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Risk-Based Approach for Informing Sustainable Infrastructure Resilience Enhancement and Potential Resilience Implication in Terms of Emergency Service Perspective

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Abstract: Infrastructure resilience ascribes into the United Nations' agenda for sustainable development. The more information supporting infrastructure resilience enhancement, the higher chance that it will be done objectively and effectively, and especially in a sustainable way. In spite of many different approaches and data sources, there is a lack of information that respects the emergency service point of view. The main research objective is to investigate factors determining sustainable infrastructure resilience enhancement that reflects direct protection of the most important values (human life and health) by connecting multiple variants of infrastructural resilience corresponding with the voice of emergency service and based on real data risk assessment. The methodology consists in formulation of a reference model for informing sustainable infrastructure resilience enhancement, risk assessment for infrastructure safety in terms of emergency service perspective and risk-based rationalization of the enhancement manners. The model stems from urban resilience and city resilience. Its components are physical resilience, structure and setting resilience, organizational resilience, economic resilience and legal resilience. These elements are related to hazards' character, operational specification and resource requirements, operationalizing the model in terms of emergency conditions. For risk rationalization purpose, 1,255,826 events which occurred in 2015–2019 are analysed. Nearly 70% of the summary value of infrastructural risk is related to residential buildings and other categories of objects (garages, auto repair shops, monuments of material culture, objects of natural environment, hydro-technical objects, military objects, ex-territorial objects and others). Sustainable-related manners are specified notably for abovementioned buildings and objects. Deepening the analysis of cognitive limitations gives ideas for further research.

Keywords: resilience; emergency; infrastructure; resilient infrastructure; risk; sustainability

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1. Introduction

Sustainable development is a prime direction of the United Nations (UN) in the time framework of 2015–2030. Seventeen Sustainable Development Goals (SDGs) and 169 targets, which stem from the UN direction, reflect current issues transforming our world. UN Resolution 70/1 in 2015 [1] states that the development should be conducted in a sustainable way, to care for people in all forms of their existence, to protect the planet against natural and man-made hazards, to increase a common prosperity and to spread peace among nations and societies. A chance to achieve these objectives in the assumed time horizon strongly depends on partnership and cooperation between all world developers.

SDGs describe a holistic operational approach and concern all safety-related dimensions of the development. Consequently, they respect an entire spectrum of values which are important nowadays—values that are worth protecting nationally and internationally. Nevertheless, in the context of their unity, some of the values seem to be more important than others. This fact is highlighted when the most serious hazards occur. During floods (e.g., Italy 2019, Great Britain 2020), wildfires (Australia 2019, Spain 2019, etc.), hurricanes (e.g., Western Europe 2020) or pandemics (the whole world 2019–2020), human life and health (as well as property and environment in a scope of people's survival needs) gain in importance. Moreover, such events prove what is the most crucial for people existence in general, regardless of parentage, pigmentation, creed, ethnicity or beliefs.

Focusing on human life and health, building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation (SDG9), making cities and human settlements inclusive, safe, resilient and sustainable (SDG11) as well as taking urgent action to combat climate change and its impacts (SDG13) are worth addressing. The three interpenetrate each other and precisely concern sustainable infrastructure resilience enhancement, which is a core element of these goals' specification.

It is worth mentioning that current infrastructure resilience research concerns various resilience variants and presents points of view of disaster managers, ecologists, urban designers, local community representatives, etc. [2–4]. All of them can be implemented to increase infrastructure capability to rebound from threat circumstances, to absorb external shocks, to adapt to dynamic environmental changes and to modify organizational structure, operational mechanisms and external relations with infrastructure operators [2]. However, in most cases, they deal indirectly with the most important, utilitarian values and marginalize a voice of entities that protect the values in emergency conditions (direct danger to human life, time stress, etc.). It states a serious gap in infrastructure resilience theory (Gap 1).

Emergency service mindset for sustainable infrastructure resilience enhancement (SIRE) may shed light on a direct protection of human life and health. To express the sustainability character, a relevant approach should be based on established resilience concepts, respecting multiple resilience variants and adapting them to emergency service purposes. This can give additional, valuable research input to resilience science and sustainability science, especially in relation to UN Sustainability Development Goals [5]. Such proceeding will be an example of a holistic manner, with a high potential to identify extraordinary facts about SIRE [6,7]. Furthermore, it will face the next gap (Gap 2)—focusing mostly on selected resilience issues in emergency discussion [2,8–11], when a comprehensive analysis is characterized by a great potential to obtain new ideas for infrastructure resilience enhancement [12,13].

Current emergency perspectives of SIRE boil down to life-safety and collapse prevention, where the primary objective is to design the minimum level of threat (risk) to be tolerated. This has its expression in building codes and other formal regulations [14,15]. From a practical point of view, it is advisable to ensure that the emergency service approach for SIRE is operationalized on the basis of real data (real level of risk which is not tolerated every time), in an exact connection with the most serious kinds of events (hazards) affecting the most important utilitarian values. This is relatively hard to achieve using only codes and formal regulations. So, the third gap (Gap 3) of the research can be noticed—a lack of bottom-up manners using real emergency data which present not minimal acceptable but real level of risk to rationalize SIRE manners. As far as this point is concerned, a risk-based approach (especially quantitively-specified) [16,17] with a rationalization module is desirable. Operationalizing emergency service data can be significantly useful to prioritize the SIRE manners in terms of risk assessment results [18].

Preconcluding, the main research objective is to investigate factors determining sustainable infrastructure resilience enhancement in emergency service mindset. The specific objectives may be outlined as follows:

1. To elaborate a reference model for SIRE which deals directly with the most important, utilitarian values and considers mindset of entities that protect the values in emergency conditions (direct danger to human life, time stress, etc.);
2. To assess infrastructure risks respecting emergency conditions in a holistic way;

3. To formulate the risk-rationalized manners for SIRE using real data related to emergency interventions.

This paper proposes an approach which stems from multiple resilience concept, morphological analysis and quantitative risk assessment method. The sustainability orientation allows us to evaluate the resilience concepts with the emergency-related one. The morphological approach gives foundations for identification of the riskiest categories of infrastructural objects. The risk assessment concretizes the identification by the use of real data. For this purpose, data collected by the State Fire Service (SFS) entities in 2015–2019 is implemented. Analysis of 1,255,826 events serves to rationalize SIRE manners. The paper takes into account the emergency service point of view that is relatively rare in infrastructure sustainability and resilience research. The point of view is expressed by direct use of the emergency service data base. Relevant classes of consequences correspond with crucial emergency operational measures (e.g., hazard zone dimension, extinguishing intensity, number of victims, required resources). Furthermore, three core emergency service operational issues determine SIRE manners. There are hazard attributes (common exposure to population, a wide spectrum of classes of consequences and cascading potential for development), operational specification (urgency, continuity and substitutability of tasks, operations and activities) and resource requirements (adequacy, limitation and substitutability of resources). Authors verified the manners also with respect to their operational experiences related to emergency services.

Due to its practicality, the research delivers an output useful for decision-makers responsible for BRI SIRE. It operationalizes SDG9 (in terms of development of sustainable and resilient infrastructure to support human well-being for all), SDG11 (regarding creating conditions for making housing, public services, cultural and natural heritage safe and effectively protected against hazards) and SDG13 (strengthening resilience and adaptive capacity to climate-related hazards and natural disasters in all countries). As buildings and infrastructure must withstand extreme events to be named resilient [19], this study gives practical information on how to do this in a sustainable way.

2. Theoretical Background

2.1. Sustainability and Resilience of Infrastructure—General Premises

Bibri and Krogstie state that sustainability is a difficult concept which relates to multiple areas of socioecological system operation [20]. Synthetically, sustainability means the ability to maintain entity (system) at a certain (desired, optimal, rational, etc.) level of operation. In general, sustainability concerns chronic types of threats [21]. The long-term specification of sustainability goals is expressed by the focus on social, environmental and economic issues in terms of increasing quality of life for the present and the future generations [22].

The infrastructure context of the research allows us to reduce the general perception into urban sustainability and sustainable city phenomenon, especially when the sustainability approach is a perspective way for cities to better cope with existing and future conditions [23]. Consequently, infrastructure sustainability is an ability of the infrastructural dimension of the city (urban area) to improve the quality of inhabitants' life as well as efficiency of urban services and operation. Simultaneously, it respects economic, social, environmental and cultural needs for current and future generations [24]. A city which fits this definition can be named a sustainable city.

Focusing on resilience, it broadly means the capacity for quick recovery from widely perceived difficulties and obstacles. Typically, it concerns acute types of threats and treats about broad response due to the entity (system) operation [21].

Different ideas for resilience shed light on multiple dimensions of this issue. It can be perceived widely, in the context of vulnerability [25], adaptation to hazards [26], general characteristics (robustness, stability, redundancy, diversity, flexibility, modularity, self-organization, efficiency, etc.) and management stages (planning/preparation, absorption, recovery and adaptation) [27] and is implemented in many cities around the world [28,29]. More selectively, Bec, Moyle and Moyle connect it with economic and psychological factors [30]. McEvoy states that climate resilience should be dealt with as an element of urban development. An influence also on the infrastructure sphere may be noticed [31,32]. This is especially important for critical infrastructure protection [33,34].

Many directions for scientific exploration of resilience can cause confusion about its essence when infrastructure resilience is described. To overcome this cognitive obstacle, as infrastructure is an integral component of the city, there should be a strong correspondence between city resilience and infrastructure resilience definitions. Especially, when "infrastructure systems are widely acknowledged to be a lifeline in the community and play a pivotal role in sustaining (...) urban resilience and sustainability" [35]. Therefore, city resilience "(...) is defined as the capacity of individuals, communities, institutions, businesses, and systems within the city to survive, adapt, and grow no matter what kinds of (...) stresses and (...) shocks they experience" [36]. In conclusion, infrastructure resilience definition expresses the capacity to withstand in case of, desirably, a whole spectrum of stresses and shocks (e.g., hurricane, fire, explosion). This utopian assumption is rationalized by Linkov at al., who boil down the meaning to increase the withstanding capacity in accordance to at least some of the consequences of the threat occurrence, to ensure continuity of the most important functions, to minimize the reconstruction time and to ensure that infrastructure will be more resilient for such kind of threat in the future [37]. These can be done by increasing "(...) the ability to prepare and plan for, absorb, recover from and more successfully adapt to adverse events". [38].

It is worth emphasizing misunderstandings which concern sustainability and resilience. Marchese at al. [39] present three important concepts, which describe their mutual relations. Firstly, resilience is dealt with as a component of sustainability. From the operational point, when the system resilience increases, the system is more suitable. However, this relation does not need to be bilateral in all cases. Secondly, sustainability is a component of resilience. In this meaning, when the system sustainability increases, the system is more resilient. Analogically to the previous approach, the relation does not need to be bilateral as well. Thirdly, sustainability and resilience are separate objectives.

Each abovementioned concept has relevant proponents and opponents, related to the area of application [39]. This highlights a complexity of analysed issues and shows potential chances for SIRE to meet global sustainability goals. Although from the emergency perspective the resilience seems to be more important than sustainability (at the highest level of generality), one concept can be implemented to the other, and vice versa. So, synergy effect might be generated [40] and used for SIRE in terms of emergency conditions (filling Gap 1).

2.2. Building Resilient Infrastructure in a Sustainable Way

Based on general premises of sustainability and resilience of infrastructure, we can conclude that relations between sustainability and resilience are bidirectional—sustainability can influence the system resilience and resilience may determine the system sustainability. Many ideas prove this in theory and practice. In accordance with the UN development framework [1], the infrastructure resilience is connected with sustainable urban operation [41,42], and more precisely, with sustainability in the light of extreme events (e.g., natural hazards) [43]. Moreover, Kloosterman, Veeneman and van der Hoek conclude that sustainable societal infrastructure influences conflicting claims of infrastructures [44], which proves a strong connection between resilience and sustainability in the analysed context. Infrastructure is an element of local society and is connected with other elements (resources, processes, people, institutions, activities) [35,45] Thus, a sustainable way of thinking about infrastructure resilience enhancement relates to multiple groups of environmental, social and economic indicators [46]. The prime challenge is to connect sustainability and resilience into one concept which will be useful for SIRE purposes in the light of the emergency mindset. Sustainability holistic specification seems to face Gap 2 and to state a preliminary intention of the sustainability–resilience connection. This is why, in the described context, the connection can be dual. Firstly, direct and indirect associations with SDG9, SDG 11 and SDG13 are noticed. Secondly, sustainability can constitute a comprehensive framework for SIRE, order multiple resilience variants and create a coherent notion of SIRE.

At this stage, one can expect a lack of tools and methods to evaluate and improve such an infrastructure resilience concept [38]. Following Gap 3, the bottom-up manner using real emergency data which present not minimal acceptable but real level of risk is desired. Its elaboration will allow to create foundations for risk assessment which is very typical for building (infrastructure) resilience analysis [14,47,48]. Furthermore, the risk-based approach can rationalize manners for SIRE. Even if its holistic specification can give unique possibilities for identification of extraordinary findings, focusing on many unimportant determinants and other kinds of elements in one analysis requires often much workload (especially when a strong variant of morphological analysis is taken into account) [49,50]. When the riskiest areas of research are considered, there will be a great chance to aim only at the most important SIRE issues.

Moreover, "it can be difficult to validate or generalize what effective resilience means in practice" [51]. Thus, successful exploration of resilience by various risk management activities proves the risk usefulness in terms of resilience analysis and measurement. When "globally or nationally accepted thresholds to characterize high or low resilience do not exist" [52], risk can indirectly express this issue.

3. Materials and Methods

3.1. General Cognitive Model

Specific research objectives play a reference role in a general cognitive model composition. Figure 1 presents the model elements and relations between them.

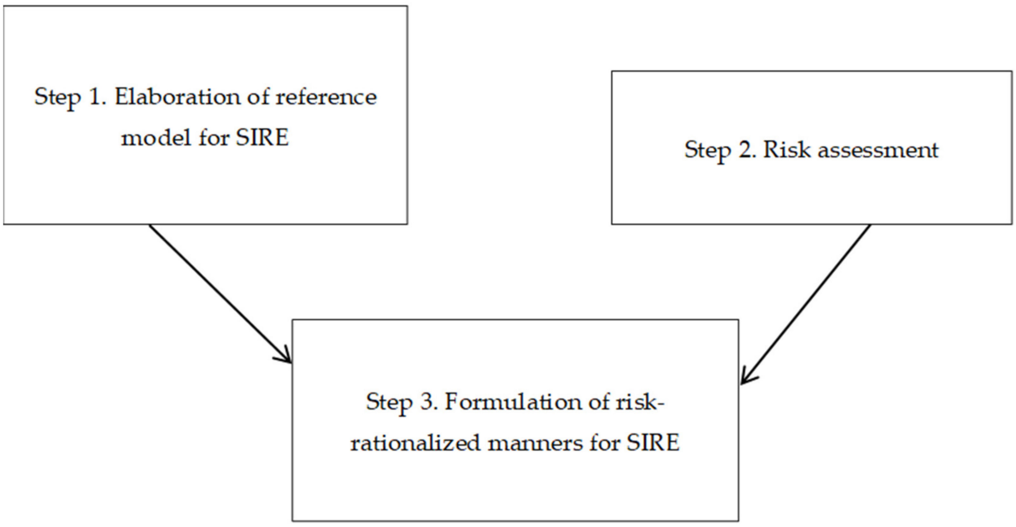

Figure 1. General cognitive model of the research.

The general cognitive model of the research orders particular steps of the research methodology. It serves as a simplified structure of relevant activities which are planned to achieve specific research objectives. Each step is dedicated to a relevant specific objective and can be developed as follows.

Step 1. Elaboration of SIRE model

From the viewpoints of science and practice, a process of SIRE needs to be recurrent. Thus, the reference model for infrastructure resilience is desired. Due to UN Resolution 70/1 as well as sustainability and resilience essence, the model should:

1. Correspond with UN directions of the world development and relevant challenges;

2. Refer to systemic character of the infrastructure which is an element (subsystem) of the entire community (system of subsystems);
3. Refer to sustainability essence;
4. Be concrete (possible to be measured, giving additional information for risk assessment purposes).

The model formulation will be helpful in SIRE manners' design. Then, all of the model elements should be taken into consideration from the holistic point of view.

Step 2. Risk assessment

The second step requires collection of information that allows for the creation of a situational picture on infrastructure safety. The more detailed the information, the more effective is the process of the risk assessment. So, the information should meet the following requirements:

1. To be based on real data;
2. To concern kinds of events affecting the most important, utilitarian values;
3. To be confirmed by legal safety authorities (institutions);
4. To be actual (approximately 5 years);
5. To be implementable to a general risk assessment method.

The last requirement presents a prime reason for the information collection. As safety is an intangible phenomenon, risk can play the role of safety measure [16,17]. This justifies an implementation of risk assessment into a collection of information concerning infrastructure resilience (resilience understood as an aspect of safety). So, a risk assessment method (adequate for the research assumptions) should be used.

Step 3. Formulation of risk-rationalized manners for SIRE

The manners for SIRE should stem from infrastructure categories which are taken into account in the risk assessment. A correspondence to the SIRE model is also required. So, in terms of methodological effectiveness, formulation of the manners should be done in a holistic way, considering all the categories, in light of all elements of the model.

Such use of holistic approach can result in a relatively complex catalogue of the manners. This is why an evaluation technique is simultaneously needed to rationalize the manners and make their catalogue more implementable to the practice. In a reference to previous requirements, the technique should allow for the rationalizations of the manners regarding the risk assessment results.

3.2. Operationalization of the Model Elements

3.2.1. Elaboration of Reference Model for SIRE

Theoreticians and practitioners have been looking for a universal resilience model for many years [53,54]. So far, several solutions that can be used for SIRE analysis have been developed. Following other researchers who carried out a widely designed literature exploration, the resilience building should consider stakeholders' involvement regarding such aspects as collaboration and networking, awareness and commitment, learning as well as training and preparedness [36], giving reference to the resilience maturity model [55]. This catalogue can be developed by "community-based risk assessments, disaster and risk reduction; integrated urban planning, development and logistics; integrating solutions into all aspects of city management (system solutions); addressing most vulnerable groups; financing, including the private sector; cooperation and implementing process on the ground; decision supporting tools, legislation and flexible implementation networks; political will; integration of environmental aspects: green urban economy, urban agriculture, green infrastructure, renewable energy" [55,56]. This is the same as the Rockefeller Foundation framework, which describes the resilience concept using 4 categories, 12 indicators, 48–54 subindicators and 130–150 variables [57]. As the infrastructure resilience is an integral part of the community resilience, the first is determined by factors ascribed into such areas of operation as science and technology, community organization and institutes, the natural environment and social-economic status [58], environmental component, public service and management system [59]. The factors can also be related to the urban resilience principles: response and adaptive capacity, participation and inclusiveness, spatial planning, social equity and learning [60] and in the next approach to urban structure and setting resilience, physical resilience, sociohuman resilience, economic resilience as well as managerial, institutional and legal resilience [19]. In addition, they match the critical infrastructure elements resilience assessment areas (CIERA model areas: technical resilience and organizational resilience) [48]. A cognitively interesting mindset relates to a quantitative method for assessing resilience of interdependent infrastructures. It connects the infrastructure resilience with absorptive, adaptive and restorative capabilities, highlighting rather general directions for SIRE manners design than concrete resilience variants, kinds or areas [6]. The system resilience analysis can be carried out with the respect of logical and physical resilience, personal resilience, organizational resilience and cooperative resilience as well [7].

Many ideas for the infrastructure resilience concept indicate different approaches, that fragmentarily or fully meet each other. Their coherence stems from the same object of analysis and all of them include infrastructure component (directly or indirectly). Nevertheless, particular propositions are based on relevant foundations and marginally match the emergency view on SIRE. Given that infrastructure resilience enhancement manners need to be designed in a sustainable way, it is required to connect chosen resilience areas of analysis (variants, indicators, etc.) into one reference model for SIRE. As far as Gap 1 and Gap 2 are concerned, the urban resilience concept [19] can be a starting point to achieve this goal after emergency and sustainability concretization. Its critical implementation into the research framework allows to formulate the model, as it is presented in Figure 2.

1. Physical resilience: in general, particular infrastructure elements (buildings, systems, subsystems, installations, etc.) need to be resistant to all kinds of hazards, the current ones and provided ones. As a full spectrum of natural disasters and man-made hazards is concerned, the infrastructure physical characteristics should be adequate for the hazards' specification and development mechanisms. From a practical point of view, this should ensure at least the lowest accessible level of quality for infrastructure functionalities that are most important currently and are said to be significant in the future [61,62].
2. Structure and setting resilience: infrastructure (and its particular elements) cannot be considered separately from other infrastructures and their elements. Relevant interconnections show that they are interdependent and, mainly, the infrastructure (or a system of infrastructures) is as resilient as its weakest element. This is why considering the interconnections is vital for effectiveness of the resilience building process to ensure a proper level of human life quality [63], just like the cascading effect of hazards occurrence [64].
3. Organizational resilience: infrastructure is mostly operated by people and they commonly constitute an organization (of work, institutions, etc.). So, sufficient organizational resilience is crucial to keeping the highly desirable synergy effect between infrastructure and staff in the organization, without regard for operational circumstances (in terms of hazards and operational threats that occur currently and could occur in the future) [65]. Following Rehak, this purpose can be met by focusing on risk management, organizational innovation processes and educational and development processes [66].
4. Economic resilience: Every sustainability- and resilience-centred operation needs resources which are finally convertible into financial capabilities of the infrastructure operator, owner and/or supervisor. It has a primary role in pre- and postevent activities, significantly determining real capabilities for prevention as well as infrastructure reconstruction and recovery [19].
5. Legal resilience: formal framework for SIRE is put to the test especially when some unexpected event occurs. When inadequacy to actual situational conditions is noticed, legal acts are generally changed. As it often takes some time and is loaded with merit and technical defects, legal resilience measured by flexibility and generality is required. It is crucial in the context of chronic types of threats that affect social, environmental and economic issues of human existence and operation.

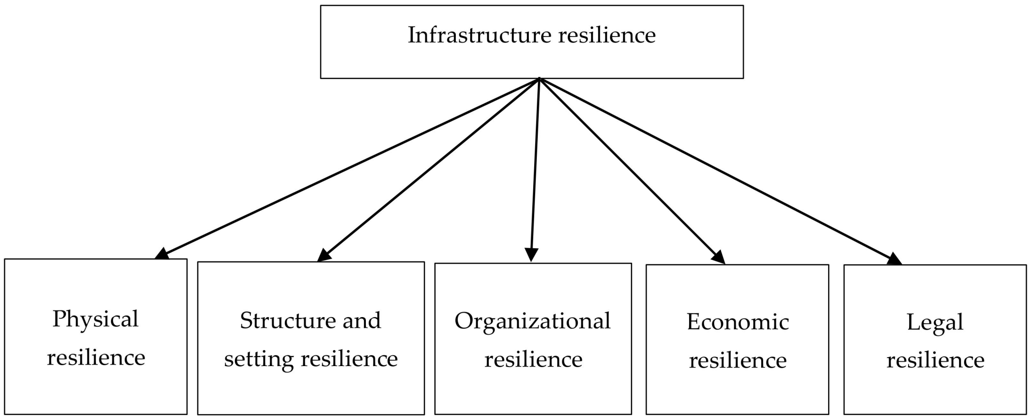

Figure 2. Reference model for sustainable infrastructure resilience enhancement (SIRE) (RM-SIRE).

The model gives general directions to formulate infrastructure resilience enhancement manners in a sustainable way. Considering its composition, significant variants of resilience are connected, facing Gap 2. Moreover, the model is related to community resilience (as a superior system where infrastructure is a relevant subsystem) matching to all stages of disrupting event (prepare, absorb, recover, adapt) and major subcomponents of any system (physical, information, cognitive and social) [67]. In addition, it presents a multidimensional view into sustainable connection of multiple variants of resilience (physical, structure and setting, organizational, economic, legal), strongly ascribing to SDG9, SDG11 and SDG13 [1]. Owning to its universality, its potential is expressed by a possibility of implementation in many different cognitive (theoretical and practical) mindsets for SIRE. The perspective of emergency service can be one of them (Gap 1). However, the model concretization needs to meet characteristic aspects of the chosen perspective, preferably in a holistic way (e.g., a morphological approach).

3.2.2. Risk Assessment

Resilience generates learning processes to improve the system capacity for dealing with hazards and the processes are supported, among others, by raising risk awareness [68]. For this reason, risk assessment can be understood as a way to find out a general view on the resilience needs, also in the context of emergency service and notably when resilience and risk have been commonly taken into consideration [69,70].

Considering Gap 1 and Gap 3, it is not so critical to have information about the resilience level as the risk level. Theoretically, very resilient infrastructure objects can be seriously affected by hazards and need still additional effort to increase their resilience. So, generally, high resilience level does not inherently imply low risk level. Risk awareness influences knowledge about directions to increase the resilience and this is crucial from emergency service which operates, controls, investigates and regulates infrastructure conditions. Consequently, risk assessment can be used for SIRE rationalization.

Lack of bottom-up manners using real emergency data to rationalize SIRE manners (Gap 3) justifies searching for data and information collected directly by emergency service. That is why the data base from SFS is implemented [71], especially when real data-based solutions give generally the most exact foundations for the risk assessment [72].

SFS is a prime, executory societal security institution in Poland. Because it organizes the state firefighting rescue system (SFRS) [73], it is said as the crucial emergency entity in the state. Usefulness of the data base is emphasized by the fact that SFS is the main institution directly dedicated to active infrastructure protection against societal security hazards (natural disasters and man-made hazards). Regarding this, it describes all events when serious hazard occurs and human life, health, property and environment are in danger. This states the base to be a reference in the analysed context, notably when data collection process is structured, formalized and obligated by the law [74].

The data base is comprised of two categories of events. The first category contains fires (F), which are understood as uncontrolled combustion processes in undesirable places. The second category mentions local hazards (LH), which means any kind of negative phenomenon apart from fires and state danger to people, property or environment, resulting from civilization development, people operations or natural disasters [74].

Table 1 collects information about particular classes of consequences ascribed to particular categories of events.

Table 1. Classes of consequences in State Fire Service (SFS) data base.

Consequence Measure (C)	Class of Consequence	Categorization Premises
1	Small F (S/F)	burning area of 70 m^2 or volume of 350 m^3 or forests, fields, peat bogs and wasteland at area lower than 1 ha events which require maximum 4 extinguishing jets
2	Medium F (F/M)	burning area from 71 m^2 to 300 m^2 or volume of 351 m^3 to 1500 m^3 or forests, fields, peat bogs and wasteland at area from 1 ha to 10 ha or events which require from 5 to 12 extinguishing jets
3	Big F (F/B)	burning area from 301 m^2 to 1000 m^2 or volume of 1501 m^3 to 5000 m^3 or forests, fields, peat bogs and wasteland at area from 10 ha to 100 ha or events which require from 13 to 36 extinguishing jets
4	Very big F (F/VB)	parameters that exceed values for F/B
1	Small LH (LH/S)	scope-limited events, conducting without the use of specialized equipment (excepting measurement instruments which identify no agents)
2	Locally-limited LH (LH/L)	urgent failures of machines, instruments, vehicles and another object, when: maximum 1 victim is dead or maximum 3 victims are supported by medical rescue teams (from outside SFRS) or maximum 4 fire service teams (12–24 rescuers) participate in the action
3	Medium LH (LH/M)	urgent failures of machines, instruments, vehicles and another object, when: 2–3 victims are dead or 4–10 victims are supported by medical rescue teams (from outside SFRS) or maximum 5–12 fire service teams (15–72 rescuers) participate in the action or 1 special rescue unit supports the primary rescue resources
4	Big LH (LH/B)	urgent, unforeseen event, which refers to mass danger to human life, health, property or environment, exceeds quantitative values of LH/M and requires SFRS resources in strength of 1 battalion (to 480 rescuers)
5	Catastrophic LH (LH/C)	urgent, unforeseen event, which refers to mass danger to human life, health, property or environment and requires SFRS resources in strength of at least of 1 battalion (at least 480 rescuers)

Source: own elaboration based on [74].

Particular classes of consequences reflect emergency service information needs (e.g., size of the hazard zone, required resources, number of victims) and are described in SFS operational guidelines [75]. The class of consequence of the event is elaborated by the officer in charge of the emergency action directly during the action with the use of the guidelines. Then, information about the event class of consequence is reported to the SFS data base by the officer.

Division of all negatively-perceived events into particular consequence classes opens an opportunity to implement the data into general risk assessment method, when risk is "(...) a derivative of accidents frequency and relevant results (consequences)" [75] and corresponds with other risk assessment methods dedicated to infrastructure safety [76]. The data base gives both required factors and the risk can be assessed with the use of the following equation:

$$RY_{(F/LH)i,j} = PY_{(F/LH)i,j} \times C_i \tag{1}$$

where: $RY_{(F/LH)i,j}$: F/LH risk index for i-class of consequences and j-category of infrastructural objects in Y-year; $PY_{(F/LH)i,j}$: frequency of events for i-class of consequences and j-category of infrastructural objects in Y-year; C_i: consequence measure which corresponds to i-class of consequences.

Infrastructure can be divided into particular categories of infrastructural objects (j-category of infrastructural objects), indicating more precise information about emergencies in the analysed period of time. SFS data base gives such kind of division, which is displayed in Table 2.

Table 2. Categories of infrastructure objects.

Code	Name of the Category	Kinds of Infrastructural Objects in the Category
O1	Public utility buildings	Office administration facilities, banks Research and education facilities (incl. didactics buildings, schools, kindergartens) Health service facilities (incl. hospitals, sanatoriums, social care homes, clinics, childcare facilities) Commercial-service facilities (incl. shops, department stores, gastronomical places, wholesale warehouses) Passenger service facilities (incl. railway stations, bus stations, river and marine ports) Spectacle, entertainment and sport facilities Religious and sacral facilities Museums, antique building museums, exhibitions, galleries Libraries, archives Penitentiary facilities Other Public utility buildings
O2	Residential objects	Hotels and flophouses Orphanages Dormitories, student residence halls Barracks Retirement homesHoliday houses, guesthouses Shelters Single-family houses (incl. semi-detached houses and terraced houses) Farms Others
O3	Production objects	Factories Outbuildings Social objects Technological installations outside the buildings Technological machines and devices Administration facilities Pipelines
O4	Warehouse objects	Warehouses and shelters in production areas Warehouses and shelters (excepted O1 and these in production areas) Warehouses and shelters in areas dedicated to people presence Building sites and building backrooms Storage squares Containers and tanks Fuel stations and gas stations Fuel bases and gas bases

Table 2. *Cont.*

Code	Name of the Category	Kinds of Infrastructural Objects in the Category
O5	Agricultural buildings	Buildings and installations for processing of agricultural produce Livestock, breeding and warehouse buildings, greenhouses Farm buildings
O6	Others	Garages Auto repair shops Monuments of material culture (not buildings) Objects or set of objects of natural environment Hydrotechnical objects Military objects Exterritorial objects (incl. Consulates, embassies) Others

Source: own elaboration based on [74].

Table 3 presents numbers of events that occurred in 2019 as a statement from the SFS data base. It proves the base potential in the light of risk assessment, as an exact relation between event frequency ($PY_{(F/LH)i,j}$) and their consequences (C_i) is noticed.

Table 3. Numbers of events in 2019.

C_i	Class of Consequence (*i*)	Category of Infrastructural Objects (*j*) *					
		O1	**O2**	**O3**	**O4**	**O5**	**O6**
1	F/S	2240	30,997	2023	827	1947	12,847
2	F/M	73	964	310	174	704	400
3	F/B	12	32	56	40	100	26
4	F/VB	5	1	26	12	24	3
	Totally:	2330	31,994	2415	1053	2775	13,276
1	LH/S	6601	20,670	462	265	273	7800
2	LH/L	10,839	75,288	2724	713	3631	66,676
3	LH/M	301	936	185	159	31	461
4	LH/B	6	15	3	1	1	26
5	LH/C	0	0	0	0	0	0
	Totally:	17,747	96,909	3374	1138	3936	74,963

* the objects are codded in Appendix A.; Source: own elaboration based on [71].

Use of Equation (1) allows us to recalculate values in Table 3 into risk indexes for particular categories of infrastructural objects in the analysed year. Table 4 shows results of direct multiplication of $P2019_{(F/LH)i,j}$ and C_i.

To meet the research objectives and increase the awareness about infrastructural safety during the last five years, additional calculations to estimate yearly-average risk index is required. Equation (2) presents relevant relations, as follows:

$$\overline{RTH}_{(F/LH)i,j} = \overline{PY}_{(F/LH)i,j} \cdot C_i \quad (2)$$

where: $\overline{RTH}_{(F/LH)i,j}$: yearly-average F/LH-risk index for *i*-class of consequences and *j*-category of infrastructural objects in analysed time horizon (TH); $\overline{PY}_{(F/LH)i,j}$: yearly-average frequency of events for *i*-class of consequences and *j*-category of infrastructural objects in analysed time horizon (TH); C_i: consequence measure which corresponds to *i*-class of consequences.

Moreover, appointment of distribution for summary yearly risk indexes for F/LH allow us to analyse relevant trends and conclude whether some changes are highly expected during the next years. The following equation presents a computational apparatus to do this using data from the SFS data base.

$$RSY_{(F/LH)i,j} = \sum_{i} RY_{(F/LH)i,j} \quad (3)$$

where: $RSY_{(F/LH)i,j}$: summary yearly F/LH risk index for *i*-class of consequences and *j*-category of infrastructural object in *Y*-year.

Equation (2) gives summary values of risk for all events in the calculated year. From this point, comparison of infrastructure risk (and safety as well) levels in these particular years is possible.

Table 4. Risk indexes for particular categories of infrastructural objects in 2019 ($R2019_{(F/LH)i,j}$).

C_i	Class of Consequence (*i*)	Category of Infrastructural Objects (*j*)					
		O1	**O2**	**O3**	**O4**	**O5**	**O6**
1	F/S	2240	30,997	2023	827	1947	12,847
2	F/M	146	1928	620	348	1408	800
3	F/B	36	96	168	120	300	78
4	F/VB	20	4	104	48	96	12
	Totally:	2442	33,025	2915	1343	3751	13,737
1	LH/S	6601	20,670	462	265	273	7800
2	LH/L	21,678	150,576	5448	1426	7262	133,352
3	LH/M	903	2808	555	477	93	1383
4	LH/B	24	60	12	4	4	104
5	LH/C	0	0	0	0	0	0
	Totally:	29,206	174,114	6477	2172	7632	142,639

Source: own elaboration based on [71].

3.2.3. Formulation of Risk-Rationalized Manners for SIRE

The last step is conducted to create a catalogue of manners for SIRE. Pursuing the holistic result of the enhancement process, the morphological approach is highly recommended, especially when it is successfully implemented into sustainability and disaster risk reduction issues [77,78].

To achieve the research objectives, the morphological analysis must concern:

1. All categories of objects (6 categories).
2. All classes of consequences (9 classes).

Logical multiplication of 6 categories and 9 classes gives a total number of 45 potential analysis connections. Moreover, it maximizes chances to identify all realistic and rationally-determined manners. Nevertheless, the total number can be too high to formulate practical guidelines, especially for decision makers who expect short and concrete tips. Considering the risk assessment results can limit the total output from the morphology analysis only to the connections justified by the infrastructural risk values and specification. The connections prioritization is possible, because use of Equation (2) indicates objects which are more in danger than others. Thus, the objects can be risk-ordered and consequently prioritized (1st priority for the most risky objects, 2nd priority to the less risky objects, etc.).

Figure 3 presents a simplified view into the prioritization result.

The abovementioned figure presents a result of prioritization for connections "category of object—class of consequence" sorted on the basis of the risk assessment (see Section 4.2). It highlights a holistic attribute of the morphological analysis when each element from one group of elements is analysed in connection to each element from the other group of elements. Each connection has a number which expresses a risk-based priority. It means that "LH/L-O2" connection has the highest priority ("1") due to infrastructural risk calculated with the use of SFS data base (the highest risk). For the next example, the "F/S-O1" connection has the last priority in the analysed context (the lowest level of risk). The prioritization process allows us to emphasize connections which require the main attention in SIRE. Number of priorities depends on relevant merit-related assumptions of the analysis and the risk values (order of values, value differences, etc.), so it should be adapted to current cognitive needs and the risk assessment results. Taking into account all possible connections refers to a holistic, morphological mindset.

Morphological analysis		Categories of objects					
		O1	O2	O3	O4	O5	O6
Classes of consequences	F/S	3	2	3	3	3	2
	F/M	3	3	3	3	3	3
	F/B	3	3	3	3	3	3
	F/VB	3	3	3	3	3	3
	LH/S	2	2	2	3	3	3
	LH/L	2	1	2	3	2	1
	LH/M	3	3	3	3	3	3
	LH/B	3	3	3	3	3	3
	LH/C	3	3	3	3	3	3

Figure 3. Prioritization of connections "category of object—class of consequence". Source: own elaboration based on [50,78].

The prioritization is crucial from the point of view of SIRE manners' formulation. The manners should be formulated for the riskiest connections in terms of all elements of the reference model for SIRE. Consequently, the holistic aspect will be considered and Gap 2 will be met. In addition, particular SIRE manners should be formulated on the basis of experts' knowledge.

4. Results and Discussion

4.1. SIRE in Emergency Service Perspective

As reference model for SIRE presents general directions to formulate relevant manners, the emergency service perspective can make them concrete in the light of protection of the most important, utilitarian values. This means an exact relation to life and health of the infrastructure users, safety of the infrastructure itself as well as safety of property and environment connected with the infrastructure if the connection may affect human life and health quality.

As one would expect, the described perspective evaluates a primary understanding of SIRE. The perspective forces us to take into consideration three issues [8,79]:

1. Hazards' character (common exposure to population, a wide spectrum of classes of consequences and cascading potential for development);
2. Operational specification (urgency, continuity and substitutability of tasks, operations and activities);
3. Resources requirements (adequacy, limitation and substitutability of resources).

This is why, in the context of emergency service, SIRE needs to be understood in terms of the following framework areas:

1. Physical resilience: infrastructure must be physically resilient for cascading development of societal hazards in entire spectrum of their consequences. Due to their complexity, substantial

physical barriers to limit the hazards' access to infrastructure are required. In addition, human resources, which protect the infrastructure, should be ready to use different kinds of specialized equipment for this purpose.

2. Structure and setting resilience: owning to the mentioned interdependency, one's need to consider cascading connections in lines "hazard—Hazard", "hazard—Infrastructure" and "infrastructure—Infrastructure". Such way of thinking forces a necessity for multiresponse to natural disasters and man-made hazards. Consequently, a sufficient collaboration background is required to effectively face challenges in terms of the interentity protection process.
3. Organizational resilience: hazards affect organizations (e.g., infrastructure operator) and cause organizational threat occurrence. Thus, in analogy to the previous framework area, cascading connections between societal hazards and organizational threats must be considered. To ensure organizational resilience in relevant conditions, a system approach for the organization operation can be useful due to its complexity, complementarity and correspondence with external safety systems (e.g., SFRS). The system approach opens for creation of the response process with the use of multiple entities which have predominantly a positive effect on SIRE.
4. Economic resilience: the emergency specification shed a light into economic resilience of infrastructure operator, owner and/or supervisor (e.g., public administration authority). This is why the financial supply needs to be resilient from hazards' development (also when cascading effect materializes), ready for activation in terms of emergency circumstances. Furthermore, it should be based on economic establishment of operator, owner and/or supervisor, at the very least during the first response phase.
5. Legal resilience: urgency, which is typical for emergency status of infrastructure protection operations facing natural disasters and man-made hazards, is the opposite of the character of legal procedures and mechanisms. Nevertheless, the two must ensure that emergency-related acts are flexible. This means that loopholes and emergency legislation procedures are highly desirable. From a practical point of view, legal resilience should be equated with mechanisms to ensure flexibility of resources as well.

Considering the emergency service realm of SIRE, a relevant framework can be created. The framework is described in Table 5. Exemplary SIRE manners are formulated on the basis of the authors' knowledge and operational experiences in emergency and crisis management (incl. critical infrastructure protection) [80,81].

Table 5. SIRE framework.

No.	RM-SIRE Element	SIRE Framework Area	Example of SIRE Manner
1	Physical resilience	1.1. Physical resilience in terms of cascading development of societal hazards in entire spectrum of consequences	Additional protection systems (active or passive) against hazards which occur in neighbouring objects using few levels of protection
		1.2. Resilient physical barriers	Substantial physical barriers limiting access to infrastructure
		1.3. Physical-related flexibility of resources	Preparation of adequacy-equipped, different entities
2	Structure and setting resilience	2.1. Cascading connections between hazards and infrastructures	Multiscenario continuity management of different infrastructure operations (also the infrastructure operators)
		2.2. Multiresponse for hazards	Response involvement of entities responsible for protection interrelated infrastructures
		2.3. Collaborative background	Collaboration patterns and agreements between infrastructure protection entities

Table 5. *Cont.*

No.	RM-SIRE Element	SIRE Framework Area	Example of SIRE Manner
3	Organizational resilience	3.1. Cascading connections between societal hazards and organizational threats	Multiscenario, risk-based emergency planning for infrastructure protection
		3.2. System approach for operation	Development of substantiality in organizational system operations
		3.3. Organizational-related flexibility of resources	Elaboration of organization mechanisms for substitutable involvement of protection entities into action and training evaluation of the mechanism in the organization
4	Economic resilience	4.1. Financial resources resilient from hazards' development	Differentiation and diversification of financial sources
		4.2. Emergency economics	Extra financial mechanism ready for emergency activation
		4.3. Economic establishment of resources	Self-sufficiency of infrastructure protection entities (incl. infrastructure operators)
5	Legal resilience	5.1. Legal flexibility for preparation, response and reconstruction	Legal loopholes in acts concerning preparation, response and reconstruction of infrastructure
		5.2. Emergency legislation	Extra legislation mechanism ready for activation in terms of emergency conditions
		5.3. Legal background for flexibility of resources	Elaboration of legal mechanisms for substitutable involvement of protection entities into action

Source: own elaboration based on [80,81].

The framework shows concrete directions for relevant manners' formulation. Moreover, it can deliver input for additional and deeper analysis of infrastructure safety and emergency operations' efficacy. For example, risk analysis for cascading-related hazards and organizational threats, operational efficacy methods identification and efficiency cooperation analysis can be enumerated.

4.2. Emergency Service Reception of Infrastructure Resilience (Risk Assessment)

Emergency service perception of infrastructure resilience can be visualized by risk assessment which is based on SFS data base. Considering the voice of entities which operate in emergency conditions (direct danger to human life, time stress, etc.) allows for the consideration of a viewpoint of the most important, utilitarian values' protection and faces Gap 1.

SFS data base describes 1,255,826 events that occurred in 2015–2019 that affected the most important, utilitarian values (human life and health as well as property and environment in a scope of human survival needs). They are divided into 261,655 of F-events and 994,171 of LH-events [71].

Appendix A (Tables A1–A5) includes data about these events, respecting categories of infrastructural objects, classes of consequences and particular years of calculation. In addition, Table 6 presents summarized data for the events in the analysed time horizon.

Table 6. Data summary for numbers of events in 2015–2019.

C_i	Class of Consequence (*i*)	Category of Infrastructural Objects (*j*)					
		O1	O2	O3	O4	O5	O6
1	F/S	11,763	1,53,580	10,034	4191	9947	57,365
2	F/M	394	4850	1495	793	4031	1556
3	F/B	71	150	264	204	491	114
4	F/VB	27	3	113	93	111	15
	Totally:	12,255	158,583	11,906	5281	14,580	59,050
1	LH/S	28,955	86,399	2150	1326	1843	42,567
2	LH/L	49,781	367,465	15,217	3478	23,639	364,246
3	LH/M	955	3135	625	506	115	1599
4	LH/B	29	42	23	8	3	61
5	LH/C	0	4	0	0	0	0
	Totally:	79,720	457,045	18,015	5318	25,600	408,473

Source: own elaboration.

Figure 4 visualizes the summary results below.

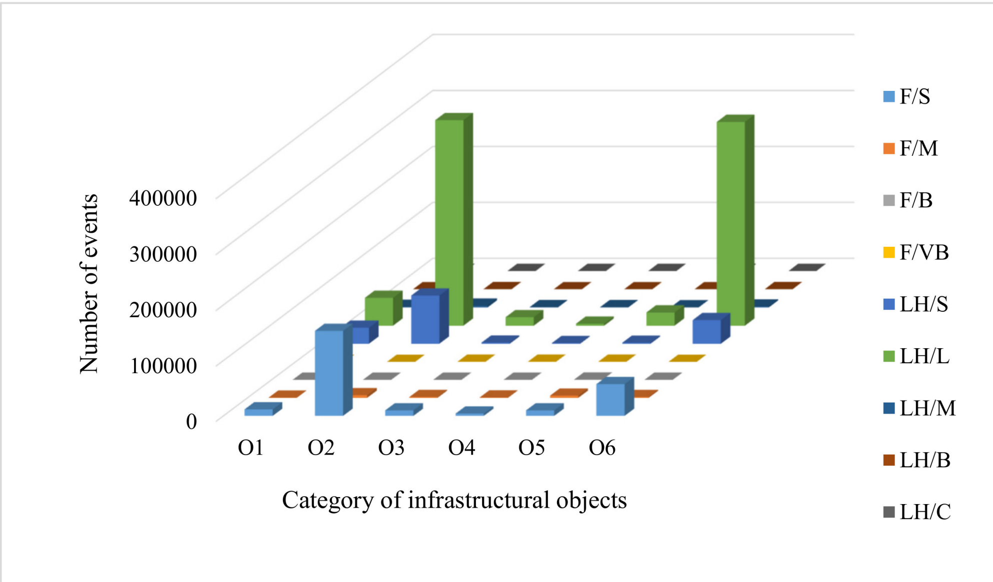

Figure 4. Data summary for numbers of events in 2015–2019. Source: own elaboration.

Two kinds of events stand out from the rest. These are LH/L-O2 and LH/L-O6. They commonly state 58% of a total number of events during the last five years. This means that surely most of the negatively perceived circumstances were related to urgent failures of machines, instruments, vehicles and other objects, which caused maximum one victim dead or maximum three victims supported by medical rescue teams (from outside SFRS) or required maximum four fire service teams'(12–24 rescuers) participation in the action. The circumstances occurred generally in residential objects and other objects. The next kind of event also concerns these categories of objects. F/S-O2 and F/S-O6 are noticed. This situation is expected from a general view into fire statistics and the hazard specification, when, a number of fires is inversely proportional to the class of consequences. Such trend can be a reason why LH/S-O2 events have relatively high influence on infrastructure safety.

In terms of the risk, use of Equation (1) gives input to Appendix B (Tables A6–A10) which includes data concerning risk indexes for particular categories of infrastructural objects in 2015–2019. In accordance with Equation (2), estimation of yearly-average risk indexes of F/LH (for *i*-class of consequences and *j*-category of infrastructural objects) in 2015–2019 is possible. Table 7 presents a juxtaposition of the estimation results.

Table 7. Yearly-average F/LH-risk index for *i*-class of consequences and *j*-category of infrastructural objects in 2015–2019 ($\overline{R2015-2019}_{(F/LH)i,j}$).

C_i	Class of Consequence (*i*)	Category of Infrastructural Objects (*j*)					
		O1	**O2**	**O3**	**O4**	**O5**	**O6**
1	F/S	2352.6	30,716	2006.8	838.2	1989.4	11473
2	F/M	157.6	1940	598	317.2	1612.4	622.4
3	F/B	42.6	90	158.4	122.4	294.6	68.4
4	F/VB	21.6	2.4	90.4	74.4	88.8	12
1	LH/S	5791	17,279.8	430	265.2	368.6	8513.4
2	LH/L	19,912.4	146,986	6086.8	1391.2	9455.6	145,698.4
3	LH/M	573	1881	375	303.6	69	959.4
4	LH/B	23.2	33.6	18.4	6.4	2.4	48.8
5	LH/C	0	4	0	0	0	0

Source: own elaboration.

Figure 5 visualizes yearly-average F/LH-risk index distribution, considering classes of consequences and categories of infrastructural objects.

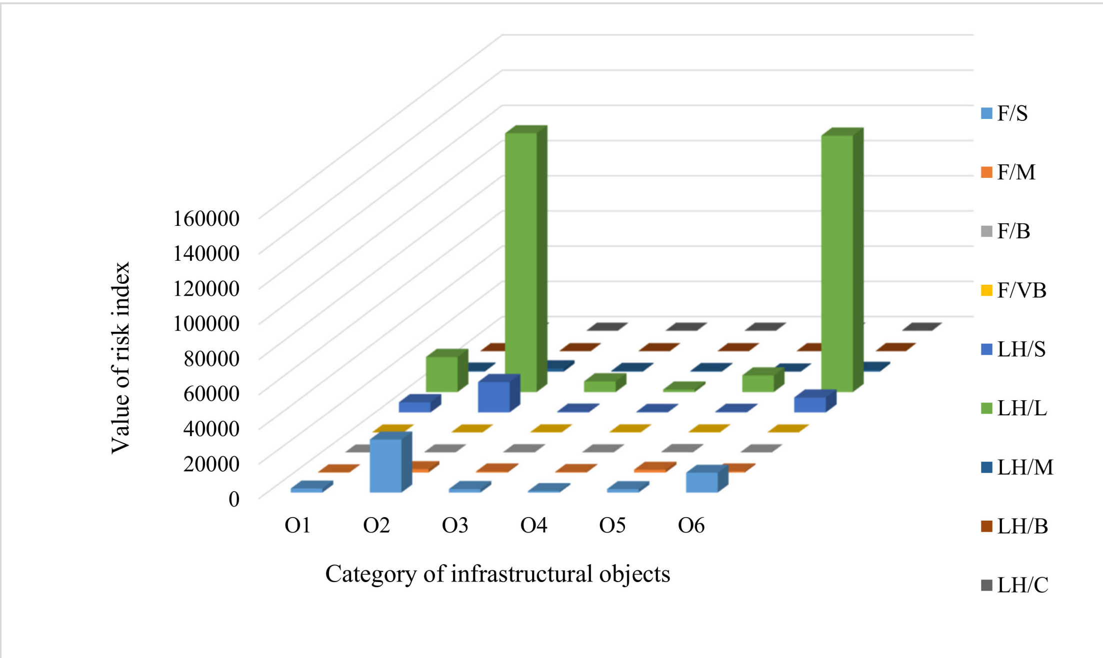

Figure 5. Yearly-average F/LH risk indexes for *i*-class of consequences and *j*-category of infrastructural objects in 2015–2019 ($\overline{R2015-2019}_{(F/LH)i,j}$). Source: own elaboration.

In principle, risk assessment confirms previous results for number of events. The highest risk is calculated for LH/L-O2 and LH/L-O6. The two cover more than 69% of summary value of infrastructural risk. A risk-related distance between these kinds of events from other kinds of events increases because classes of consequences are taken into account.

Knowledge about actual risk levels due to hazards which effect the most important, utilitarian values creates the current picture for infrastructure safety. Information concerning the object trends is also valuable. Based on previous results, it is possible to get summary yearly F/LH-risk indexes for *i*-class of consequences and *j*-category of infrastructural object in the analysed years. These are compiled in Tables 8 and 9.

Table 8. Summary yearly F-risk indexes for *i*-class of consequences and *j*-category of infrastructural object in 2015–2019.

$RSY_{(F)i,j}$	O1	O2	O3	O4	O5	O6
2015	2597	30,647	2931	1419	4902	13,048
2016	2709	32,095	2772	1168	3743	10,999
2017	2534	33,341	2655	1256	3503	10,239
2018	2590	34,634	2995	1575	4027	12,856
2019	2442	33,025	2915	1343	3751	13,737

Source: own elaboration.

Table 9. Summary yearly LH-risk indexes for *i*-class of consequences and *j*-category of infrastructural object in 2015–2019.

$RSY_{(LH)i,j}$	O1	O2	O3	O4	O5	O6
2015	23,441	138,809	6489	1535	9102	158,628
2016	25,231	146,542	5886	1725	7658	148,439
2017	26,760	176,390	7524	2157	11,503	203,527
2018	26,860	195,067	8175	2243	13,583	122,867
2019	29,206	174,114	6477	2172	7632	142,639

Source: own elaboration.

Figures 6 and 7 present a time distribution of summary yearly F/LH-risk indexes. They show tendencies for infrastructural safety levels in accordance with the last five years.

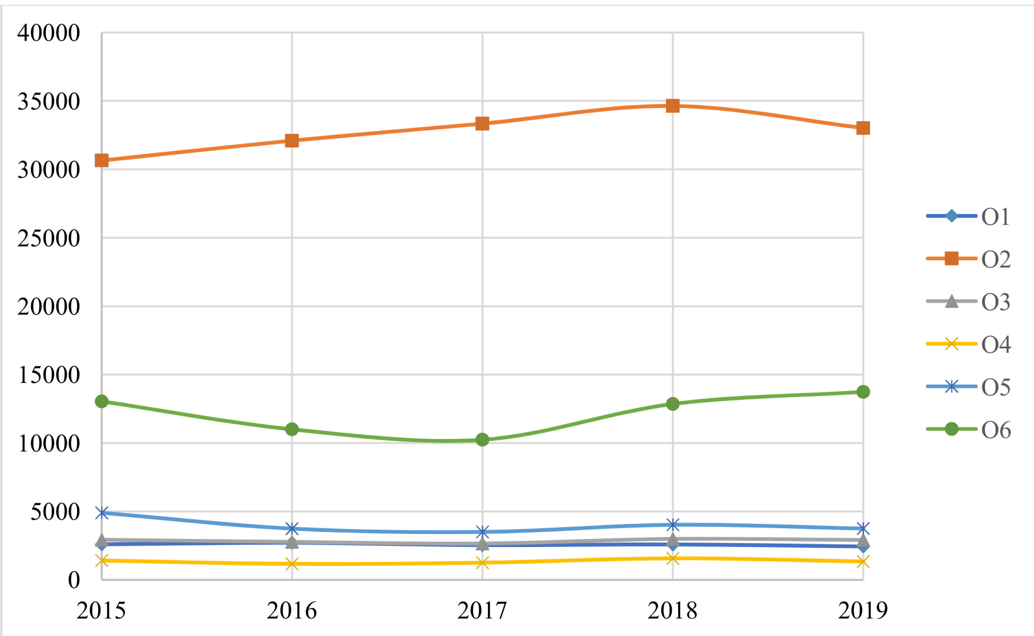

Figure 6. Summary yearly F-risk indexes for *i*-class of consequences and *j*-category of infrastructural object in 2015–2019. Source: own elaboration.

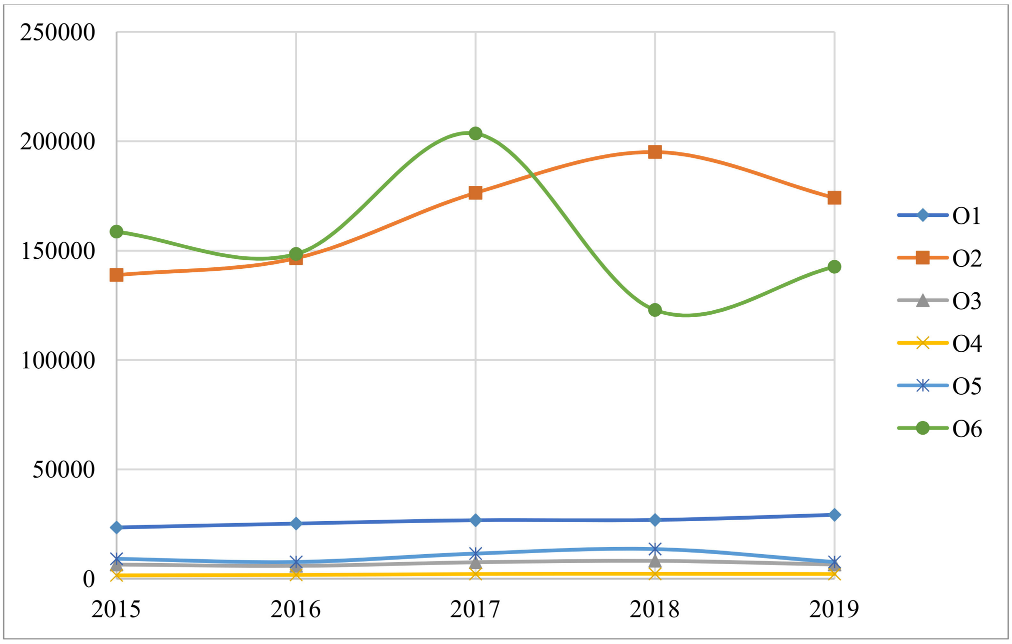

Figure 7. Summary yearly *LH*-risk indexes for *i*-class of consequences and *j*-category of infrastructural object in 2015–2019. Source: own elaboration.

Figure 7 shows the time-related distribution of summary yearly *LH*-risk indexes for *i*-class of consequences and *j*-category of infrastructural object.

As far as F-events are concerned, they all present stable levels of infrastructural safety. The highest risk for residential buildings (O2) is noticed. It is more than two times higher than the risk level for the second category of objects (O6). The rest of the categories of objects are characterized by relatively low risk of fire in presented time perspective. In all cases an amplitude of changes is low and stable fire risk level for the infrastructure is expected.

Quite a different situation can be observed when LH-events are considered. Two tendency characteristics are identified. The first one comprises information for O2 and O6. The trends are dynamic, and difficult to predict in the coming years. Probably risk for O2 will decrease with apposite tendency for O6. The second characteristic is ascribed to the rest of the infrastructural objects. Their risk levels are clearly lower in comparison to O2 and O6. Furthermore, changes of amplitude are negligible and present a stable level of safety.

4.3. Rationalization of SIRE Manners

Rationalization of SIRE manners states a quintessence of the proposed methodology. It presents a mindset of emergency service and corresponds directly with the most important, utilitarian values (Gap 1). It connects multiple risk variants into one SIRE concept, filling Gap 2. In addition, the rationalization depends on risk assessment which uses real emergency data. Consequently, Gap 3 is taken into consideration.

Operationalizing, formulation of risk-rationalized SIRE manners requires a deepen exploration of final risk assessment results (see Figure 5 in Section 4.1). Vertical-horizontal analysis allows us to appoint three groups of infrastructures which holistically reflect risk assessment output:

1. High-risk infrastructure (LH/L-O2 and LH/L-O6)—Priority 1;
2. Medium-risk infrastructure (F/S-O2, F/S-O6, LH/S-O1, LH/S-O2, LH/S-O3, LH/L-O1, LH/L-O3 and LH/L-O5)—Priority 2;
3. Low-risk infrastructure (F/S-O1, F/S-O3, F/S-O4, F/S-O5, F/M-O1, F/M-O2, F/M-O3, F/M-O4, F/M-O5, F/M-O6, F/B-O1, F/B-O2, F/B-O3, F/B-O4, F/B-O5, F/B-O6; F/VB-O1, F/VB-O2, F/VB-O3, F/VB-O4, F/VB-O5, F/VB-O6; LH/S-O3, LH/S-O4, LH/S-O5, LH/L-O4, LH/M-O1, LH/M-O2,

LH/M-O3, LH/M-O4, LH/M-O5, LH/M-O6, LH/B-O1, LH/B-O2, LH/B-O3, LH/B-O4, LH/B-O5, LH/B-O6, LH/C-O1, LH/C-O2, LH/C-O3, LH/C-O4, LH/C-O5 and LH/C-O6)—Priority 3.

Titles of the groups follow risk-related priorities ascribed to particular logical connections between classes of consequences and categories of objects. Most of cases relate to the last group. This fact highlights the two-extremes nature of the risk distribution. On the one site, there are objects mostly affected by hazards which influence the most important, utilitarian values (high-risk infrastructure). On the other site, there are the other categories of objects (medium-risk and low-risk ones). Differences between these two are clearly noticeable when the risk values are announced.

The rationalization essence states in formulation of manners only for the objects ascribed into the high-risk infrastructure (priority 1). The distance between the risk values related to the medium-risk group (priority 2) is so high that there is no risk-based reason to create the manners for other groups of infrastructures (for priority 2 and priority 3). As a logical consequence, risk-rationalized manners for SIRE are catalogued in Table 10 (for LH/L-O2) and Table 11 (for LH/L-O6).

Table 10. SIRE manners catalogue for LH/L-O2.

SIRE Framework Area	SIRE Manners
1.1. Physical resilience in terms of cascading development of societal hazards in entire spectrum of consequences	Private protection systems (mainly the passive ones) against urgent failures of machines, instruments, vehicles and other objects which occur in the neighbourhood using few levels of residential protection
1.2. Resilient physical barriers	Locally-determined politics for residential building concerning safe distances and physical barriers limiting access to local infrastructure
1.3. Physical-related flexibility of resources	Localization of temporary emergency units in residential areas (e.g., fire unit and medical units using the same station)
2.1. Cascading connections between hazards and infrastructures	Multiscenario continuity management of different processes describing local society (power supply, water supply, access to fuel and food, etc.)
2.2. Multiresponse for hazards	Involvement of local society representatives in the response for hazards (e.g., voluntary service)
2.3. Collaborative background	Collaboration patterns and agreements between safety institutions and voluntary groups, private individuals, etc.
3.1. Cascading connections between societal hazards and organizational threats	Multiscenario, risk-based emergency planning for local society protection with the use of the first disposal of emergency units
3.2. System approach for operation	Education for safety to improve private potential to protect residential objects
3.3. Organizational-related flexibility of resources	Involvement of local society representatives into response actions in *LH/L*
4.1. Financial resources resilient from hazards' development	Differentiation and diversification of financial sources using private and business supply sources in terms of *LH/L*
4.2. Emergency economics	Local emergency funds as extra financial mechanism ready for activation in case of necessity
4.3. Economic establishment of resources	Education to ensure economic self-sufficiency of local society
5.1. Legal flexibility for preparation, response and reconstruction	Legal loopholes in general and local acts concerning preparation, response and reconstruction of residential objects
5.2. Emergency legislation	Extra legislation mechanism ready for activation in terms of emergency conditions at lower levels of public administration
5.3. Legal background for flexibility of resources	Elaboration of legal mechanisms for substitutable involvement of individuals

Source: own elaboration based on [80,81].

Table 11. SIRE manners catalogue for LH/L-O6.

SIRE Framework Area	SIRE Manners
1.1. Physical resilience in terms of cascading development of societal hazards in entire spectrum of consequences	Private and business protection systems (active and passive ones) against urgent failures of machines, instruments, vehicles and other objects which occur in neighbourhood using few levels of private and business protection
1.2. Resilient physical barriers	General politics for building which concern safe distances and physical barriers limiting access to untypical infrastructures
1.3. Physical-related flexibility of resources	Localization of temporary emergency units in areas where untypical objects are localized
2.1. Cascading connections between hazards and infrastructures	Multiscenario continuity management of different processes describing untypical objects and their connection with local society (accordingly to power supply, water supply, access to fuel and food, etc.)
2.2. Multiresponse for hazards	Involvement of infrastructure operators in the response for hazards (e.g., military fire service)
2.3. Collaborative background	Collaboration patterns and agreements between safety institutions and untypical infrastructure operators/owners
3.1. Cascading connections between societal hazards and organizational threats	Multiscenario, risk-based emergency planning for local society protection and for business with the use of the first disposal of emergency units
3.2. System approach for operation	Education for safety to improve operators' potential to protect their objects as well as common trainings with emergency units
3.3. Organizational-related flexibility of resources	Involvement of infrastructure operators into response actions in LH/L
4.1. Financial resources resilient from hazards' development	Differentiation and diversification of financial sources using private, business and public supply sources in terms of LH/L
4.2. Emergency economics	Public and local emergency funds as extra financial mechanism ready for activation in case of necessity
4.3. Economic establishment of resources	Self-sufficiency of infrastructure operators
5.1. Legal flexibility for preparation, response and reconstruction	Legal loopholes in general and local acts concerning preparation, response and reconstruction of untypical objects
5.2. Emergency legislation	Extra legislation mechanism ready for activation in terms of emergency conditions at all levels of public administration
5.3. Legal background for flexibility of resources	Elaboration of legal mechanisms for substitutable involvement of emergency support from other public institutions, voluntary groups and business representatives

Source: own elaboration based on [80,81].

5. Conclusions

Infrastructure resilience reflects the current sustainable-related direction of the developing world. SIRE can be done with the use of multiple different approaches and tools. Among them are the most important, utilitarian values (human life and health as well as property and environment in a scope of human survival needs) which are worth emphasising. From the quality point of view, SIRE should be based on real data and risk is desirable as a safety measure and factor which determines relevant manners' rationalization. Moreover, emergency service data is significantly needed.

In the analysed context, infrastructure sustainability is an ability of the infrastructural dimension of the city (urban area) to improve the quality of inhabitants' life as well as the efficiency of urban services and operation. This is closely related to infrastructure resilience, which can be defined as the capacity to withstand in the case of, desirably, a whole spectrum of stresses and shocks (including natural disasters and man-made hazards). The relation between sustainability and resilience in terms of

SIRE is bidirectional. Sustainability can influence the system (community, infrastructure, city) resilience and resilience may determine the system sustainability. Precisely, direct and indirect associations with SDG9, SDG11 and SDG13 are noticed. Moreover, sustainability can constitute a comprehensive framework for SIRE, order multiple resilience variants and create coherent notion of SIRE. The very important method for rationalizing all potential directions for SIRE is risk assessment. Its practical implementation allows us to express the mindset of entities that protect the most important, utilitarian values, and consequently priorities analysis areas for SIRE. Due to the priority-oriented direction of research, the results do not give an answer for a question about resilience levels for evaluated objects. It is based on the assumption that very resilient objects can be significantly affected by serious and/or numerus hazards. The high resilience level does not imply simultaneously low risk level. Therefore, from the emergency service point of view, risk awareness influences knowledge about directions to increase the resilience. Consequently, risk assessment can be used for SIRE rationalization.

SIRE model comprises five elements: physical resilience, structure and setting resilience, organizational resilience, economic resilience and legal resilience. When issues which determine the risk assessment perspective (the emergency one) are taken into consideration, one can formulate SIRE framework. Thus, the framework elements (SIRE manners) should concern common exposure for population to hazards, wide spectrum of classes of consequences and cascading potential for the hazards' development, urgency, continuity and substitutability of tasks, operations and activities as well as adequacy, limitation and substitutability of resources. It is worth highlighting the model cognitive potential, because its universality and comprehensiveness open many SIRE mindsets (not only the emergency service one).

Risk assessment is a tool for building situational awareness in terms of infrastructure safety levels related to natural disasters and man-made hazards. In accordance with SFS data base, the tool is built on four classes of consequences for fires and five classes of consequences for negative phenomena that are not fires and state danger to people, property or environment, resulting from civilization development, people operations or natural disasters. Residential buildings and other categories of objects in the light of locally-limited local hazards (LH/L-O2 and LH/L-O6) are categories of infrastructural objects connected to the highest number of events in 2015–2019 (58% of the total number of events in the analysed period of time). These numbers correspond with infrastructural risk values (more than 69% of summary value of infrastructural risk). Furthermore, trend analysis allows us to assume that these values and risk differences between particular categories of objects and particular classes of consequences will be generally approximate in value during the coming years (with the exception of the above-mentioned LH/L-O2 and LH/L-O6). The 2015–2019 period of time refers to the last events documented by SFS in the data base. It is sufficiently long to identify a general view into the infrastructure risk profile. In addition, relevant data analysis allows for preliminary determination of trends. Further research for the previous and next periods of time are said to be a proper way for monitoring of the infrastructure risk situation, increasing the trends' relevancy and making the risk awareness more reliable.

All these issues shape SIRE manners at the stage of their risk-based rationalization. Risk assessment results allow to enumerate three groups of infrastructures. Owing to the two-extremes nature of the risk distribution, it is justified to focus on the high-risk infrastructure. So, sustainable BRI manners should be formulated only for LH/L-O2 and LH/L-O6. This does not mean a full acceptation for other cases but rather shows which of them needs the main attention and which can be just monitored (with the use of such classical risk treatment manners as acceptation, transfer, reduction, etc).

Deepening analysis of SIRE manners for a risk-limited number of cases gives information about their specification. In general, they can be formulated using top-down and bottom-up approaches. In the top-down direction, mostly institutional collaboration mechanisms, flexible legal solutions and common infrastructure protection awareness are noticed. Relevant information can be valuable especially for public administration, public services as well as institutional infrastructure operators, owners and supervisors. From the bottom-up mindset, the most complex user group is considered, namely individuals and social groups responsible for residential buildings. The SIRE model allows us to connect these two perspectives into the SIRE in a holistic way. In addition, it gives practical guidelines for decision makers who create national and local infrastructure politics, collaboration mechanisms and educational programs and have influence on incentive solutions (tax concessions, insurance benefits, etc.)—both crucial for SIRE effectiveness.

In conclusion, all research objectives are achieved. However, relevant limitations and directions for further research need to be described. First of all, SDG9, SDG11 and SDG13 introduce the research but also reduce the cognitive perception. They mostly refer to the infrastructure resilience, for sure. However, analysis for other SDGs can be useful for identification of untypical and unobvious SIRE determinants. Secondly, the emergency perspective limits kinds of hazards to fires and negative phenomena that are not fires and state danger to people, property or environment, resulting from civilization development, people operations or natural disasters. Furthermore, it strongly determines understanding of particular classes of consequences, boiling it down to the size of the hazard zone, information about victims and emergency resources dispatched to the action. Even if this context seems to be the most appropriate for SIRE affected by the most serious events, other contexts are worth investigating (e.g., Police, insurance institutions, critical infrastructure operators) to deepen exploration of this area of knowledge. Thirdly, the rationalization process is based only on the risk assessment, as the risk is a very objective safety measure. Ex ante and ex post analysis of SIRE manners will allow us to answer questions for their foreseen and real effectiveness and will open practical knowledge by a description of concrete case studies.

The paper contributes to sustainability knowledge by a proposition of a novel approach for SIRE which reflects direct protection of the most important values (human life and health) in emergency service mindset. Unique connection of sustainability, resilience and risk is described. A rarely described point of view (emergency service) is expressed. These issues can give a new quality to sustainability research. They prove that sustainability can be simultaneously a research objective and research tool to achieve this objective. Universality of this conclusion could have a significant influence on other areas of interest for sustainability theoreticians and practitioners.

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Appendix A

Data about numbers of events that occurred in 2015–2019.

Table A1. Numbers of events in 2015.

C_i	Class of Consequence (i)	Category of Infrastructural Objects (j)					
		O1	**O2**	**O3**	**O4**	**O5**	**O6**
1	F/S	2336	28,481	2020	891	2263	12,324
2	F/M	109	1035	324	167	1045	321
3	F/B	9	32	61	42	139	22
4	F/VB	4	0	20	17	33	4
	Totally:	2458	29,548	2425	1117	3480	12671

Table A1. *Cont.*

C_i	Class of Consequence (*i*)	Category of Infrastructural Objects (*j*)					
		O1	O2	O3	O4	O5	O6
1	LH/S	5498	14,582	396	201	727	10,134
2	LH/L	8789	61,510	2903	554	4165	73,934
3	LH/M	115	388	89	74	15	202
4	LH/B	5	7	5	1	0	5
5	LH/C	0	3	0	0	0	0
	Totally:	14,407	76,490	3393	830	4907	84,275

Source: own elaboration based on [71].

Table A2. Numbers of events in 2016.

C_i	Class of Consequence (*i*)	Category of Infrastructural Objects (*j*)					
		O1	O2	O3	O4	O5	O6
1	F/S	2511	30,198	1934	720	1883	10,398
2	F/M	70	903	302	132	785	258
3	F/B	14	29	46	36	74	23
4	F/VB	4	1	24	19	17	4
	Totally:	2599	31,131	2306	907	2759	10,683
1	LH/S	6375	14,894	385	189	256	8102
2	LH/L	9215	65,187	2613	670	3684	69,805
3	LH/M	134	418	85	64	10	237
4	LH/B	6	5	5	1	1	4
5	LH/C	0	0	0	0	0	0
	Totally:	15,730	80,504	3088	924	3951	78,148

Source: own elaboration based on [71].

Table A3. Numbers of events in 2017.

C_i	Class of Consequence (*i*)	Category of Infrastructural Objects (*j*)					
		O1	O2	O3	O4	O5	O6
1	F/S	2332	31,461	1933	807	1805	9655
2	F/M	67	902	261	145	695	254
3	F/B	16	24	40	29	80	24
4	F/VB	5	1	20	18	17	1
	Totally:	2420	32,388	2254	999	2597	9934
1	LH/S	5426	17,325	423	282	310	9420
2	LH/L	10,316	78,584	3384	803	5536	96,478
3	LH/M	222	624	103	87	39	357
4	LH/B	9	5	6	2	1	20
5	LH/C	0	1	0	0	0	0
	Totally:	15,973	96,539	3916	1174	5886	106,275

Source: own elaboration based on [71].

Table A4. Numbers of events in 2018.

C_i	Class of Consequence (i)	Category of Infrastructural Objects (j)					
		O1	O2	O3	O4	O5	O6
1	F/S	2344	32,443	2124	946	2049	12,141
2	F/M	75	1046	298	175	802	323
3	F/B	20	33	61	57	98	19
4	F/VB	9	0	23	27	20	3
	Totally:	2448	33,522	2506	1205	2969	12,486
1	LH/S	5055	18,928	484	389	277	7111
2	LH/L	10,622	86,896	3593	738	6623	57,353
3	LH/M	183	769	163	122	20	342
4	LH/B	3	10	4	3	0	6
5	LH/C	0	0	0	0	0	0
	Totally:	15,863	106,603	4244	1252	6920	64,812

Source: own elaboration based on [71].

Table A5. Numbers of events in 2019.

C_i	Class of Consequence (i)	Category of Infrastructural Objects (j)					
		O1	O2	O3	O4	O5	O6
1	F/S	2240	30,997	2023	827	1947	12,847
2	F/M	73	964	310	174	704	400
3	F/B	12	32	56	40	100	26
4	F/VB	5	1	26	12	24	3
	Totally:	2330	31,994	2415	1053	2775	13,276
1	LH/S	6601	20,670	462	265	273	7800
2	LH/L	10,839	75,288	2724	713	3631	66,676
3	LH/M	301	936	185	159	31	461
4	LH/B	6	15	3	1	1	26
5	LH/C	0	0	0	0	0	0
	Totally:	17,747	96,909	3374	1138	3936	74,963

Source: own elaboration based on [71].

Appendix B

Risk indexes for particular categories of infrastructural objects in 2015–2019.

Table A6. Risk indexes for particular categories of infrastructural objects in 2015 ($R2015_{(F/LH)i,j}$).

C_i	Class of Consequence (i)	Category of Infrastructural Objects (j)					
		O1	O2	O3	O4	O5	O6
1	F/S	2336	28,481	2020	891	2263	12,324
2	F/M	218	2070	648	334	2090	642
3	F/B	27	96	183	126	417	66
4	F/VB	16	0	80	68	132	16
	Totally:	2597	30,647	2931	1419	4902	13,048
1	LH/S	5498	14,582	396	201	727	10,134
2	LH/L	17,578	123,020	5806	1108	8330	147,868
3	LH/M	345	1164	267	222	45	606
4	LH/B	20	28	20	4	0	20
5	LH/C	0	15	0	0	0	0
	Totally:	23,441	138,809	6489	1535	9102	158,628

Source: own elaboration.

Table A7. Risk indexes for particular categories of infrastructural objects in 2016 ($R2016_{(F/LH)i,j}$).

C_i	Class of Consequence (i)	Category of Infrastructural Objects (j)					
		O1	O2	O3	O4	O5	O6
1	F/S	2511	30,198	1934	720	1883	10,398
2	F/M	140	1806	604	264	1570	516
3	F/B	42	87	138	108	222	69
4	F/VB	16	4	96	76	68	16
	Totally:	2709	32,095	2772	1168	3743	10,999
1	LH/S	6375	14,894	385	189	256	8102
2	LH/L	18,430	130,374	5226	1340	7368	139,610
3	LH/M	402	1254	255	192	30	711
4	LH/B	24	20	20	4	4	16
5	LH/C	0	0	0	0	0	0
	Totally:	25,231	146,542	5886	1725	7658	148,439

Source: own elaboration.

Table A8. Risk indexes for particular categories of infrastructural objects in 2017 ($R2017_{(F/LH)i,j}$).

C_i	Class of Consequence (i)	Category of Infrastructural Objects (j)					
		O1	O2	O3	O4	O5	O6
1	F/S	2332	31,461	1933	807	1805	9655
2	F/M	134	1804	522	290	1390	508
3	F/B	48	72	120	87	240	72
4	F/VB	20	4	80	72	68	4
	Totally:	2534	33,341	2655	1256	3503	10,239
1	LH/S	5426	17,325	423	282	310	9420
2	LH/L	20,632	157,168	6768	1606	11,072	192,956
3	LH/M	666	1872	309	261	117	1071
4	LH/B	36	20	24	8	4	80
5	LH/C	0	5	0	0	0	0
	Totally:	26,760	176,390	7524	2157	11,503	203,527

Source: own elaboration.

Table A9. Risk indexes for particular categories of infrastructural objects in 2018 ($R2018_{(F/LH)i,j}$).

C_i	Class of Consequence (i)	Category of Infrastructural Objects (j)					
		O1	O2	O3	O4	O5	O6
1	F/S	2344	32,443	2124	946	2049	12,141
2	F/M	150	2092	596	350	1604	646
3	F/B	60	99	183	171	294	57
4	F/VB	36	0	92	108	80	12
	Totally:	2590	34,634	2995	1575	4027	12,856
1	LH/S	5055	18,928	484	389	277	7111
2	LH/L	21,244	173,792	7186	1476	13,246	114,706
3	LH/M	549	2307	489	366	60	1026
4	LH/B	12	40	16	12	0	24
5	LH/C	0	0	0	0	0	0
	Totally:	26,860	195,067	8175	2243	13,583	122,867

Source: own elaboration.

Table A10. Risk indexes for particular categories of infrastructural objects in 2019 ($R2019_{(F/LH)i,j}$).

C_i	Class of Consequence (*i*)	Category of Infrastructural Objects (*j*)					
		O1	**O2**	**O3**	**O4**	**O5**	**O6**
1	F/S	2240	30,997	2023	827	1947	12,847
2	F/M	146	1928	620	348	1408	800
3	F/B	36	96	168	120	300	78
4	F/VB	20	4	104	48	96	12
	Totally:	2442	33,025	2915	1343	3751	13,737
1	LH/S	6601	20,670	462	265	273	7800
2	LH/L	21,678	150,576	5448	1426	7262	133,352
3	LH/M	903	2808	555	477	93	1383
4	LH/B	24	60	12	4	4	104
5	LH/C	0	0	0	0	0	0
	Totally:	29,206	174,114	6477	2172	7632	142,639

Source: own elaboration.

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