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Resilience of Social-Infrastructural Systems: Functional Interdependencies Analysis

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Abstract: Critical infrastructures serve human activities and play an essential role in societies. Infrastructural systems are not isolated but are interdependent with regard to social systems, including those of public health and economic and sustainable development. In recent years, both social and infrastructural systems have frequently been in dysfunction due to increasing natural or human-made disasters and due to the internal and external dependencies between system components. The interconnectedness between social-infrastructural systems (socio-economic systems and technical-infrastructural systems), implies that the damage to one single system can extend beyond its scope. For that reason, cascading dysfunction can occur and increase system vulnerability. This article aims to study the functional interdependencies between social-infrastructural systems and to propose a methodology to analyse and improve the resilience of these systems. Combining Actor Network Theory and the Functional Models approach, the social-infrastructural Interdependence Resilience (SIIR) framework was proposed. To assess the applicability of the approach, the framework was applied to study the interdependence of a social-infrastructural system in the Nantes Metropolis. The studied system was composed of the local Highway Infrastructure (an infrastructural system) and the Emergency Medical Service (a social system). The results (1) show the feasibility of SIIR for investigating the interdependencies of two urban systems, and (2) provide a guideline for decision-makers to improve the functional interdependencies of urban systems.

Keywords: social-infrastructural system; interdependencies; actor network theory; functional analysis; cascading dysfunction; failure mode analysis; critical infrastructures

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1. Introduction

The term "urban" refers to a place-based characteristic that is related to the transformation of the natural environment into a built environment [1]. A city, as well as an urban area, is a complex system composed of multiple subsystems, and numerous are the interactions between these subsystems and the external environment [2]. In accordance with the research of Meerow et al. (2016) [3], this study identifies four types of subsystems in the urban system: technic-infrastructural systems (infrastructural systems), socio-economic systems (social systems), nature and energy flow systems (environmental systems) and government-organisational systems (organisational systems) (Figure 1).

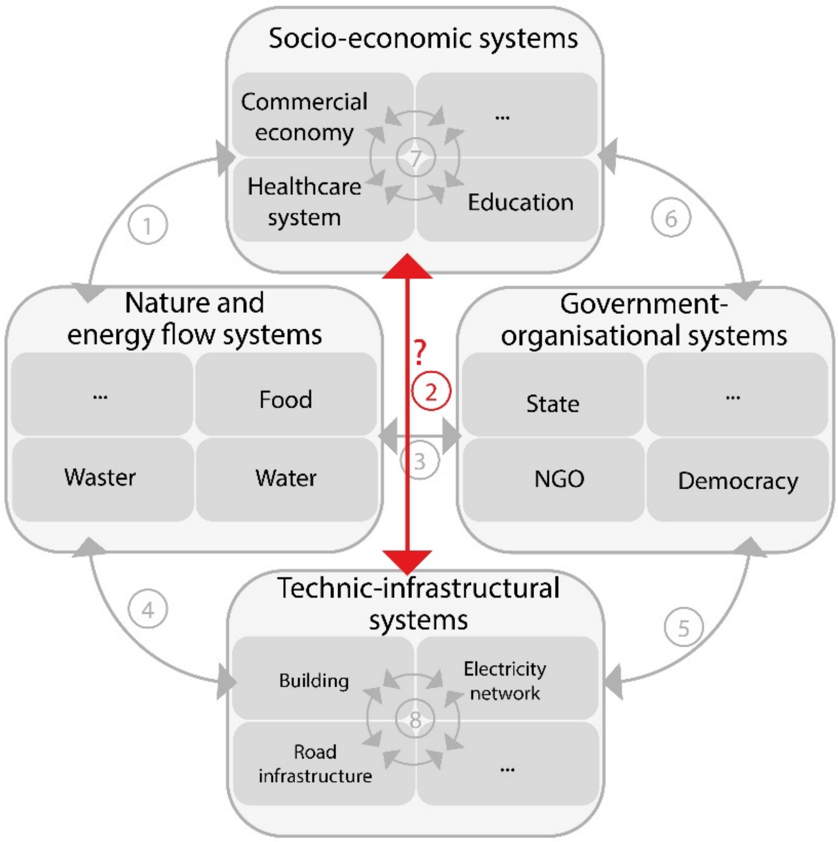

Figure 1. Urban subsystems and the interdependencies identified within.

In recent times, both natural and manmade disasters have exposed modern societies to many hazards due to the complex interconnection between urban subsystems [4]. All subsystems and components of the urban system are, in fact, mutually dependent and not isolated. In this context, dependence resilience has become an important goal for urban management. Meerow et al. (2016) believed that "urban resilience refers to the ability of an urban system and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales, to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity" [3]. Therefore, the urban sub-system and its components are the major aspects that should be considered in urban resilience research.

Among urban subsystems, infrastructural and social systems are those assets that are indispensable for the maintenance of critical urban functions. In particular, the European Commission identifies Critical Infrastructure (CI) as those assets that are indispensable to societies. Socio-economic subsystems (social systems) concern the items that have a direct impact on human life, such as the economy and public health. Furthermore, the boundaries of the socio-economic dimension involve administrative borders and attributes connected to the locality, such as livelihood and urban services [5].

If the services are identified as crucial and therefore must operate reliably, interdependencies between urban subsystems quickly appear as critical [6]. For example, in July 2021, a tragic flood affected central Europe, particularly Germany, Belgium, Netherlands and other nearby countries, causing over 200 deaths. During the flood, many people were trapped in isolated areas with no possibility of rescue due to the disruption of road traffic and telecommunication systems. The government was also unable to contact the affected people and ascertain their condition, resulting in severe delays to rescue missions. In this event, the dysfunction of infrastructures exacerbated the consequences of floods with regard to the dependencies between the emergency recuse service (a social system) and the road or telecommunication infrastructures (an infrastructural system). However, if the decision-makers had assessed the dependencies between socio-infrastructure systems, measures to prevent the cascading effects could have been implemented and the consequences of this flood could have been reduced. Therefore, the methodology for identifying the dependencies of social-infrastructural systems is worth investigating.

In the scientific literature there has been an increasing interest in the dependencies between infrastructural systems (Figure 1, number 8) [7–13] and between social systems (Figure 1, number 7) [14,15]. The research on resilience and dependencies between the different subsystems that compose the urban system has focused only on the connection between social and ecological systems (Figure 1, number 1) [16–20]. At the same time, research that has focused on studying the dependencies between social and infrastructural systems has only analysed negative impacts (Figure 1, number 2) [21–24] or their relativity [25–29]

Based on the state of the art, the aim of the contribution was to propose a framework for identifying the interdependencies between urban social-infrastructural systems (systems composed of a social and an infrastructural part). In this context, dependence refers a state of being determined or significantly affected by external forces, while interdependence means mutual dependence [30].

To study the two systems, Actor Network Theory was introduced to analyse both the "human" and "non-human" parts of the systems [31]. We can differentiate two studied subsystems: infrastructural systems are mainly characterised by a greater number of non-human components in the built environment, while social systems are mainly characterised by a greater number of human components in the social environment (Figure 2). Therefore, identifying how infrastructural systems and social systems depend on each other means analysing the functional connections between the components of the two systems (Figure 1, number 2) [32–34]. Based on functional dependencies, this study further aims to understand the potential cascading effects and possible failure modes to define interdependencies between the two systems to improve resilience (Figure 1, red line).

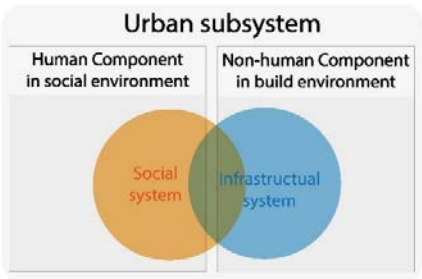

Figure 2. Difference between "human" and "non-human" components in social and infrastructural systems.

To test the approach, the SIIR framework was applied to two systems of the Nantes Metropolis, in particular to the social-infrastructural system composed of the Nantes Highway Infrastructure of Nantes Ring Road (an infrastructural system) and the Mobile Emergency and Resuscitation Service—SMUR (a social system). Although the functional model was applied to the transport system of highway infrastructure, there are also similarities with other transport infrastructures such as those of railways.

2. Materials and Methods

The proposed Social-infrastructural Interdependence Resilience (SIIR) framework is based on 2 scientific theories (Table 1):

- The Actor-Network Theory (ANT) [31,35–42]; and
- The Functional Models theory, related to the Functional Flow Block Diagram (FFBD) [2,33,34,43–45], the Event Tree Model (ETM) [46,47], and Failure Modes and Effects Analysis (FEAM) [21,44,45,48].

Table 1. The SIIR methodological approach, methods, and theories involved.

Step	Method or Theory	Description
1. General state of the systems		
Systems components analysis (actors) and functional analysis	Functional Model—Actor Network Theory (ANT) and the Functional Flow Block Diagram (FFBD)	Identification of all important components (actors) in the studied systems. The ANT helps identify human components (collective and individual) and non-human components (physical structures and main functions of systems). Identification of components' functions and the functional dependencies between these components.
2. Potential effects due to hazards		
Cascading dysfunctions analysis and failure modes analysis	Functional model—Event Tree Model (ETM)Functional Model—Failure Modes and Effects Analysis (FEAM)	Identification of cascading dysfunctions due to hazards, based on ETM. Identification of affected components (that lose functions due to hazards) and the indirectly affected components (that lose functions due to the dysfunction of other components, due to the functional interdependencies). Identification of failure modes and effects analysis.

The 2 steps of the proposed framework are highlighted in Table 1 and are detailed in the following paragraphs. In synthesis, the first step allows us to understand the general state of the studied systems, while the second step allows us to investigate the sequence and type of potential cascading effects caused by hazards.

The details of framework will be presented in the following paragraphs, before an application to a case study in Section 3. In the following discussion, we explain how the results could be used to improve the resilience of the socio-infrastructure system.

2.1. I Step: Systems Components (Actors) Analysis and Functional Analysis

The "Actor Network Theory" (ANT), developed by Michel Callon, Bruno Latour, and John Law, is a theoretical and methodological approach to investigate the relationships of existents in heterogeneous social or natural networks [35–39]. The theory is useful to identify components (that in this case are called actors) of urban systems. The term "component" is generally used to descript the physical existing elements in infrastructural systems [2,32–34,43–45]. Nevertheless, in this research, we will uniformly use "component", signifying "actors", for describing the physical or abstract existents in social and infrastructural systems.

In this study, there are 3 key points identified in the theory. The first concept is to consider that human and non-human components (both referred to as "actants") have their own interests and the same capacity to influence the development of actor networks by enacting relations and enrolling other actors [31,40]. Therefore, in urban subsystems, the ANT identifies human and no-human components: human components are categorized as individual or collective, while non-human components are divided into physical structures and non-physical existents. A function can be also identified as a type of non-physical component. The second principle is that the components have no inherent qualities, and that their forms and characteristics are the effects and outcomes of interaction or power with other actors [42]. Finally, the network and actors are uncertain and reversible because the qualities and form of the actor are continuously displaced through time and space [35,41,42]. Thus, to understand how the urban system works, it is necessary to make the actors "relatively stable"; this expedient is called "translation" and refers to the position of a network in a particular condition (time and space).

The ANT is necessary to identify the components in studied social-infrastructural systems, including the components that do not have a physical structure and cannot be analysed with functional analysis [49,50]. In social systems such as the health system, there is a preponderant human part. Moreover, the non-physical and non-human components, such as function, capacities, organisation, etc., are considered indispensable in urban networks in this study. Therefore, identifying components only on the spatial level may not be sufficient in the study of the social-infrastructural system. As each social-infrastructural system is specific to a local context, the study of systems requires specific analysis and the collection of multiple data (through autonomic observation or government documents), although the methodology remains the same.

All components of the studied social-infrastructural systems (represented as actor-networks) are identified to analyse the functions and the served components of these functions. In practice, considering the network as a social-infrastructural system, all components are considered to have their own needs for the functions of other components (internal or external actors). Their mutual nature leads them to work together to create a socio-infrastructure system (the actors network in ANT) around them and ensure the system functions (the actors network interest in ANT).

After the identification of system components, the application of FFBD enables the analysis of the functioning and performance of a system or subsystem in establishing the role and the functional relationships between the components in the inside and outside environment (internal and external) [2,43]. The functional analysis allows the understanding of the functional behaviour of a system or its components facing external hazards, analysing its failures, reconstructing the failure scenarios, and determining the most efficient or critical parts of the system. Then, it is possible to identify the cascading dysfunctions analysis and failure mode analysis [33,34,44,45].

This study focuses on the interdependence between the 2 studied subsystems in the case of social-infrastructural systems. The interdependencies are based on functional dependencies, which concern the main functions of one system and the actors served by them in the other system. The functional dependencies of components can form a complex network. To first identify the functional dependencies and then the interdependencies, it is important to analyse the sequence of the events and clarify the cascading dysfunctions.

2.2. II Step: Cascading Dysfunction Analysis and Failure Mode Analysis

Cascading dysfunctions or cascading effects can be defined as the sequence of events in human subsystems that result in physical, social, or economic disruptions caused by a physical event or the development of an initial technological or human failure. In this research, a cascading dysfunction occurs when a functional disruption to one infrastructure causes the failure of a component in a second infrastructure, which subsequently causes a functional disruption in the second infrastructure [7,46]. For a better understanding of the cascading dysfunctions due to different causes (original or non-original events), in this research, three types of dysfunctions are defined:

1. Direct dysfunction: components lose function due to the original hazard;
2. Indirect internal dysfunction: components lose function due to the failure of a components inside the same sub-system; and
3. Indirect external dysfunction: components lose function due to the failure of a component outside the same sub-system.

The events sequence can allow us to understand the cause and effect of each dysfunction event, and to understand the directly and indirectly affected systems under different hazards. In the case of social-infrastructural resilience, 2 circumstances are possible: hazards affect infrastructural systems and their dysfunction affects social systems, or hazards affect social systems and their dysfunction affects infrastructural systems.

This step is applied to analyse failures due to component dysfunction (cascading events), combining the causes (previous components in the cascading events) and the effects (subsequent components in the cascading events). Every component may have both roles of "cause" and "effect": the former means that their dysfunctions affect the functions of other components, while the latter means their functions are affected by the defined hazard or the dysfunctions of other components. The continuous development of events results in increased affected components, and even those which are directly affected can be affected multiple times. However, an unlimited analysis would leave the study unfocused. Therefore, we focus our analysis on the events where the 2 systems are first linked, which means the moment when components of one of the 2 studied systems are affected for the first time by a failure dysfunction in the other system. The state of the art [21,44,45,48] identifies 4 main characteristics of failure modes in this study: time, space, quantity, and quality. This study partially modifies them to obtain 4 failures modes highly relevant to their effects on component function in terms of the duration of dysfunction (time), the geographical area involved in dysfunction (space), the number of factors in dysfunction (quantity), and the degree of reduction in competence and quality of operations (quality).

In this contribution, we will only discuss the development of the failure events and the failure modes of components concerning the sequence of dysfunctions events to provide support to decision-makers to better identify improve measures.

3. Application of SIIR Framework

In the following paragraphs, the SIIR methodology is applied to study the dependencies between Highway Infrastructure (RI) and Emergency Medical Service (EMS) in Nantes. In particular, the Nantes Ring Road network is used as an infrastructural system, and the local Emergency Medical Service as a social system.

With rich history and development, Nantes has been the administrative capital and economic/cultural centre of the French west. It is also a city vulnerable to urban disasters, and is at risk of meteorological events, floods, health crises, industrial issues, and problems due to the transport of dangerous goods [51]. The high level of urbanisation makes this city more vulnerable, and thus a healthy urban system supported by resilient social-infrastructural interfunctions is necessary.

The Nantes Ring Road is a HI with a length of more than 42 km that represents an important link at the local, regional, and national levels [52]. Due to the high utilization of this HI network, disruption of traffic due to flooding, for example, could lead to congestion on the connected roads. Furthermore, the EMS is a key component of the French health emergency service, in addition to the specialised emergency reception and treatment services. The role of the EMS in the Nantes Metropolis is engaged by the Mobile Emergency and Resuscitation Service (SMUR), which provides the patient or injured person with the necessary care on the spot before transporting him or her, in the best possible conditions, to the most suitable care structure. In Nantes, the EMS uses the HI for service mobility. Meanwhile, the EMS helps the HI ensure road safety in the case of accidents.

3.1. Components and Functional Analysis

The first step of the proposed framework SIIR is to identify the critical components, the dependencies among them, and their interfunctions in the studied social-infrastructural systems. The investigation is based on an observation of Nantes city and information from Regional Directorate for the Environment, Planning and Housing (DREAL) of Pays de la Loire [52], Samu-Urgences of France (SUdF) [53], and CHU of Nantes [54].

The critical components and the functions of the two studied systems are listed in the appendix (Appendix A). Concerning the research on interfunctions, we aim to investigate:

1. The functions of the HI, and their served components in EMS; and
2. The functions of EMS, and their served components in the HI.

Figure 3 presents the internal critical components and their internal dependencies in the EMS, including 4 categories: human components (individual and collective) and non-human components (physical structures and non-physical characteristics). Auxiliary services of the HI provide medical services for the local Nantes EMS, serving "Land vectors", "Ambulance drivers", "Doctors", "Nurses", "Patients" and "Manager" structures (the HI aims to ensure the organisation of "Manager" structures). At the same time, the EMS provides services to all components involved the "Individual actors" in the HI.

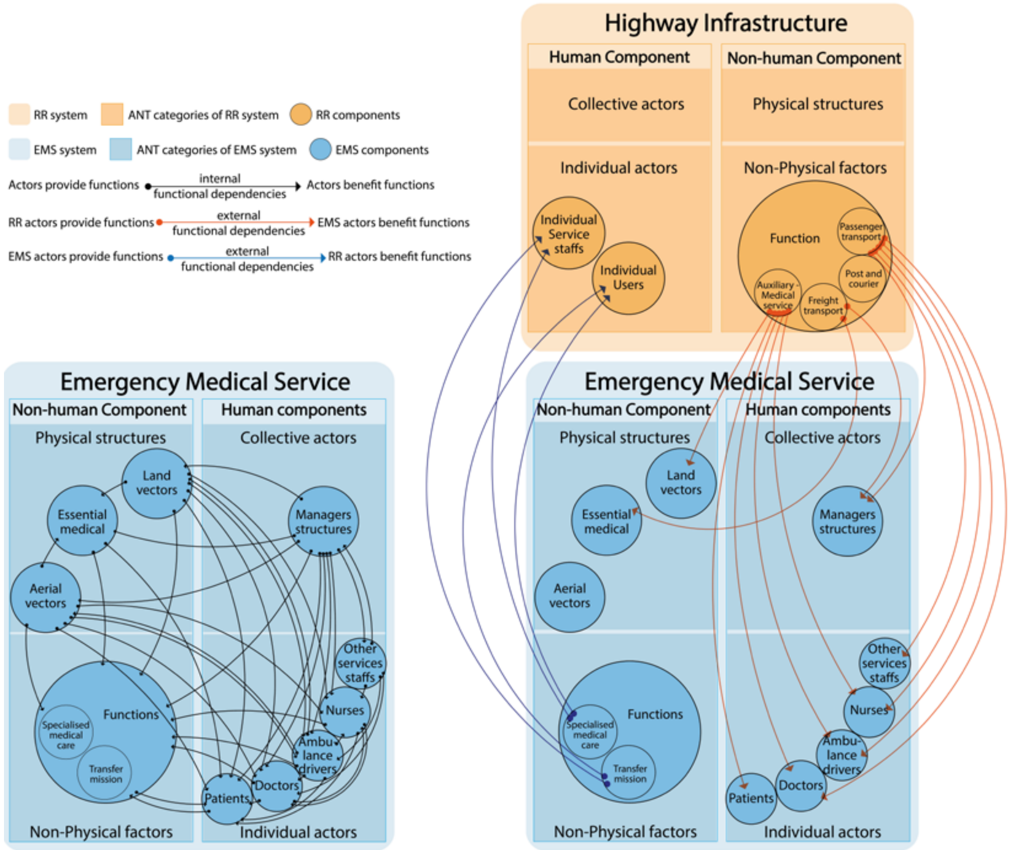

Figure 3. Internal and external dependencies of the EMS systems.

3.2. Cascading Dysfunctions and Failure Mode Analysis

In this step, with a resilience scenario including an original hazard event, we analyse the affected components and their failure mode. Flood and pandemic crisis in Nantes are identified as the original hazards. Nantes was determined as a High Flood Risk Area (TRI) by prefectural decree of 26 November 2012 [55] due to major flood event consequences at the national level and the need for protection of the 11 municipalities concerned. According to SLGRI of Nantes, nearly 250 km of the road network are likely to be disrupted in case of an extreme flooding event. Additionally, like all metropoles worldwide, the Nantes health system was shocked by the COVID–19 pandemic in 2020. To cope with the increasing demand on the hospital systems by COVID–19 patients, the 3-week "White Plan" (Plan Blanc), announced by Nantes CHU in 2020, indicated the possibility of deferring or rescheduling certain non-urgent treatments by moving medical resources [56].

In the face of an original hazard event like a health crisis, the emergency medical system in Nantes would be affected first. The failure modes of EMS would then affect the performance and efficacy of the HI transport security service. In this health crisis scenario, 3 types of dysfunctions are identified in HI–EMS systems (Figure 4):

1. Direct dysfunction: "Managers" structures, which organise medical planning, are directly affected by a health crisis;
2. Indirect internal dysfunction in internal components of the EMS affected by the dysfunction of "Managers" structures (only "Function" is discussed because it is related to the HI system);

3. Indirect external dysfunction: HI components are affected by the failures of EMS "Function".

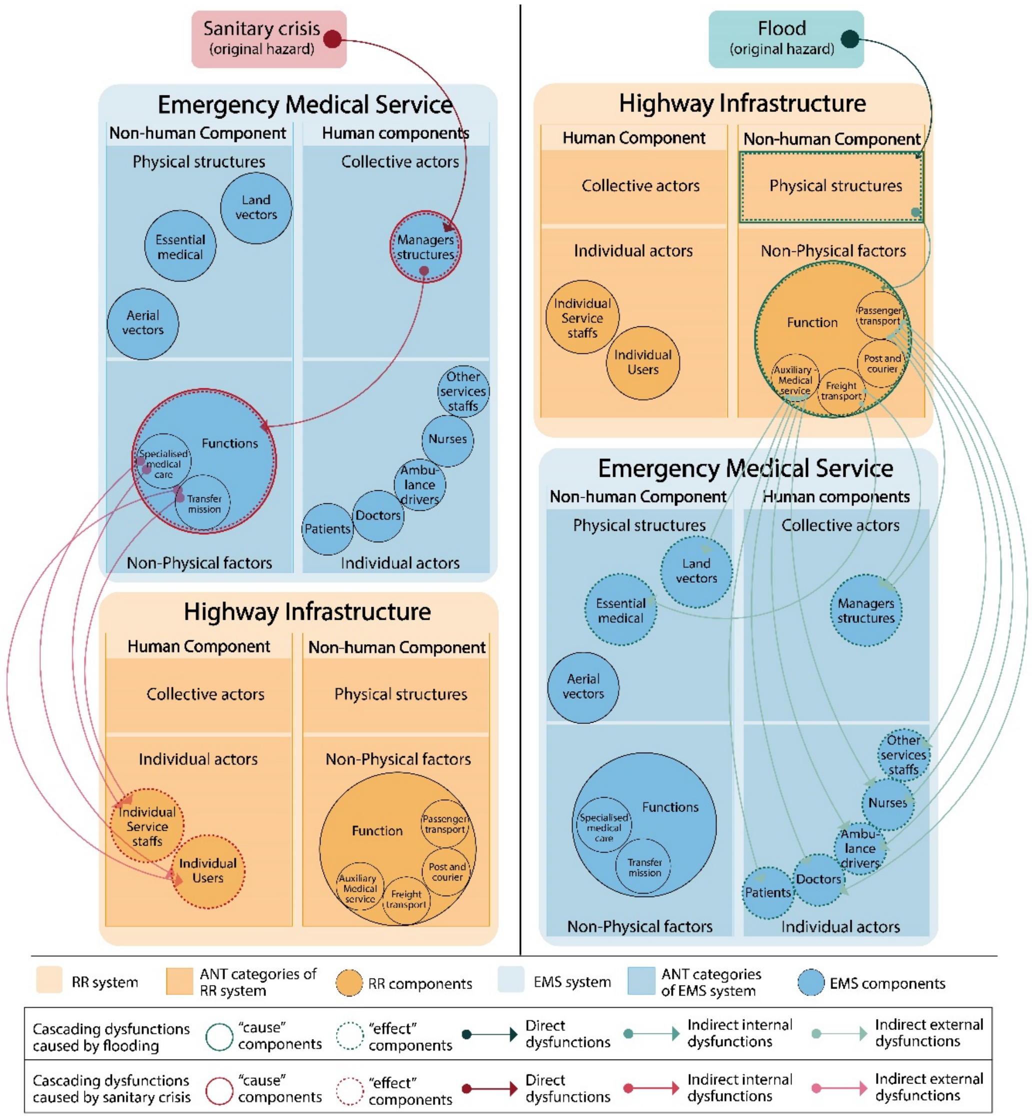

Figure 4. The direct and indirect effects on the HI–EMS system facing flooding and a health crisis.

In the cascading events caused by a health crisis, the "Indirect external dysfunction" involves only the "Individual actors" in the HI system which are affected by the failure of EMS "Functions" (Figure 4).

However, with urban flooding, HI physical structures are generally affected directly. Subsequently, other components in HI and EMS systems could be affected by the dysfunction of "physical structures" of HI. Furthermore, in this scenario there are 3 types of dysfunctions that can be identified (Figure 4):

1. Direct dysfunction: the physical structure of HI network is directly affected by flooding
2. Indirect internal dysfunction: in the HI network, internal components are affected by the dysfunction of others internal components (only "Function" is discussed because it is related to EMS system);
3. Indirect external dysfunction: the EMS components are affected by the failures of the HI "Function".

As shown in Figure 4, the "Indirect external dysfunction" involves almost all the components in the EMS system, which is affected by the failure of HI "Functions". Some components have both “cause” and “effect” roles, while some components have only a role of “effect” as they are the last affected components.

The external dysfunctions events are key to our study because it is well documented that the failure of one system affects the performance of other systems. In Nantes city, flooding occurs more frequently than health crises, and the “Medical service” is the most urgent function under regular circumstances. Therefore, in this study, we will discuss the components involved in the “Medical service” during flooding scenarios to investigate the failure modes of the components, including the temporal, spatial, quantitative, and qualitative failure modes. The result in Figure 5 shows that different failure modes of HI function cause different failure modes in the involved EMS components. For example, spatial failure of “Medical service” triggers a temporal failure in the “Ambulance” structure but a quality failure in the “Manager” structures. The failure of the “Medical service” of the HI would result in partial failure modes of the affected components in the EMS. In Figure 5, the failure modes that have a white background are not relevant to HI functional failure. The identification of the connections of failure modes helps to better predict the types of cascading effects.

Systems	Components	Failure modes Temporal	Spatial	Qualitative	Quantitative
“Cause” component					
Highway infrastructures	Functions	Unavailability of medical functions for a long/short time	Interruption of traffic in a large/small area	Serious/minor reduction in quality of medical functions (provide roads or spaces)	Partial/total medical functions are not available (provide roads or spaces)
↓		↓	↓	↓	↓
“Effect” component					
Emergency Medical Service	Land vectors	n/a	No accessibility of land vectors in the area	Serious/minor reduction in quality (transport performance or medical operation performance)	n/a
	Ambulance drivers	n/a	No accessibility of ambulance drivers in the area	Serious/minor reduction in quality	n/a
	Manager structures	n/a	n/a	Serious/minor reduction in quality of manager structures	n/a
	Doctors	n/a	No/Compromised accessibility of doctors in the area	Serious/minor reduction in quality (operational ability)	n/a
	Nurses	n/a	No/Compromised accessibility of nurses in the area	Serious/minor reduction in quality (operational ability)	n/a
	Patients	Increase in time spent by patients in waiting medical services	No/Compromised accessibility of patients in the area	Severe/minor aggravation of the patient's physical and psychological state	Decreased condition of patients and possible increased deaths

Figure 5. The connection (causes/effects) between the failure modes of HI functions and EMS components. The different background colours identify connections between causes and effects.

4. Discussion

Through the investigation of functional dependence between the Highway Infrastructure and Emergency Medical Service, this study proves that the urban social-infrastructural systems are interdependent (Figure 6). In urban resilience, dependence refers to an urban subsystem being determined or significantly affected by another urban subsystem, while interdependence refers to a mutual dependence of two subsystems. The SIIR framework aims to contribute to both the research and operational fields in the management of the urban resilience of interdependent systems.

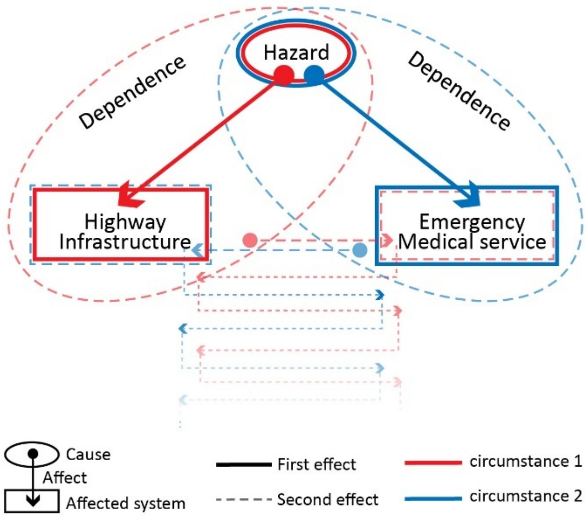

Figure 6. Interdependencies between social and infrastructural systems.

4.1. Methodology for Urban Resilience Research

The SIIR framework provides an approach to investigate the interdependences between two urban subsystems and to finally improve urban resilience. Following the ANT, we assume that human and non-human components have the same capacity to affect the development of actor networks [31,35–41], although this perspective is not investigated in detail as is not the subject of the article.

Although in this paper the SIIR is applied to social-infrastructural systems, the framework could be applied to other urban subsystems. Therefore, the acronym "SIIR" could be changed to "X-X-IR", where X represents all types of urban subsystems (social, infrastructural, organisational, or environmental). With the X-X-IR it is possible to analyse all the interdependencies existing between subsystems in urban areas (Figure 1, number 3,4,5,6).

Another aspect of the study deserving interest is its potential application to the interdependence resilience study of more than two urban subsystems. Since we can identify functional dependencies between two systems, this approach could also be used to identify functional dependencies of multiple systems. Cascading dysfunctions analysis and the adaptation analysis of improved modes would become more difficult due to the greater number and complexity of interfunctions. However, this possibility should be seen as a promising development in urban resilience research.

4.2. Results for Managers Involved HI–EMS in Practice

The results of applying the SIIR to the case study in Nantes could support managers of HI–EMS systems in finding improvement measures to better understand functional interdependencies and predict cascading dysfunctions.

Based on the results of the case study, we firstly found that the functional dependencies in internal HI or EMS systems were constantly changing and reversible in a complex network. At the same time, through a detailed investigation of the dependencies between the functions of one system and the components of the other system, it was possible to identify the interdependencies between the two systems. This analysis highlights the concrete intersections of the HI–EMS systems.

The interpretation of the systems by the ANT and functional analysis also allows the understanding of possible dysfunctions of both "human" and "non-human" components of the studied systems across spatial-temporal dimensions.

Functional analysis and cascading dysfunctions analysis are crucial for predicting the cascading effects of hazards. For example, in our second scenario, urban flooding is the original hazard, directly affecting the physical structure of the HI network and thus indirectly affecting the EMS system. Therefore, when facing urban floods, managers of

EMS can supply the SIIR framework and identify the internal affected components and their failure modes, even if the EMS system is not directly affected. For managers of the HI network, the SIIR framework clarifies the subsequent components of cascading effects, so that they can quickly alert the risks to the EMS system and perform maintenance measures.

To test the approach, it is possible to use an emergency event in Nantes, the management of which is directly dependent on the functionality of the Nantes Ring Highway. The Stade de la Beaujoire —Louis Fonteneau of Nantes Football Club (Nantes FC), with a capacity of 35,322 spectators, is an important sporting infrastructure in Nantes city [57]. In the case that an accident occurs in the stadium, spectators will need the rapid intervention of emergency services, and the on-site services may not be sufficient for all spectators. With the absence of essential medical equipment for all possible patients, victims must wait for the services of the EMS (SMUR in Nantes). The nearest hospital to Nantes FC is 2.2 kilometres away in a straight line, with a driving distance of approximately 6.4 kilometres. The fastest route for an ambulance from the hospital to the club is identified in green in Figure 7, which crosses the section between the "Porte de la Chapelle" and the "Porte de la Beaujoire". However, this section is the most vulnerable part of the Nantes Ring Highway in terms of flooding. For example, in March 2020, this section was closed on both sides for at least 2 days [58]. In this situation, the ambulance could use the alternative route suggested by DIRO [59], as shown in Figure 7 in red. This would increase the distance and time for the ambulance route, resulting in delays in rescues.

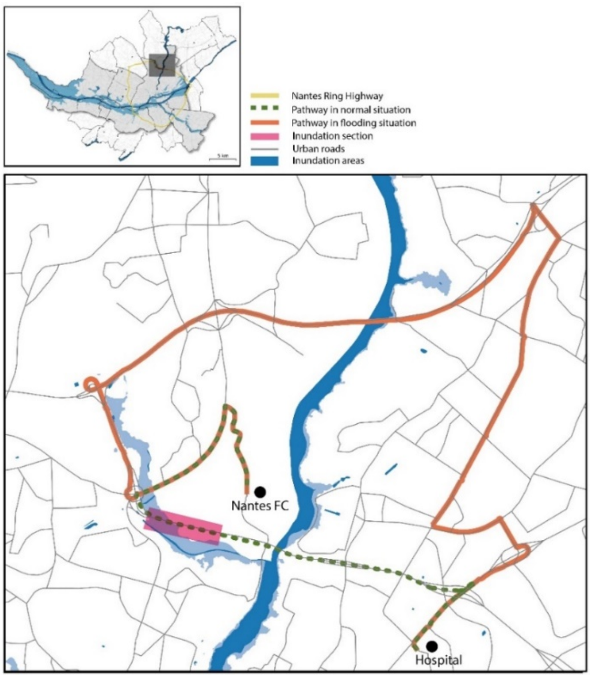

Figure 7. Pathway of the EMS ambulance in a normal situation and in a flooding situation.

The probability of such a situation is rather low, but the scenario helps to better understand the impact of road disruptions on ambulance performance and on rescue services.

In considering the ambulance travel speed regulations and using GIS calculations, we found that the ambulance delay was 5.64 minutes in case of a flood on the HI (Table 2). Taking a heart attack as an example of a possible emergency, we assumed that victims needed rapid defibrillation as offered by the EMS. According to CARDIAC SCIENCE, the survival rate is reduced by at least 10% (from 100%) for each minute without medical treatment [60]. This means that the survival rate for victims would decrease from around 65 % to 34%. This simplified calculation does not consider potential factors that could further negatively influence the travel speed of ambulances, such as possible traffic on the alternative route.

Table 2. Comparison between normal situation and flooding situation. Source: Formation ambulancier [61].

Maximum Travel Speeds of Ambulances in France			Normal Situation		Flooding Situation	
Road types	Speed (km/h)		Distance (m)	Travel Times (m)	Distance (m)	Travel Times (m)
Zone 20/30	50	Details of pathway	1022.4	1.23	1843.3	2.21
Zone 50	70		839.04	0.72	2844.68	2.44
Urban road	90		2027.02	1.35	4127.85	2.75
Highway	130		2549.2	1.18	5879.7	2.71
/		Total	6437.66	4.47	6437.66	10.11
		Survival rate	65%		34%	

The result shows that a failure in HI function can significantly affect the performance of the EMS system and thus affect human safety. Following the identification of the cascading effects sequence, the managers can find improved modes to solve failure modes as soon as possible. Moreover, the improvement measures should be adapted to both systems and be understood by the involved actors. In the example presented, the Nantes Highway System can limit the traffic flow on the alternative roads to ensure that ambulances can pass through quickly. The EMS system can also adapt its own operations to enable victims to be treated more quickly, for example by sending ambulances from other EMSs. In any case, it is important that the managers of both systems understand and communicate with each other to be able to adjust their operations when anticipating cascading effects.

Similarly, during a health crisis such as the COVID-19 epidemic, EMS and HI managers need to understand the direct and indirect impacts of the scarcity of resources on both systems in order to implement disaster prevention and performance recovery measures, etc. EMS managers can mobilise external reinforcements for accidents in HI, for example using temporary workers, students, retirees, and volunteers. Road infrastructure managers could supply temporary safety vehicles to replace some of the functions of the EMS system.

5. Conclusions

Urban cascading effects in multi-domains could go beyond the temporal and spatial limits of the original hazard due to the interdependence of social-infrastructural systems and that of their components. Urban resilience is directly dependent on the functional interdependence of social-infrastructural systems.

The SIIR methodology starts with a perspective of dependencies and interfunctions to investigate the interdependencies of two urban subsystems. The SIIR framework is characterized by two steps:

1. Systems components analysis and functional analysis to study (in detail) the characteristics and function of the systems by identifying all components (four categories: “Collective actor”, “Individual actor”, “Physical structure” and systems’ “Main function”) in the two studied systems and analysing the functions of these components and the components served by these functions.

2. Cascading dysfunctions analysis and failure modes analysis for evaluating potential effects due to hazards, by:

- Analysing cascading effects based on the assumed scenario to identify the sequence of component failures and to clarify the causes and consequences.
- Identifying the failure modes of each affected component and how they are related to implement resilience.

This study demonstrates the interdependence of urban socio-infrastructure subsystems. The continuous observation of the development of the disaster event from the standpoint of cascading failure function helps to better understand the interdependence resilience of social-infrastructural systems and finally to better manage the urban sub-system.

The proposed SIIR framework is applied to HI–EMS systems and provides a guideline to managers for improving the functional interdependencies of urban subsystems. The SIIR framework starts with a perspective of dependencies and interfunctions for investigating the interdependencies of two urban subsystems. The suggested methodology can be applied to any subsystem in urban areas (organisational-government and nature-energy flow systems) for all types of hazards. Inevitably, it would have different actors, functions, failure modes, and improvement modes. Therefore, this methodology can support decision-makers in the management of emergencies and can be adapted to local context.

Future research will aim to test the interdependence approach between different urban subsystems and to study the interdependence between three or more subsystems.

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Appendix A

The appendix lists all actors of the two studied systems and their principal functions.

Categories		Actors	Principal Functions
HI	Human actors—collective	Managers	Ensure the daily operation of HI, providing comfort and safety to users, through the management and maintenance of roads
		Project managers	Project management of investment operations (public or private) and management of the noise observatory of the HI and of the flood-warning project for the eastern part of Highway Infrastructure
		State partners	Define and fund projects
		Safety observation	Produce and disseminate information on road safety
		Collective users	Organize mobilisation for different activities (posters, couriers, travellers, merchandise, health emergency services, etc.)
	Human actors—individual	Individual users	Mobilise different activities (posters, couriers, travellers, merchandise, health emergency services, etc.)
	Non-human actors—physical structures	Individual staffs	Work for affiliated institutions to ensure system functions
		Rest areas	Supply energy and fuel to vehicles and provide material and spiritual needs to users in dedicated service areas
		Counting regulation	Provide information on road traffic
		Access regulation	Improve traffic flow on the Highway Infrastructure by controlling the injection of vehicles

Categories		Actors	Principal Functions
HI	Non-human actors—physical structures	Green spaces	Protect water resources and enhance ecological transparency
		Maintenance and intervention centre	Provide support to state institutions (such as the police), cleaning, ordinary and extraordinary maintenance (road signs, lighting, localised damage, etc.)
		Drainage system	Remove surface water from the roads as quickly as possible (drainage) to ensure safety with minimum nuisance to users, implement effective subsurface drainage to maximise the lifecycle of infrastructures, minimise the impact of run-off on the external environment in terms of flood risk and water quality
		Physical structures	Enable mobility by the construction of horizontal structures or structures in elevation or in excavation
		Vehicles	Transport passengers and goods on the ground
	Non-human actors—functions	Transport function	Serve individual and collective users in mobility: passenger, freight, postal, or auxiliary transport services (including medical services)
EMS	Human actors—collective	Manager structure	Organize the first emergency care of patients and that after transport to the nearest indicated health structure, or organize inter-hospital transport
	Human actors—individual	Doctors	Manage patients for the development the first diagnosis
		Nurses	Provide first aid to patients in case of medical emergencies in a public or private context, stabilise patients, and enable transport
		Ambulance drivers	Provide transport for medical teams and patients, ensure logistical activities during missions, monitor vehicle maintenance
		Other service staff	Work for affiliated institutions to ensure system functions
		Patients	Receive medical treatment
	Non-human actors—physical structures	Land vectors	Provide mobility of the SMUR teams (including the necessary equipment) and of patients from their location to the hospital, or also inter-hospital transfers
		Aerial vectors	Provide mobility for the SMUR teams (including the necessary equipment) and of patients from their location to the hospital, as well as inter-hospital transfers
		Medical equipment	Provide the equipment recommended for pre-hospital monitoring
	Non-human actors—functions	Primary and transfer missions	Offer emergency medical services to patients

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