 1, diminishes the effect by half. The consequences for health and air quality are lessened by around 50% when compared with the first case. This case also shows that the emissions standards and regulations are tremendously affected because of the aforementioned strategy, with negative effects to be minimized to 2% as opposed to 17% when compared with Scenario 1. Finally, this scenario/strategy shows that it improves the overall sustainability of urban mobility (receiver), diminishing its negative effects to one third of the previous in Scenario 1.

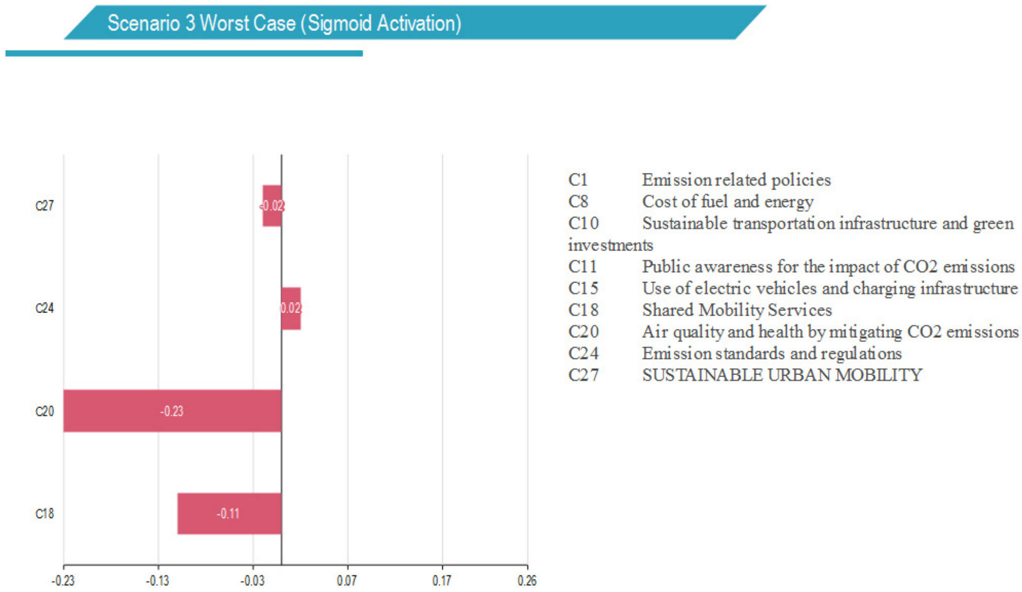
For the best-case scenario of Scenario 2, we see comparable results with Scenario 1 in terms of C10, C11, C18, and C24. However, in the worst case, we see a tremendous increase on the C20, but ~50% when compared with Scenario 1 (C20 → 21% as opposed to 14%). The most significant change in the whole scenario is the best case of the receiver, where we see an increase of 26% as opposed to the corresponding 3% in Scenario 3. We realize that the effect on infrastructure development and environmental regulations is transitive; however, such an increase in the overall trend of the receiver was unexpected. The only explanation is the initiation of the regulations towards regional sustainability and the direct effect on air quality and health by mitigating CO_2 emissions.

Figure 8. Worst- and Best-Case analysis results for Scenario S_2. (**a**) Worst-Case Scenario 2 (Sigmoid Activation); (**b**) Best-Case Scenario 2 (Sigmoid Activation).

4.3. Scenario (S_3)—Economic Stability and Public Awareness after the Energy Crisis

In this scenario, we assume that, apart from economic growth, we also experience an increase in public awareness towards the creation of all the infrastructure needed to achieve urban sustainability by diminishing the fossil fuel footprint and providing clean air transportation.

As Figure 9a for the worst case depicts, there is a considerable improvement in the trends related to shared mobility services when compared with Scenarios 1 and 2. As people realize and are aware of, services like car and small vehicle sharing can significantly reduce the number of private vehicles on the road, leading to reduced congestion and emissions. At the same time, the government and competent authorities on the regional level can support and regulate these services to ensure they are accessible, affordable, and integrated with public transportation systems. In the case of Larissa, the mayor's decision to integrate all transportation services under public operation may help the city alleviate the negative effects of air pollution. This strategy can significantly reduce emissions, improve air quality, and enhance the overall quality of life in urban areas. As shown, the trend of emission standards and regulations turns positive even in the worst-case scenario by a small but positive percentage of 2%. Finally, overall sustainable urban mobility gets the smallest negative trend in the worst scenario so far of the 2%.



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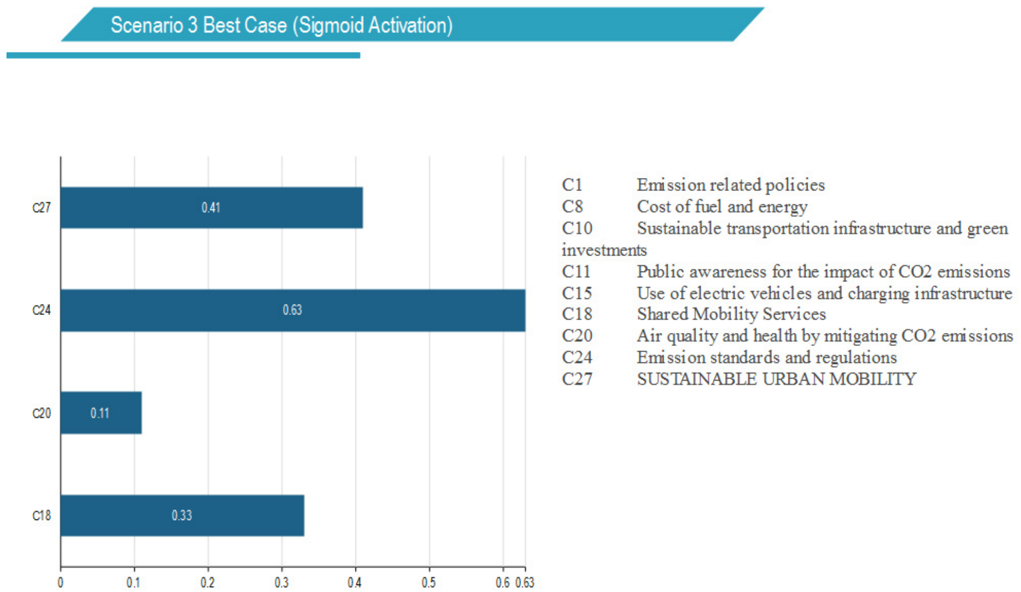


(**b**)

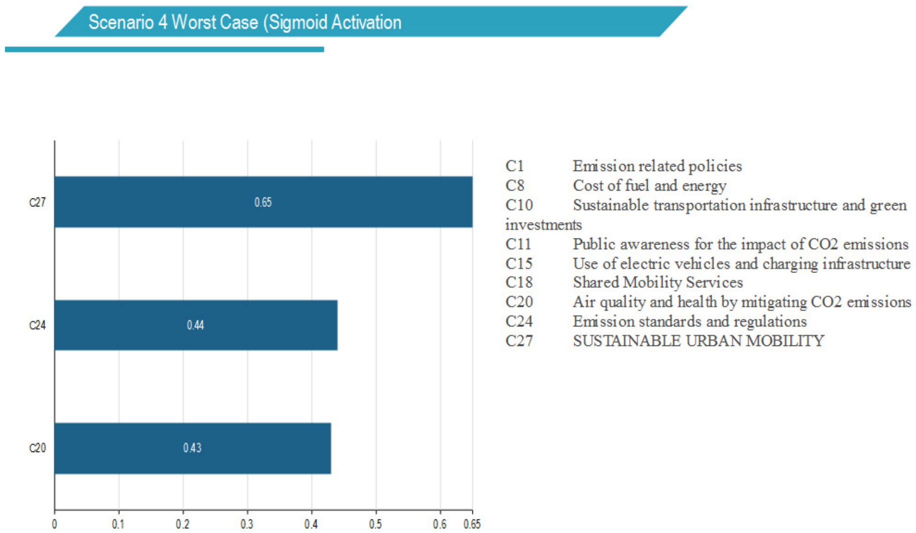
Figure 9. Worst- and Best-Case analysis results for Scenario S_3. (**a**) Worst-Case Scenario 3 (Sigmoid Activation); (**b**) Best-Case Scenario 3 (Sigmoid Activation).

In the best-case scenario of Scenario 3 (Figure 9b), we see that changing behavior might result from increasing public understanding of the advantages of sustainable urban mobility and the necessity of cutting CO_2 emissions. Citizens may make informed decisions and proactively select sustainable transportation options with the aid of campaigns, educational initiatives, and information dissemination. At the same time, partnerships between the public and corporate sectors, as well as civic groups, can speed up the deployment of environmentally friendly transportation solutions. Public-private partnerships can promote infrastructure, technology, and service investments, allowing for the development of comprehensive and long-term urban transportation networks. This is shown in the trend increases for C18, C20, and C24 of 33%, 11%, and 63%, respectively, that aere described as a strategy above. Overall, sustainable urban mobility presents an increase of a very promising 41%.

4.4. Scenario (S_4)—Full-Grown Economy and Technology with Public Awareness

This is the most optimistic scenario, assuming the best possible conditions for the economic growth of Greece and under the conditions of a fully grown economy with high levels of public awareness in terms of mitigating CO_2 in transportation and achieving sustainable urban mobility.

Even in the worst-case scenario, all trends have turned positive, with C20 achieving a 43% increase, C24 achieving a 44% increase, and the receiver getting an impressive 85% increase. In the best case, the trends are even better and highly optimistic, with C18 getting 32%, C20 getting 75%, C24 getting 78%, and the receiver getting an overall 94% increase in sustainable urban mobility (Figure 10).



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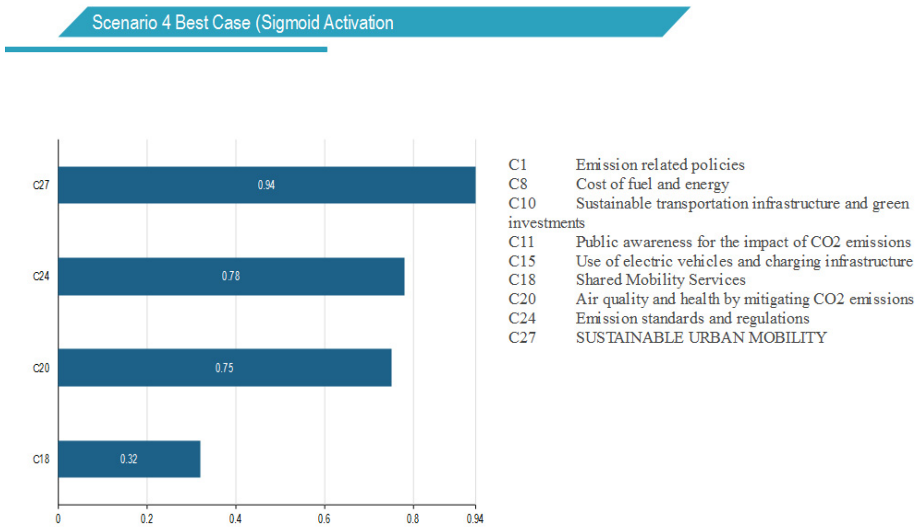

(**b**)

Figure 10. Worst- and Best-Case analysis results for Scenario S_4. (**a**) Worst-Case Scenario 4 (Sigmoid Activation); (**b**) Best-Case Scenario 4 (Sigmoid Activation).

5. Conclusions

In order to create a DSS to investigate the characteristics and likely developments of sustainable urban mobility in Greece, this study established a well-defined methodology based on the creation of an FCM model to identify the trends of urban mobility in reaction to different scenarios. Initially, a detailed literature review determined the pool of factors that affect the sustainability of urban mobility in regions. All factors that were discovered to have an impact on urban sustainability were fine-tuned in terms of two important criteria: (a) to fit in with the idiosyncrasies of Larissa, Greece, and (b) to be recommended by a set of experts from academia and the regional transportation industry. For the urban region under study, the urban mobility landscape in Larissa, Greece, indicates a major hub in Thessaly, with road and rail connections to other cities and a population of ~200,000 that is characterized by congested transportation due to the predominance of private vehicles. Recently, the city has started a major project to improve public transportation (mainly buses), include other ways of sharing transportation services, improve traffic flow, and provide smart mobility initiatives.

In terms of all the factors that affect sustainable urban mobility, they were grouped into six (PESTEL) categories, highlighting the fact that social factors are always imposed and interpreted differently in each of the preceding categories, while economic, political, and legal concepts are dominant and have strong relationships with technical and environmental concepts in the development of urban sustainability initiatives. The FCM used all factors as concepts in the model. However, the number of concepts and the complexity of the FCM due to the high relevance and causal relationships between concepts made the model unsuitable for DSS. For that reason, the extraction of the most critical concepts from each PESTEL category, along with the inclusion of drivers and receivers, created a more concise FCM.

The analysis investigated the potential results of four scenarios utilizing critical concept presumptions and inputs, beginning with the current real-life scenario (middle of the energy crisis situation). Larissa, Greece, is currently highly affected by the high energy prices due to the war in Ukraine, with gas, natural gas, and electricity prices being extremely high. For that reason, most of the initiatives towards urban sustainability are still ongoing. We created four possible scenarios, assuming progression in terms of the worst and best possible input from public investments and sustainable transportation infrastructure development. In parallel, monetary policies are assumed to be initially stable while public awareness of technical and environmental solutions is gradually increased. Based on the cost of fuel and energy, emission-related policies, and the use of electric vehicles, we made best and worst cases in the FCM, ranging their defuzzified values from −1 (worst case) to +1 (best case) when compared with the steady state of the model. The activation functions were sigmoid and hyperbolic tangent, thus creating four possible runs for each scenario, for a total of 16 simulations covering all assumptions.

Within the perspective of Sustainable Urban Mobility, the first Scenario's (Energy Crisis) worst-case indicates no meaningful improvements to sustainable transportation rules, no shared mobility services, and no increase in public awareness of CO_2-induced emissions from transportation. Certain elements, such as sustainable transportation infrastructure and green investments, have been reduced by 17%; public awareness has also been reduced by 9%; and the receiver (Sustainable Urban Mobility) by 11%, according to the analysis. At the same time, air quality and health, as well as shared mobility services and emission standards and regulations, are experiencing large drops of 21%, 50%, and 17%, respectively. Since the energy crisis is the primary concern, this scenario assumes no political reforms or the adoption of sustainability goals. The best-case scenario would enhance emission-related policies somewhat to provide an alternative to the cost of fossil fuel energy. While there is a modest increase in the previous concepts, the impact on sustainable urban mobility is minimal. According to the analysis, favorable changes in emission-related legislation, energy costs, and electric vehicle usage are insufficient to promote sustainable urban transportation unless additional factors are addressed and adjusted.

Scenario 2 expects that economic growth will strengthen while monetary policy will remain stable. In this scenario, the primary approach is to emphasize investments in cutting-edge technologies such as electrification technologies, shared mobility services, and Mobility as a Service systems in order to reduce reliance on fossil fuels and encourage long-term economic growth. Secondary initiatives could include consistent investments in green technology firms that benefit the area's environment. The analysis considers both the best and worst-case scenarios for the driver concepts, assuming identical values in all circumstances. In the worst-case scenario, the sustainable transportation infrastructure decreases significantly, whereas public awareness and shared mobility services are comparable to Scenario 1. The greatest significant benefit, however, is shown in the mitigation of CO_2 emissions, where the negative impact is decreased by half when compared to Scenario 1. This results in a 50% reduction in health and air quality impacts. Emissions standards and regulations are also less affected, with a 2% decrease compared to 17% in Scenario 1. Overall, this scenario enhances urban mobility by lowering negative effects to one-third of those in Scenario 1. In the best-case scenario, all factors are affected in a comparable way as in Scenario 1, but the most noticeable difference is in the receiver, where there is a 26% rise against a 3% increase previously. This surprising increase in the receiver's general trend can be related to the implementation of legislation aimed at regional sustainability as well as the direct impact on air quality and health through CO_2 emission reduction. In general, Scenario 2 highlights the favorable impacts of economic growth and targeted investments in cutting-edge technologies on sustainable urban transportation, as evidenced by improvements in infrastructure, environmental regulations, and the receiver's general trend.

Scenario 3 implies not only economic growth but also an increase in public awareness of the need for urban sustainability infrastructure and reducing the fossil fuel footprint for cleaner air mobility. In the worst-case scenario, trends in shared mobility services improve significantly when compared to Scenarios 1 and 2. The public's comprehension and awareness of the benefits of services such as automobile and small vehicle sharing result in fewer private vehicles on the road, reducing congestion and emissions. To ensure accessibility, affordability, and integration with public transit networks, the government and regional authorities can support and regulate these services. However, in the best-case scenario, shifting behavior is driven by increased public awareness of the benefits of sustainable urban mobility and the need to reduce CO_2 emissions. Citizens' informed judgments, aided by campaigns, educational initiatives, and information dissemination, result in the proactive selection of sustainable transportation alternatives. Collaborations between the public and private sectors, as well as civic groups, hasten the deployment of environmentally friendly transportation solutions. Public-private partnerships encourage infrastructure, technology, and service investments, allowing for the creation of comprehensive and long-term urban transportation networks.

Finally, Scenario 4 is the most optimistic, assuming the best possible conditions for Greece's economic growth and a fully developed economy, as well as high levels of public knowledge about CO_2 mitigation in transportation and attaining sustainable urban mobility. More specifically, in the worst-case scenario, all trends have shifted to the positive side, suggesting significant progress, and the total sustainable urban transportation trend (receiver) has increased by an astonishing 85%. This indicates that, even in difficult circumstances, there are beneficial improvements in lowering CO_2 emissions and encouraging sustainable transportation. In the best-case scenario, the trends are even more positive and upbeat, with the overall sustainable urban transportation trend (receiver) increasing by 94%. These findings suggest that, given optimal economic growth and public awareness conditions, significant progress may be achieved toward attaining sustainable urban mobility and reducing the CO_2 footprint of transportation.

The DSS analyzed four realistic scenarios in order to assess the trend of Sustainable Urban Mobility in Larissa, Greece, considering the best and worst cases relative to the critical driver factors/concepts. The worst case occurs when no emission-related policies are created, fuel costs are low, and electrified vehicle usage is minimal. On the contrary, the best case occurs when emission-related policies are enhanced, fossil fuel energy costs are high, and electrified vehicle usage is high.

When we focus on sustainable transportation and mobility regulations due to energy crisis situations (S1), the system experiences a moderate decrease/increase corresponding to the worst/best case, respectively. When the energy crisis gradually fades away as expected, we initially concentrate on the economic stability of the region (S2). This is expected after any crisis; therefore, the social movement and the public awareness of the related environmental issues are left behind. However, the overcoming turn of cost into a less important factor makes the DSS drastically decrease/increase Sustainable Urban Mobility in the worst/best cases, respectively. Gradually, we include into the picture the social and public awareness aspects in scenarios S3 and S4. As expected, the decrease/increase of the Sustainable Urban Mobility trend is forecast by the DSS. At the same time, we notice that the rate of such a decrease/increase is diminished. This is explainable by two facts: (a) the cost of energy and the economic viability of a region are far more significant compared to the public awareness effect of the environmental effects of sustainable mobility, and (b) such public awareness social actions in general follow the economic and energy status of a region.

The methodology used for the region of Larissa, Greece, can be easily generalized, transferred, and applied in other regions under the conditions that correspond to the new region's dynamics. There is, however, a need to follow the series of steps in the order imposed to achieve the most accurate results: (1) understand the local context, including the urban mobility challenges; (2) adapt the PESTEL framework to suit the specific factors that influence urban mobility and CO_2 reduction in the new region; (3) gather the relevant data and information on the identified PESTEL factors for the new region, keeping in mind that this process may involve collaborating with local authorities, researchers, and stakeholders to collect accurate and up-to-date information; and (4) involve all stakeholders in the creation of the DSS to ensure that the decision-making tool reflects the perspectives and interests of various stakeholders, making it more effective in guiding policy decisions.

To conclude, we may say that many observations can be made on the effectiveness and application of the FCM. To begin with, the scenarios developed were not intended to constitute administrative interventions in forcing sustainable urban mobility for the urban area under study but rather to investigate conceivable futures in which the government could play a role through political or legal policymaking in mitigating transportation-induced CO_2 effects in the city. The scenarios also revealed that suitable accommodations for the diffusion of vehicle electrification technologies as well as shared mobility services are lacking. At the same time, the government's efforts to make innovation (new shared mobility services) accessible for all residents are limited mostly by the potential financial incentives. As a result, more research is needed to establish how to keep the resource funding chain going and how much the government is willing to give up on progressing technology. The scenarios highlighted a limited lack of confidence in the future, but they did not address how to deal with it. As a result, the next stage is to develop strong, durable, and successful solutions in response to these situations.

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