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Exploring Carsharing Diffusion Challenges through Systems Thinking and Causal Loop Diagrams

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Abstract: The diffusion of carsharing in cities can potentially support the transition towards a sustainable mobility system and help build a circular economy. Since urban transportation is a complex system due to the involvement of various stakeholders, including travelers, suppliers, manufacturers, and the government, a holistic approach based on systems thinking is essential to capture this complexity and its causalities. In this regard, the current research aims at identifying cause-and-effect relationships in the diffusion of carsharing services within the urban transport systems. To do so, a causal loop diagram (CLD) is developed to identify and capture the causalities of carsharing adoption. On this basis, the main four players within the carsharing domain in urban transportation were scrutinized and their causes and effects were visualized, including (i) the characteristics, behavior, and dynamics of the society population; (ii) transportation system and urban planning; (iii) the car manufacturing industry; and (iv) environmental pollution. The developed CLD can support decision-makers in the field of urban transport to gain a holistic and systemic approach to analyzing the issues within the transport sector due to their complexity. Moreover, they can help regulators and policymakers in intensifying the diffusion of more sustainable modes of transport by highlighting the role of population, car manufacturing, the transportation system, and environmental pollution.

Keywords: car sharing; sustainable mobility; urban transport; shared mobility; system dynamics

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1. Introduction

While the urban population worldwide constituted only 30% of the world population in 1950, 55% of the world population lived in urban areas in 2018 and it is projected that this percentage will reach 68% in 2050 [1]. The growing trend of urbanization and the subsequent urban population density lead to the increasing demand for transportation in urban areas, which can result in large volumes of traffic, congestion, and serious environmental impacts in cities.

Hence, carsharing schemes have recently grown as a potential alternative for private vehicles to tackle global concerns about pollutant and greenhouse gas (GHG) emissions and urban air quality [2]. Carsharing, enjoying the sharing economy business model [3,4], is introduced as a new and more sustainable way of transportation with increasing popularity worldwide [5]. In 2021, approximately 47.5 million people were registered as carsharing users around the world, and this number is expected to grow to 48.5 million in 2022 [6]. Estimations show that the top five countries in terms of revenue from carsharing services in 2022 will be the USA (EUR 2303 million), China (EUR 1742 million), the UK (EUR 709.1 million), Japan (EUR 697 million), and Italy (EUR 682.4 million), and the highest carsharing user penetration will be achieved by Singapore (7.3%), New Zealand (6.2%), Switzerland (5.6%), Luxembourg (5.2%), and Republic of Korea (4.5%) [6].

The literature confirms that carsharing services can potentially lead to a reduction in the number of cars in cities due to their potential in replacing privately owned vehicles in well-designed transportation systems [7]. This is possible because shared vehicles are more intensively utilized than private vehicles to serve the same number of trips, and it would lead to building more sustainable cities [8] and moving towards a circular economy [9]. However, carsharing also has the potential to increase car dependency [10], which is an unfavorable outcome for urban transportation. Furthermore, a part of the carsharing fleet is composed of electric vehicles (EVs). Although operating a carsharing program composed of EVs can present several unique challenges that may make it more difficult to manage than a carsharing fleet with conventional vehicles, evidence suggests that the use of EVs in carsharing fleets is growing [11] and the share of these vehicles from the carsharing fleet is much higher than the market average in Europe [2]. This not only has the potential to reduce air pollution and GHG emissions in the transport sector but also helps car manufacturers in their learning curve and economies of scale, resulting in the acceleration of the adoption of EVs in societies [2]. Moreover, the imposition of several action plans and legislation by authorities to save the environment, such as Directive 2014/94/EU of the European Parliament and of the Council of October 2014 [12] and Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 [13], has brought some challenges for transportation systems. Therefore, as highlighted by Shams Esfandabadi [14], policymakers involved in the transportation system need to effectively analyze the consumption behavior of people, the growth of carsharing fleets, and the environmental implications of carsharing services towards a sustainable transportation system.

This research aims at identifying cause-and-effect relationships in the diffusion of carsharing services within urban transport systems. Since urban transportation is a complex system due to the involvement of various stakeholders, including travelers, suppliers, manufacturers, and the government [14], a holistic approach based on systems thinking is essential to capture the complexity of the system and its causalities. In this regard, following the systems thinking approach, an inclusive causal loop diagram (CLD) is developed in this research to identify and capture the causalities of carsharing adoption, with a focus on population, car manufacturing, the transportation system, and environmental pollution.

The remainder of this research is organized as follows. Section 2 provides a general overview of the research backgrounds, including carsharing business models, and carsharing from the lens of systems thinking. The applied method is presented in Section 3. Results are provided and discussed through the developed CLD and its various parts for carsharing services in Section 4. Finally, Section 5 concludes the research and its implications.

2. Research Background

2.1. Carsharing Business Models

Based on the relationship between the service provider and consumer, carsharing is enabled through four main business models, including (i) business-to-consumer (B2C), (ii) business-to-business (B2B), (iii) business-to-government (B2G), and (iv) peer-to-peer (P2P) [11]. In B2C platforms, carsharing is offered by a service provider to the public, and individual consumers can access a business-owned fleet through subscriptions, memberships, user fees, or a combination of pricing models [11,15]. B2C services can be one-way, allowing users to return the shared vehicle to a location different from its original pick-up location [16–18], or round-trip (also called two-way), requiring the users to pick up and drop off the shared vehicles at the same location [15,16]. In B2B carsharing business models, the service is typically offered to employees of an organization to make work-related trips, while the service in B2G is offered to a public agency [11]. In contrast with B2C, B2B, and B2G business models where the fleet is owned by a business, in P2P carsharing, which is sometimes referred to as personal vehicle sharing [11], the car is owned by a private citizen who can make it temporarily available for shared use by other private users through a platform provided by an external operator [18,19]. The external operator (i.e., the carsharing service provider) acts as a broker to make transactions between the owners and the temporary users of the vehicles by providing the required organizational resources to make the exchange possible [11]. Therefore, carsharing, by providing the benefits of a private vehicle without owning it through sharing vehicles with different drivers at different times, supports the transition of private mobility from ownership to service use [14]. It is worth mentioning that carsharing differs from ride-hailing (i.e., prearranged and on-demand transportation services for compensation, which connect drivers of personal vehicles with passengers [20]), in that there is no driver to make a suitable trip for the service user, and ride-sharing (i.e., shared rides among drivers and passengers with similar origin–destination pairings [21]), in that only the use of a vehicle is shared rather than a trip.

Carsharing travel can be categorized into four types, including long distance for entertainment and leisure, medium and short distances for commuting and business purposes, a mixed type of medium and short distances for residence and business, and a mixed type of long distance for residence and business [22].

2.2. Carsharing from the Lens of Systems Thinking

Due to the complexity of urban transportation with various stakeholders [14,23], a holistic approach with a systems thinking perspective is needed to capture all the causal links among different players. System dynamics (SD) is a behavior-oriented simulation discipline [24] with a top-down approach that is an appropriate tool for dealing with complex systems. SD has been widely applied in studies related to policy analysis and design, where information feedback, time delays, and mutual interaction lead to dynamic complexity. For instance, SD modeling has been utilized in the transportation field of research for evaluating the effectiveness of carbon tax on passenger transport [25], policy assessment for urban air pollution [26,27], freight transport decarbonization [28], evaluating regulatory policies [29], urban traffic congestion [30,31], evaluating the consequences of autonomous vehicles and pooling on urban transportation [32], the diffusion of alternative fuel vehicles [33,34], and analyzing potential impacts of different vehicle automation scenarios [35].

Nevertheless, limited research in the literature has addressed carsharing systems through a systems thinking approach. Table 1 presents an overview of the research that has applied SD for a carsharing-related issue.

Table 1. Overview of the studies using systems thinking and SD to address carsharing systems.

No.	Title	Author(s)	Study Area	Quantitative/Qualitative Modeling
1	The influence of e-carsharing schemes on electric vehicle adoption and carbon emissions: An emerging economy study	Luna et al. [4]	Fortaleza, Brazil	Quantitative
2	Assessing the effectiveness of alternative policies in conjunction with energy efficiency improvement policy in India	Menon and Mahanty [36]	India	Quantitative
3	Combining technology roadmap and system dynamics simulation to support scenario-planning: A case of car-sharing service	Geum et al. [37]	Korea	Quantitative
4	A quantitative analysis of potential impacts of automated vehicles in Austria using a dynamic integrated land use and transport interaction model	Emberger and Pfaffenbichler [35]	Austria	Quantitative
5	The construction of a high-active EVCARD online community based on user content adoption and generation model	Li et al. [38]	EVCARD company	Quantitative
6	The potential impacts of automated cars on urban transport: An exploratory analysis	May et al. [39]	Leeds, UK	Quantitative
7	Conceptualizing environmental effects of carsharing services: A system thinking approach	Shams Esfandabadi et al. [14]	General	Qualitative

While Boonsiripant et al. [40] and Jittrapirom et al. [41] used a participatory group modeling building approach to build a CLD concerning the carsharing operation in Bangkok, Thailand, Shams Esfandabadi et al. [14] developed a comprehensive conceptual framework to illustrate the environmental effects of carsharing based on the findings from the literature. Additionally, Kim et al. [42] used a focus group to reveal the complex mechanism and impact of the connected, autonomous, shared, and electrification technological disruptions on the automotive retail industry in South Korea. Lee [43] identified the motivational factors for using carsharing in the Netherlands and Korea by studying the available literature.

In a recent study with a focus on the diffusion of autonomous vehicles in Australia, Stasinopoulos et al. [44] simulated the use-stage GHG emission resulting from the transition to an autonomous vehicle fleet. In their research, both privately owned and shared autonomous vehicles are considered, and a vehicle adoption subsystem has been developed based on the Bass diffusion model [45]. Based on the insight gained from the result of the simulation, they suggested the minimization of energy consumption and the adaptation of low-GHG vehicle technologies to help the environment. The research conducted by Nieuwenhuijsen et al. [46] and Kaltenhäuser, et al. [47] also focused on the diffusion of autonomous vehicles in the Netherlands and Germany, respectively, taking into account carsharing services.

Luna et al. [4] modeled the impacts of an electric carsharing scheme on both carbon emissions and EV adoption. The main scenarios tested by Luna et al. [4] are a planned growth policy for the currently operating electric carsharing scheme in Fortaleza and a retirement policy for conventional vehicles. The supporting role of the government is highlighted in this research regarding the success of electric carsharing services in terms of their direct and indirect benefits for urban mobility. Zhou et al. [48] simulated the effect of introducing time-sharing EVs on the number of users of private cars and public transport under different levels of government subsidies in Shanghai, China, and concluded that users of conventional private cars are most attracted to time-sharing EVs under low government subsidy. Bearden [49] used SD to simulate the personal and shared mobility sector at the city level and estimate the effects of policy scenarios on the future of urban mobility in Amsterdam, the Netherlands. Moreover, a hybrid method combining a technology road-map and SD developed by Geum et al. [37] showed that the increase in the usage of carsharing services leads to the reduction in environmental burden up to a certain level, improves the traffic environment, and decreases energy consumption. Geum, Lee, and Park [37] believe that carsharing is an alternative to privately owned cars, not public transportation, and hence, the increase in carsharing usage would lead to a decrease in the use of personal cars. Therefore, there would be a reduction in energy consumption as a result of carsharing usage, which would reduce the environmental burden.

Nevertheless, the literature lacks sufficient research with the systems thinking approach to consider all aspects of shared mobility, in particular carsharing services, as a whole. On this basis, following a systems thinking approach, a CLD is developed in this research considering carsharing services from different perspectives, including population, car manufacturing, transportation system, and environmental pollution. The provided insights shed light on carsharing adoption and diffusion as a whole within the transport system.

3. Methodology

The development of SD, which is a branch of systems theory, goes back to the 1950s when Jay W. Forrester introduced it for simulating the long-term effects of policies that cannot be understood simply because of the complex nature of systems [50]. SD is a computer-aided approach for strategy and policy design, grounded in control and nonlinear dynamics theory, and is a proper method to simulate the behavior of a complex system over time [51]. The key characteristics of SD are the existence of a complex system, the existence of closed-loop feedback, and the change in system behavior over time [52]. It emphasizes the multiloop, multistate, and nonlinear character of the feedback systems [53] and holds that the behavior patterns and characteristics of a system mainly depend on the mechanism of the system's internal dynamic feedback structure [54]. Discovering and representing the feedback processes is much of the art of SD modeling. The behavior of a system arises from its underlying causal feedback structure, and causal loop diagrams (CLDs) and stock-and-flow diagrams (SFDs) are mainly utilized to represent this causal structure [55]. While CLDs emphasize the feedback structure of a system, SFDs emphasize its underlying physical structure and track accumulations of materials and information as they move through a system [53].

CLDs have been used in standard quantitative SD practices both to articulate the dynamic hypothesis and to summarize and communicate feedback insights based on the simulation model [56]. Moreover, with the advent of qualitative analysis in the 1980s, CLDs started to be used for detailed system descriptions and also stand-alone policy analysis [56]. In fact, as Wolstenholme [57] states, "causal loop qualitative system dynamics enhances linear and laundry list thinking by introducing circular causality and providing a medium by which people can externalize mental models and assumptions and enrich these by sharing them. Furthermore, it facilitates inference of modes of behavior by assisting mental simulation of maps". CLDs explicitly present the structural and agent system elements that may endogenously generate the dynamics in the behavior of the system or organization being studied [58]. In this vein, CLDs have been widely used in different domains and fields of research, such as health systems [59], social–ecological systems [60], food supply chains [61], climate change [62], technological disruptions [42], transport systems [63], and sharing economy [64]. Therefore, following the principles of systems thinking and SD modeling [53], CLDs are used to show the causal relationships between the variables linked to the diffusion of carsharing that are identified in the literature.

The present research aims at synthesizing the existing research on factors affecting the diffusion of carsharing and also the environmental impacts of carsharing diffusion to a larger scale into CLD models. Therefore, the core of the methodology applied is a comprehensive review of the existing literature. Nevertheless, as a systematic literature review with a structured search string cannot capture all relevant variables and causalities, this approach is not ideal for this research, and an iterative modeling procedure with multiple stages is required [65]. On this basis, a general search in the main scientific databases (Scopus and Web of Science) and also Google Scholar was conducted to capture relevant empirical research. Additionally, the available literature review articles (e.g., [9]) and articles with a systems thinking approach with a focus on carsharing (e.g., [14]) were scrutinized for further potentially relevant research. This search was enriched by exploring available empirical and scientific reports, such as the reports of the project STARS (https://stars-h2020.eu/ (accessed on 5 January 2022)).

Based on the target literature, an initial list of empirical relationships and causalities was identified, which was then merged and sorted to clarify the relevant parts of the developed CLD. After constructing a general CLD, where required, additional literature searches were conducted to validate the identified causalities among variables or to update parts of the developed CLD. This procedure was iteratively repeated until no further variable or causality was identified. Figure 1 illustrates the main steps taken in this research.

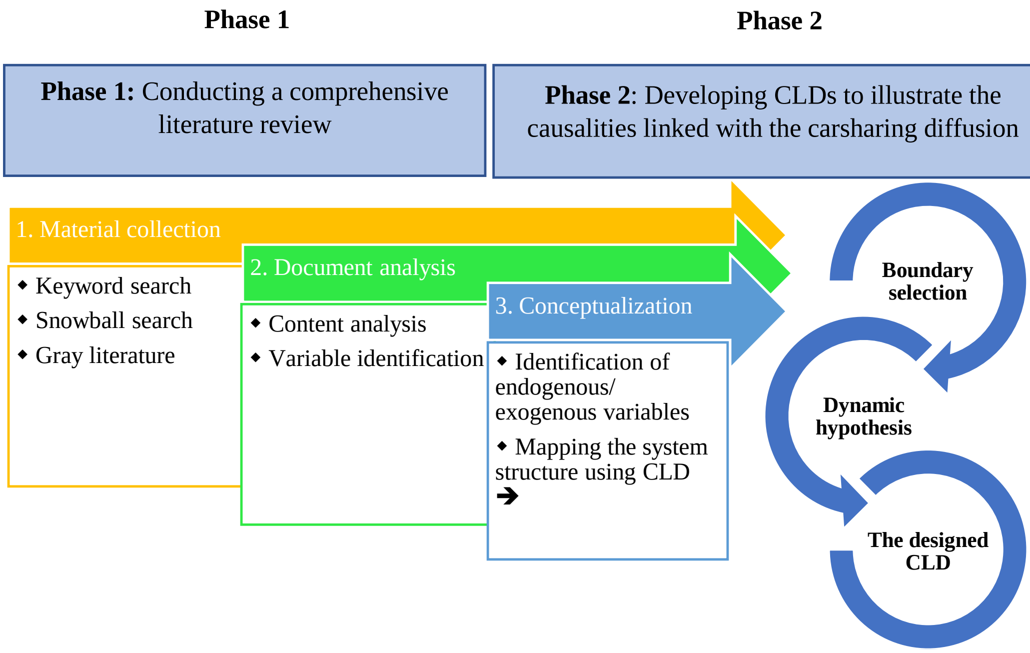

Figure 1. Research framework.

4. Result and Discussion: Cause-and-Effect Relationships in the Diffusion of Carsharing

In order to develop CLDs to provide insight into the general causalities concerning carsharing, a comprehensive literature review was conducted covering both scientific databases and the gray literature. Consequently, general CLDs reflecting the identified potential causalities in the complex system of carsharing services are developed and discussed extensively. Since the current research also points to the environmental outcomes of carsharing diffusion, environmental elements are considered in the developed CLDs too.

Having reviewed the target literature, four main aspects to analyze the motivations and outcomes of the diffusion of carsharing are identified as (1) the characteristics, behavior, and dynamics of the population; (2) the transportation system and urban planning; (3) the car manufacturing industry; and (4) environmental pollution. These four aspects affect and are affected in some ways by regulations.

For more clarity, in this section, specific colors are used for variables referring to each aspect, and therefore, the connections between them in the CLDs are more quickly understood. The colors orange, purple, red, and green refer to population, transportation, car manufacturing, and energy consumption and environment, respectively. The variables shown in blue are the ones related to 'regulation and administration', and the black variables are the exogenous ones.

4.1. Characteristics, Behavior, and Dynamics of the Society Population

The population has a very huge and complicated CLD with many variables and interconnections. However, the main message of the presented CLD is to consider the demographic characteristics of the city population, including the main residents, temporary workers, students, and even the tourists (depending on the situation of the city) and their viewpoints and willingness towards car ownership and carsharing. The city population is affected by many factors, such as the level of wellbeing as a result of environmental challenges. The disposition towards using shared vehicles or purchasing a private car is dominated by many other factors, some of which are linked with other aspects. A simplified CLD is presented in Figure 2, and to respect brevity, only some of the main cause-and-effect relationships are discussed in this subsection. To clarify the model and avoid ambiguity in understanding the complex CLD, 'city population' is put into a hexagon, by which we mean all the specifications of the population including the number of people, age distribution, and other demographic characteristics.

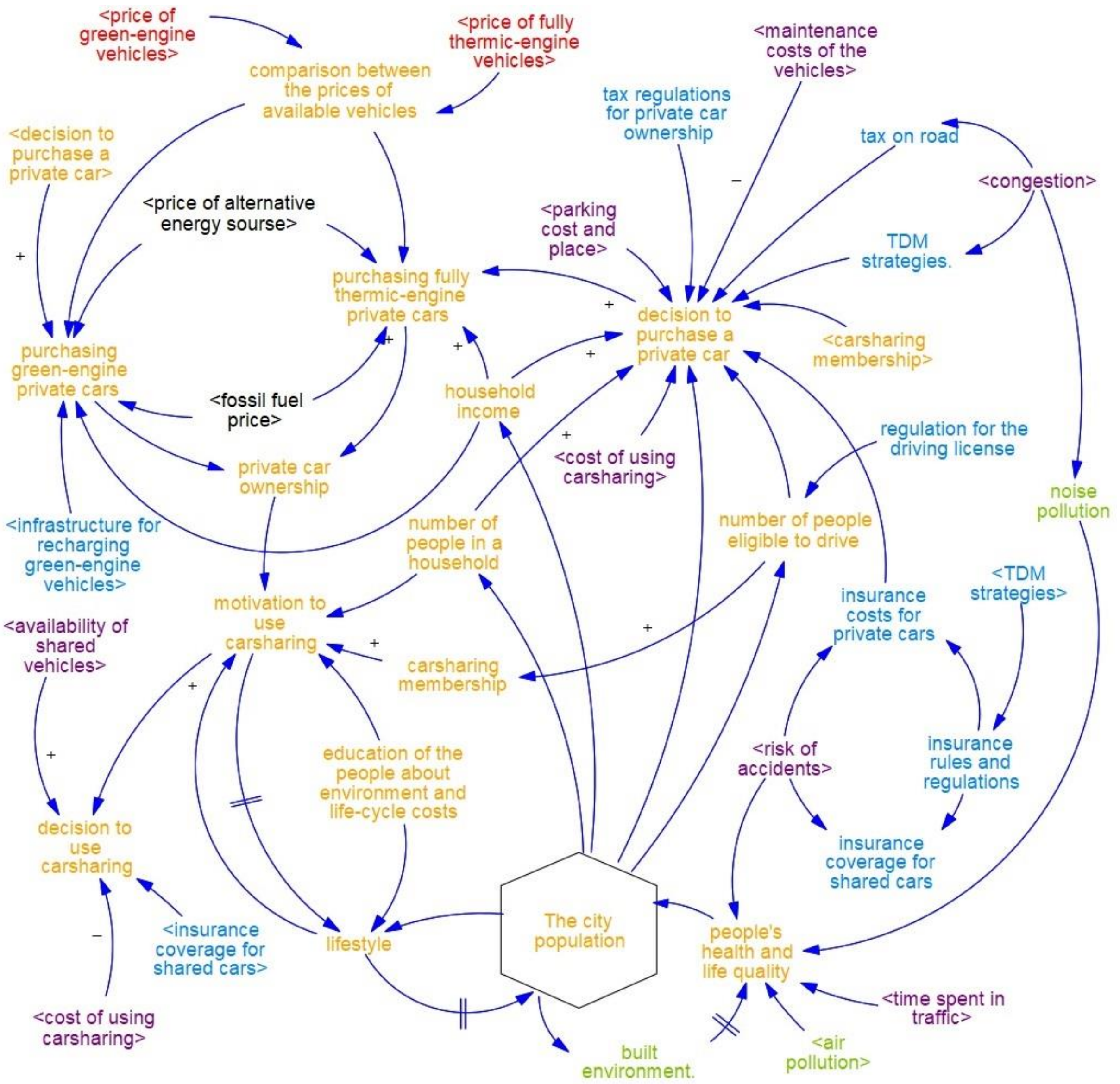

Figure 2. The developed CLD showing causal relationships between characteristics, behavior, and dynamics of population and carsharing.

The growth of the population in urban areas increases the demand for transportation. Birth, migration from rural to urban regions, migration due to studying or a temporary work position, and also tourism attractions can be mentioned as some factors that lead to the growth of the population that moves around the city. The role of each of these factors can be different for each area, which should be considered by the modeler for any specific case study. Although tourists are not the main residents of a city, for touristic areas that attract a high number of tourists at a time, the demand of this group of people in terms of mobility should be considered [64]. Depending on the rules for driving licenses and other effective factors, tourists can also be considered potential users of carsharing services. Hence, 'regulation for the driving license' can affect the number of people who are eligible to drive a car, and hence, it affects both the number of residents who can think of driving their own personal car and the number of tourists or other people who are temporarily present within that area and can use carsharing services. In the case of considering shared or autonomous vehicles in the model, the reduction in or elimination of the age limitation of the potential users should also be taken into account due to the expansion of the range of potential users of fully autonomous vehicles [66].

The limitations for the driving license are strictly linked with the age of the people, which is a demographic characteristic. Demographic characteristics of the population affect their behavior towards using carsharing, which has been studied by various researchers for different geographical areas. The study conducted by Sanvicente et al. [67] shows that although the increase in carsharing memberships in the UK can match well with the growth of the young population aged between 15 and 24 years in the country, this trend is not observed in Germany and Italy. Moreover, although the education level can be an effective factor in carsharing membership, their study highlights that it should not be considered the same for all countries. Shreds of evidence to support this finding come from the comparison between the cases of the UK, Germany, and Italy, which indicates that a linear relationship can be observed between the growth of carsharing memberships and the increase in the number of well-educated people both in the UK and Germany, while this does not apply to the case of Italy. Sanvicente et al. [67] also concluded that economic development trends, mainly income, seem not to be an influential factor for people to become a member of a carsharing service. In another study in the city of Turin, Italy, Ceccato and Diana [68] found that the members of carsharing platforms are mainly males with lower ages and higher incomes. However, Chicco et al. [69] believe that being a member of a carsharing platform cannot be considered the main incentive to put a private car away and that subscribing to these services does not necessarily indicate an occasional need for a car. Therefore, the behavior of the consumers in terms of using carsharing services should be more concentrated. A study targeting Frankfurt in Germany, Brussels in Belgium, and Turin and Milan in Italy by Chicco et al. [69] shows that, in general, members of carsharing services own, on average, fewer cars than nonmembers. However, it is not easy to claim that carsharing is the main reason for owning fewer vehicles because it is probable that people who decide to own fewer vehicles due to any reason use carsharing as a replacement. Their study also concludes that the growth rate for the number of cars owned by people who are not a member of carsharing platforms is higher than that of carsharing members. Therefore, carsharing services may be an effective factor in deferring the purchase of an additional car. The latter finding is in line with other research confirming that people use carsharing both in lieu of an additional household vehicle and as a backup vehicle, hence delaying new vehicle purchases [20,70,71]. A general review of the sociodemographic characteristics of the population affecting the demand for carsharing services is presented by Amirnazmiafshar and Diana [72].

Security and safety issues are considered critical and complex for both operators and users of shared mobility services. In this regard, Turon et al. [73], considering engineering and behavior aspects, outlined features associated with an insufficient safety level in shared mobility services as (i) the insufficient monitoring of the technical condition of offered shared vehicles, (ii) insufficient infrastructure for the safe parking of shared vehicles, (iii) insufficient knowledge of users in using shared vehicles, and accordingly, problems with driving/riding electric vehicles or charging electric vehicles in bad weather conditions, (iv) vehicles often being not properly equipped with additional protective items for users such as seats for children, and (v) not respecting rental vehicles and moving them too fast without complying with traffic regulations.

Figure 2 captures many variables as the main causes of the decision to purchase a private car. Besides the demographic characteristics of the population that impose limitations on such a decision, variables linked with other aspects can impose changes in the level of this variable over time. From the 'regulation and administration' aspect, variables such as 'tax on road', 'parking cost', 'transportation demand management (TDM) strategies', 'maintenance costs of the vehicle', and 'insurance costs for personal vehicles' are variables that can affect the decision to purchase a private car. The price of insurance coverage for personal cars is affected by the risks predicted for the vehicle, which is highly impacted by congestion and the increased probability of accidents [74,75]. Some TDM strategies, such as limited traffic zones, are also important when deciding to purchase a private car by many people. Moreover, in some countries, such as Belgium and Italy, tax schemes are defined for car ownership, including a one-time tax for the purchase of the car and an annual tax for car possession [76]. Such tax schemes can also affect the decision to purchase a private car. If people decide not to purchase or use a private car due to any reason, including purchase and running costs (e.g., fuel cost, parking cost, and insurance), carsharing can play the role of a replacement [77]. Although typically, carsharing operators provide insurance, gasoline, parking, and maintenance [78], the decision to use carsharing can also be affected by factors such as pricing schemes in carsharing services (e.g., per hour or per minute) and the parking policies adopted by the service provider (e.g., free or low-cost parking place) [79,80]. Proper carsharing pricing policies (that usually include parking costs) can be a gateway to vehicle access for people who otherwise may not be able to afford a private vehicle [81]. However, Luo et al. [82], in a study to investigate the competitive choice process between private cars and carsharing under different government policies in China, showed that with government policies, the total interest of travelers in choosing carsharing services is greater than private cars, while this is less than choosing private cars in the absence of government policies.

Purchasing more vehicles may be attractive to people and, at first glance, seem to elevate the quality of their lives. Nevertheless, the higher number of cars would make more 'congestion' (variable linked with 'the transportation system and urban planning'), leading to more noise pollution and air pollution (variables linked with 'environmental pollution') and increasing the 'risk of accidents' in cities (variable linked with 'the transportation system and urban planning'), which would be causes of lowering 'people's health and life quality' over time, and hence, the population of the city would be affected. Traffic-related health impacts have been studied by different researchers in various areas. As an example, Tashayo et al. [83] modeled the outcome of the impact of traffic-related PM2.5 concentration on health using a hybrid fuzzy inference system for Isfahan, Iran. Heart disease, blood pressure issues, sleep disorders, learning difficulties, and increased human distress have also been introduced as some of the health issues resulting from transportation noise pollution [84].

When people decide to purchase a car, they need to think about the various options among the vehicles that are offered to them, including ICE and alternative-fuel vehicles [85]. People's choice between these two categories can be affected by variables, such as the price of each of the two options (and every single vehicle within each category) [86], the price of fossil fuel energy and the alternate energy source for the vehicles [87], availability of infrastructure for recharging the green-energy vehicles [88,89], and their ability to afford the costs for each of the two options. In either case, if they purchase a car, they would be considered a car owner, and their behavior in terms of using carsharing services may differ from the ones who do not own a car. Mounce and Nelson [7] believed that strong connections exist between car ownership and carsharing in a way that car owners are more motivated to use their own car that they have previously paid for instead of using carsharing services. They may also not be inclined to leave their own always-available car and use shared cars when there is no guarantee about their availability at the time and place they are required. However, Chicco et al. [69] stated that although carsharing is not the key reason for the reduction in car ownership and owning a car is affected by various factors, such as differences in lifestyles, personal norms, values, and attitudes towards car ownership, it can enable citizens to live with fewer cars in the city.

A study in Turin, Italy, showed that the members of carsharing services mainly live in small households in which a high number of people work but the number of available cars is small [68]. Therefore, as shown in Figure 2, household size can affect both decisions to purchase a private car and the motivation to use carsharing, although, of course, not necessarily in the same direction. It is expected that larger families or families with children think more about purchasing a car than using carsharing services, and smaller families incline towards using shared mobility. However, this is not necessarily true over time for societies, since consumer behavior can be affected by many factors, with a key factor being 'lifestyle'.

The lifestyle of people affects their willingness towards using carsharing services [90]. On the other hand, the awareness of people about lifecycle costs, their potential monetary and/or time savings, and environmental benefits gained through using carsharing services may affect their transport mode choice and push them towards shared mobility [5]. Consequently, the intention to use shared mobility can affect people's lifestyles in the long run. Sanvicente et al. [67] denoted that younger people are less dependent on car ownership. As a result, if educated well about the benefits of using carsharing services, their lifestyle can be shaped into a car-free style over time. Thus, 'motivation to use shared vehicles' and 'lifestyle' both affect and are affected by each other, and two arrows in opposite directions show this mutual relationship in Figure 2. However, as can be seen in this figure, the arrow connecting 'motivation to use shared vehicles' to 'lifestyle' has a sign of '| |', which shows the delay explained. Another important delay considered in the CLD in Figure 2 is between 'lifestyle' and 'the city population' to show that, although people's lifestyle is affected by the whole society, if the 'lifestyle' is changed over time through education or due to any other variable, the lifestyle of the whole society is also changed in the long run by a delay. Finally, while the city population changes the built environment, the delay sign between the change in the built environment and people's health and life quality indicates that the effects should not be expected to be apparent as soon as the built environment is changed. Time delays between cause and effect impact the behavior of the system over time and make the behavior more complicated.

4.2. Transportation System and Urban Planning

Carsharing is a new transportation option that can be added to the existing ones and support multimodal communities [5,91]. Nevertheless, it can be considered a competitor of other modes of transportation and compete with purchasing new cars and used cars [2]. In fact, while the capacity of shared mobility services to substitute private car ownership is the most relevant expected benefit of a carsharing system, from a transportation policy viewpoint, it is also important to understand if carsharing is more in competition with private car use or with environmentally benign modes such as public transport, bike, and walk [2,68,92]. Research is still in progress on that key issue, and interim findings seem to point to the relevance of the context in which carsharing is offered and the need to provide a strong public transport service to which shared services could constitute a valid complement [69]. Different forms of carsharing serve different mobility needs and have different impacts in terms of market penetration and substitution potential of privately owned cars [69]. However, since the concentration of this research is on carsharing services and the nature of carsharing services is more similar to providing the benefits of owned cars, other modes of transportation (such as public transport, taxis, and micromobility) are not considered or discussed.

Figure 3 illustrates the CLD referring to the transportation system and urban planning. As shown in the lower part of the figure, an increase in the city population would lead to the growth of transportation demand that can be satisfied through various modes of transportation. For the purpose of this research, only 'using personal cars' and the possibility of using 'carsharing services' are considered the means to satisfy a part of the transportation demand. 'Demand for shared vehicles' is affected by the 'decision to use a shared vehicle', which is linked with the 'characteristics, behavior, and dynamics of population', but this demand can be translated into carsharing usage in the case of the availability of a shared car. In this regard, it is crucial for potential users to find available shared vehicles where and when they require them [2].

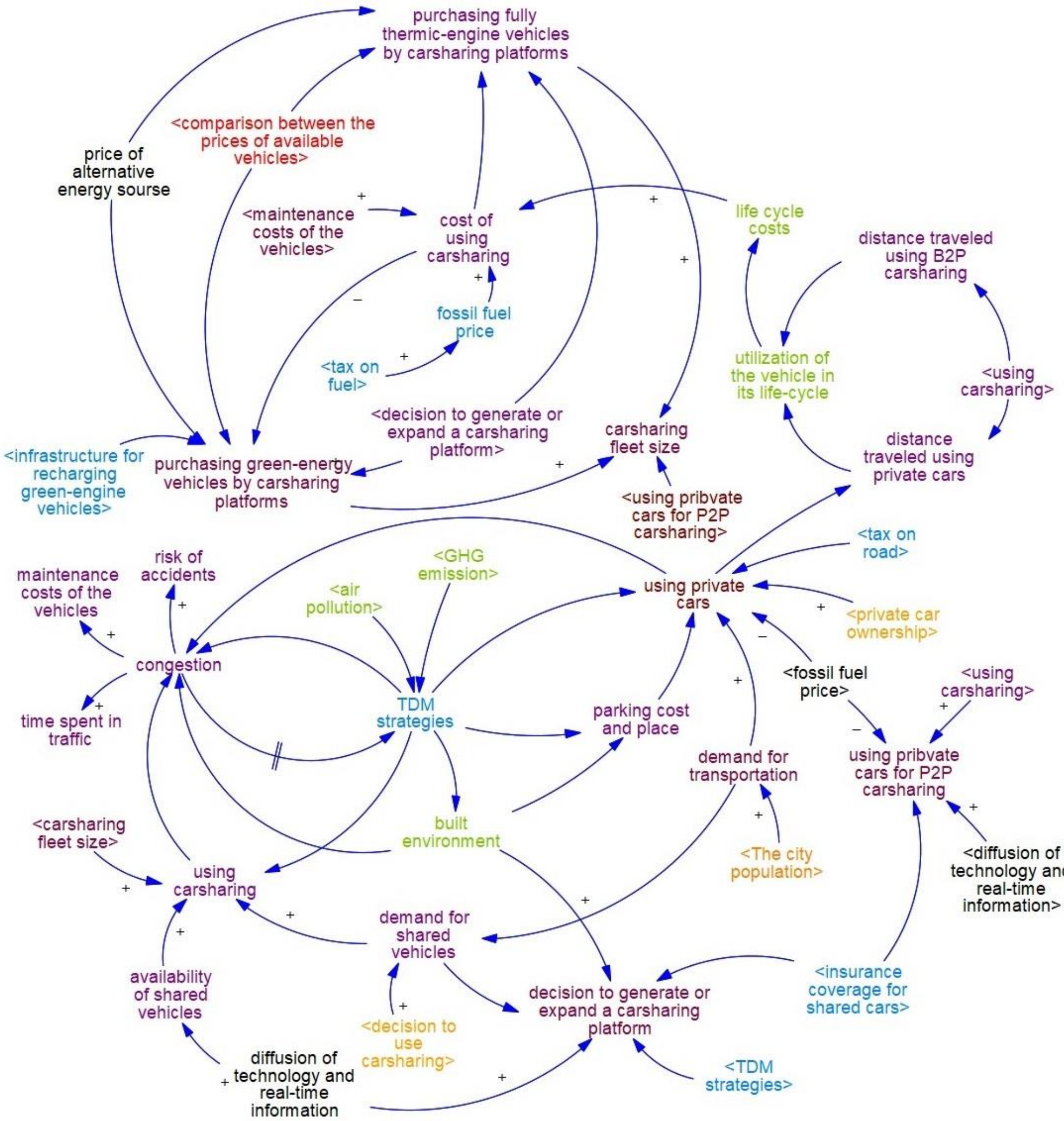

Figure 3. The developed CLD showing causal relationships between the transportation system and urban planning and carsharing.

Regardless of whether people use their private cars or a shared vehicle, the increase in the number of cars on the road leads to 'congestion', which not only results in a waste of time and energy consumption but also increases the risk of accidents. To control congestion, 'TDM strategies' may be specified by the authorities that can change the usage pattern of personal and shared vehicles in some areas [93]. TDM consists of a variety of plans and strategies used to improve the efficiency of using transport resources and can affect congestion and other important aspects of transport activities, including parking places and GHG and pollution emissions [94,95]. These strategies can be classified as (1) improved transport options, (2) incentives to use alternative modes of transport and reduce driving, (3) land use management, (4) policy and institutional reforms, and (5) supporting plans, each containing several management strategies and plans to manage transport demand in different areas [93]. The expansion of carsharing services can be seen as a TDM strategy in the classification of 'improved transport options' [93] if it can decrease the total distance traveled by car. This could more easily happen in denser areas to replace many private cars with fewer shared vehicles, especially if carsharing can complement a good public transport offer. Parking management and parking pricing are also affected by TDM, the strategies for which are put under the heading of land use management and incentives to use alternative modes of transport and reduce driving, respectively. TDM may also affect the built environment in the city to make it capable of providing more efficient transport services. The built environment (also called land use patterns) can affect the level of congestion, parking cost, and the availability of parking places. It can also affect the success of carsharing platforms due to changes in the travel behavior of people [96]. Furthermore, parking places and congestion can experience improvements if smaller size vehicles are being used as shared cars. Nevertheless, with the advances in technology, using fully autonomous vehicles within the carsharing fleet may increase the demand for shared vehicles due to providing service to previously excluded users (e.g., disabled people, elderly people, and children [9,66]), which leads to higher congestion.

Managing carsharing platforms deals with a challenge regarding balancing the supply and demand sides because of the strong dependence between the availability of shared vehicles and the number of trips made [5]. The increase in the 'demand for shared vehicles' would encourage various platform owners of the carsharing systems to initiate or expand their platforms with the use of ICT technology and the support of TDM strategies and insurance coverages. ICT tools and smart technology, such as dynamic location information on maps, are helping carsharing companies to provide and expand their services and make the experience of carsharing more user-friendly [5,67]. If the platform provides a P2P carsharing service, adding privately owned cars to this system can increase the fleet size of the platform and make more shared vehicles available. Otherwise, the platform provider needs to make a decision about purchasing fully thermic engine or green-engine vehicles according to some criteria, such as the vehicle price, the required infrastructure for recharging or refueling the vehicle, the price of energy required by the vehicle, and other costs associated with using shared vehicles, to develop its platform. It should also be taken into account that electric shared vehicles are mainly used for short-distance trips for which the users do not face the issue of 'range anxiety' [5].

Using privately owned cars as P2P shared vehicles would increase the 'distance traveled using personal cars' and using a shared vehicle from a carsharing platform would similarly increase the 'distance traveled using shared vehicles'. In either case, the 'utilization of the vehicle in its own lifecycle' would grow, and therefore, its lifecycle costs would be affected. Changes in the lifecycle costs can affect the cost of using the shared vehicle and hence the profitability of the carsharing platform, which then affects the price of using carsharing services (which is not included in the CLD in Figure 3 for simplification).

4.3. The Car Manufacturing Industry

Car manufacturers have a significant role in the supply of vehicles to carsharing fleets [2]. The CLD presented in Figure 4 focuses on the manufacturing of vehicles to be used for carsharing as well as their end-of-life (EoL).

When car manufacturers decide to manufacture new cars based on the demand for new vehicles, they are pushed by the regulations and directives towards manufacturing more environmentally friendly vehicles [13,97,98]. Furthermore, discarding vehicles should be conducted taking into account the existing rules, directives, and regulations (e.g., [99] and [100]), while manufacturers should also think of EoL issues during the product design or manufacturing phases [101,102].

The growing concerns about environmental issues have resulted in the attraction of more attention towards the utilization of electric and hybrid vehicles. The number of electric vehicles (EVs) worldwide exceeded 5.1 million in 2018, which showed an increase of 2 million with respect to 2017 [103]. On average, 10% of the fleet in the carsharing market in Europe comprises EVs, which is much higher than the share of EVs from privately owned vehicles [2]. Despite the small scale of carsharing in Europe, the purchase of a higher proportion of the manufactured EVs by carsharing service providers would help car manufacturers in their learning curve and economies of scale. As a result, the adoption of EV technology would be accelerated in societies [2].

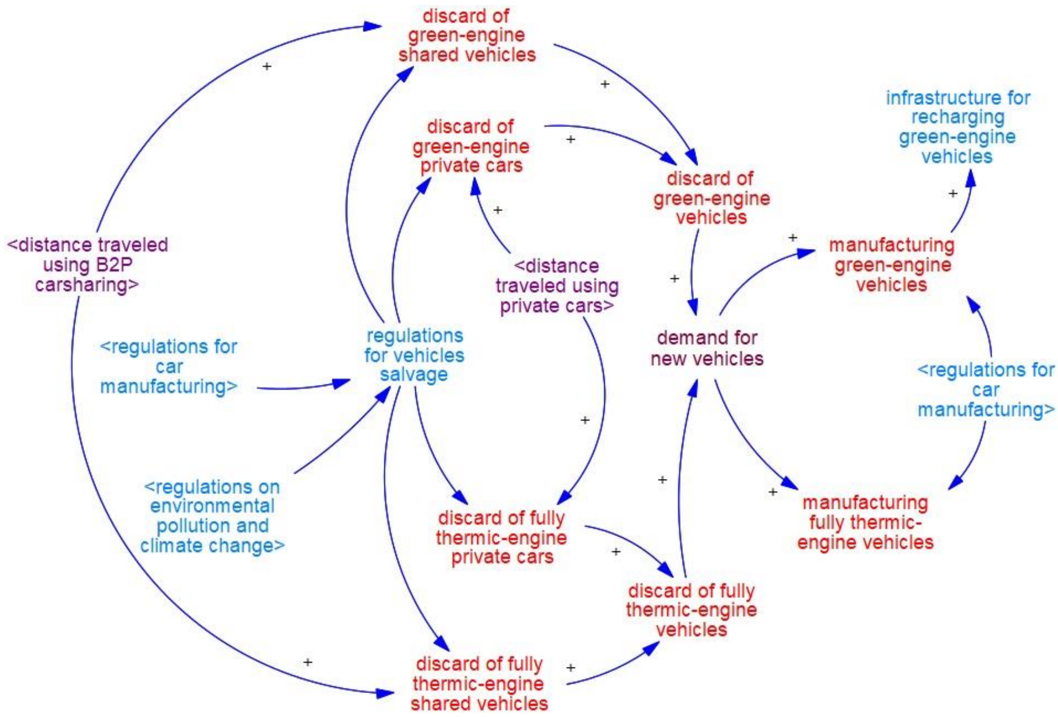

Figure 4. The developed CLD showing causal relationships between the car manufacturing industry and carsharing.

Nevertheless, EVs are constrained by the range they can travel (considering the battery charge) and also the need to recharge the battery in properly equipped places [66]. Therefore, the more electric or hybrid vehicles are manufactured, the more recharging infrastructure is required, which should be supported by the relevant authorities. Based on the report of the International Energy Agency, battery manufacturers are experiencing a transition towards the expansion of their production, and the relevant stakeholders are investing more in the charging infrastructure required for EVs [103].

Moreover, as more cars are manufactured and sold in the market, regardless of the type of fuel they consume, a higher number of cars commute on the streets, and therefore, a higher level of congestion is faced by the citizens.

4.4. Environmental Pollution

Barisa and Rosa [104] denoted that transport energy consumption and GHG emission are tied together and decoupling them is a difficult and challenging task. However, transportation activities result not only in more GHG emissions but also in the emission of air pollutants and the creation of noise pollution. Various types of emissions can be considered for vehicular transportation, including running exhaust emissions (CO, HC, NOx, CO_2, PM, and mobile source air toxics (MSATs)), running loss evaporative emissions (volatile organic compounds (VOCs)), and nonexhaust emission (PM10 and PM2.5) [105]. These emissions are shown as GHG emissions and air pollution in Figure 5.

As can be seen in Figure 5, based on the type of vehicle engine and the fuel consumed, the distance traveled by personal cars (for personal purposes or P2P carsharing) and carsharing fleets (B2C carsharing) gives rise to GHG emissions and pollutants. Furthermore, depending on the type of energy source, the amount of well-to-tank (WtT) GHG emission that is generated during the production phase of the fuel varies. The share of each category of vehicles in emissions depends on their market share and their usage level. The time spent in traffic can also increase the amount of pollution and GHG emissions.

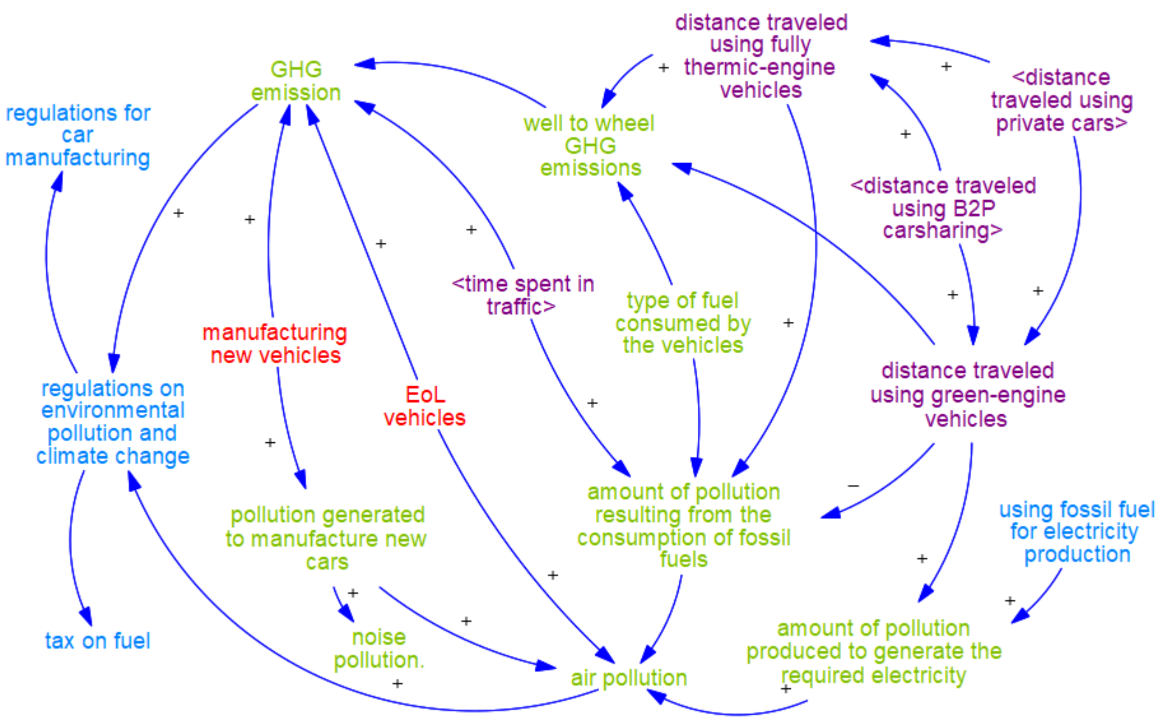

Figure 5. The developed CLD showing causal relationships between environmental pollution and carsharing.

According to the report of the International Energy Agency [106], the growth of the CO2 emissions resulting from road transport worldwide between the years 2000 and 2017 was 40%, while the total kilometers traveled during this period almost doubled. Putting the two changes together indicates that the energy performance in the transport sector has improved in recent years. Hence, a rapid shift towards less polluting and more environment-friendly vehicles is expected, in which EVs play a vital role. However, referring to the CLD presented in Figure 5, although the green-engine vehicles may not require fossil fuels, they may require electricity for their charging, for which some fossil fuel may be used; hence, some amount of GHGs and pollution is emitted to the environment. The resulting air pollution is a negative factor for people's health and life quality. The car manufacturing process also consumes much fuel for the production process, which can add to GHG and air pollution.

The increase in global GHG emissions and air pollution in recent years has attracted much attention, and many regulations and directives are set to save the environment. Regulation no. 443/2009 [98], Regulation no. 333/2014 [97], Directive 2000/53/EC [100], Directive 2014/94/EU [12], Directive 2005/64/EC [99], and Regulation no. 333/2014 [97] of the European Parliament and of the Council are examples of such regulations and directives that were previously pointed to. Imposing a tax on fuel consumed by the vehicle or considering a carbon tax can also be considered as some sort of regulation that can help to reduce the amount of fuel consumed and the emissions produced.

Although carsharing services are expected to lead to a reduction in negative environmental impacts through more intensive vehicle utilization and lowering the need for new vehicles, the 'rebound effect' resulting from the activities of these services should not be neglected [14]. The access-based consumption pattern in carsharing, like any other sharing-economy-based system, can change the spending allocation of people [107], leading to a higher level of demand, which consequently requires additional shared vehicles on the streets. This, on the one hand, affects congestion and energy consumption, which leads to more negative environmental impacts, and on the other hand, requires more vehicles to be manufactured by the automobile manufacturing industry, leading to more pollution and GHG emissions during the production process. Hence, considering the behavior of the whole system during a long period and conducting analysis through systems thinking approaches can help decision-makers to better understand and forecast such unexpected changes in the future.

A key flow that logically connects various parts of the presented general CLD is that, generally, a group of people are interested in using carsharing services where and when they need them. This interest can increase the demand for shared vehicles, which should be satisfied by the carsharing service providers. The vehicles to be added to the carsharing fleet are manufactured by the automobile manufacturing industry. Adding new shared vehicles to the fleet increases the availability of carsharing services and more people can enjoy it. Along this process, when vehicles are being manufactured, when they are being used, and when they are gathered as waste, besides noise pollution, many air pollutants and GHGs are emitted. Therefore, manufacturing a higher number of vehicles, increasing the utilization of vehicles, and discarding a higher number of vehicles result in a higher level of pollutant and GHG emissions, the control of which requires the intervention of regulators and authorities. Regulators and authorities can not only push the automotive industry towards manufacturing more environmentally friendly vehicles and also more efficient end-of-life management of the vehicle in line with circular economy principles but also regulate traffic, the built environment in cities, and other parts of the mentioned process. In the case the rebound effect linked with the higher utilization of shared cars [14] is controlled, the whole system can experience a transition towards sustainability and a reduction in negative externalities.

As discussed above, many studies have been conducted on carsharing services, considering different aspects of carsharing, such as carsharing service demand [108], carsharing business models [109], pricing and discounting schemes [110], optimization of carsharing fleet placement [111], behavioral factors in carsharing adoption [112], and governance and policy impacts [113]. However, very limited studies have been conducted [14] to investigate such types of shared mobility services as a whole with a systemic approach. Hence, the developed CLDs in this research with a focus on population, car manufacturing, transportation system, and environmental pollution associated with carsharing services provide an inclusive insight into carsharing adoption.

5. Conclusions and Future Research Direction

Carsharing, as a potential leverage to help the transition towards sustainable urban transport, has attracted attention within the context of sustainable cities in recent years. However, the current conditions regarding the utilization of shared cars are different in various countries. Therefore, while considering the available resources and the regulation as well as the population demographics, SD modeling can help analyze potential scenarios regarding the diffusion of carsharing and its resulting environmental effects.

This paper represents a source for elaborating a system thinking framework for carsharing services and provided an overview of the factors affecting the diffusion of carsharing services and their associated environmental effects. Although the target literature is scarce, the current research shows the importance of system thinking while modeling the interconnections related to the diffusion of carsharing and its resulting environmental effects. The cause-and-effect relationships captured in the presented CLDs are supported by academic and gray literature but not necessarily by the studies that have utilized a systems thinking approach. It is highlighted that the use of the systems thinking lens in modeling the interactions between carsharing services and environmental effects requires more attention from researchers. Applying systems thinking can be useful in analyzing different scenarios regarding the development of carsharing services and the resulting positive or negative environmental effects.

Considering the analytical approach of the CLDs provided, researchers can benefit from the presented diagrams by using any of the subsystems based on the boundary of the problem they deal with and quantifying the model by applying real data from their specific case study. Since the framework has tried to have a general approach and capture possible interrelationships between the components, neither the boundary nor the quantification of the model is the same for diverse cases. Nevertheless, the framework is flexible to be used for modeling carsharing services by looking at the problem from different lenses.

The provided analysis through developing CLDs for carsharing services in this research is qualitative. However, using quantitative methods to provide more accurate results on different aspects of discussed elements in the carsharing realm is highly encouraged to further advance carsharing research from a systems thinking perspective. In this regard, quantitative system dynamics simulation models can be developed based on the presented CLDs in this research to better map carsharing and its associated effects on societies in the long term, presenting promising directions for further developments in the future. Furthermore, the same approach can be taken to analyze the diffusion of bike-sharing and other similar modes of transport based on the concept of the sharing economy within the context of urban mobility.

Although the scientific community is the initial target group of this research, which is aimed at helping them facilitate their future research dealing with carsharing and its underlying environmental impacts, many more entities can benefit from the results of this research. The presented system thinking framework can help institutional managers and stakeholders in developing strategies for the expansion of carsharing services by considering the global force for the reduction in the negative environmental impacts of transportation services. It can also help legislative bodies in gaining a holistic view in accordance with the future results of their rules and regulations set today.

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