

CRITICAL INFRASTRUCTURES INTERDEPENDENCES DURING EXTREME WEATHER EVENTS: THE LEAN PERSPECTIVE

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ABSTRACT

Critical infrastructures (CIs) such as those related to transportation, water and electricity supply provide essential services to society, including construction projects. Thus, failure of CIs can hinder lean construction adoption, especially during extreme weather events with prolonged consequences. This article explores the use of lean thinking for the identification of opportunities for systemic improvement in CIs affected by a major flooding in Southern Brazil. To this end, the Functional Resonance Analysis Method (FRAM) was used for modelling the interdependences among 20 CIs affected by the floods. The FRAM model was developed based on interviews with CI representatives, site visits, and document analysis. Then, five lean construction principles were used for the identification of opportunities to enhance the resilient performance of the CIs. The principle “increase transparency” is especially important as it makes the CI operational status visible to other stakeholders and thus enhances coordination during crisis response. The principle “increase flexibility” also stands out, promoting the repurposing of CI functionalities and investment in a multi-skilled workforce.

KEYWORDS

Extreme weather events, FRAM, societal resilience, lean principles, interdependence.

INTRODUCTION

Extreme weather events (EWEs) such as floods pose significant risks to critical infrastructures (CIs) that provide essential services for modern societies, such as power supply, healthcare and transportation. To cope with these risks, CIs must display resilient performance, which is displayed through the systemic potentials of monitoring, anticipating, responding, and learning from EWEs (Hollnagel, 2017). From a production management perspective, these events are challenging owing to factors such as (i) time pressure that requires quick mobilization of a wide range of resources; (ii) changing priorities in the demand for these resources; (iii) logistical difficulties as transportation and distribution routes may be disrupted; and (iv) need for coordination between a large number of stakeholders that do not work together during everyday operations (Mishra et al., 2022; Kovacs & Moshtari, 2019).

Lean thinking has been discussed as an approach to enhance resilient performance during disaster management operations. For example, Cozzolino et al. (2012) discussed the use of lean and agile principles in the different stages of a disaster, highlighting the benefits of lean for the

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reconstruction stage. Mojtahedi & Oo (2012) discussed the application of lean tools to post-disaster housing reconstruction. Lean thinking takes a systems view of production systems by focusing on improving flow through waste reduction, rather than improving isolated process stages. At the same time, resilient performance during EWEs occurs in complex systems where variability can easily propagate across CI networks. This context suggests that lean thinking is relevant to managing CI interdependences. Interdependence refers to “a bidirectional relationship between two CI through which the state of each infrastructure influences or is correlated with the state of the other” (Rinaldi et al., 2001). This can be exemplified by the interdependences between power and water supply systems (Fekete, 2019).

This background sets the stage for the research question as follows: how can lean principles be used to support resilient performance of interdependent CIs during EWEs? This question was investigated using the 2024 floods that occurred in Southern Brazil as a case study. Five lean principles for flow process design and improvement proposed by Koskela (2000) were used as a lens for the analysis. In turn, the Functional Resonance Analysis Method (FRAM) proposed by Hollnagel (2012) was chosen for the modelling of interdependences due to its emphasis on functional couplings, which is consistent with the lean emphasis on process flow. Previous research indicates that the FRAM complements traditional lean modelling tools such as the value stream mapping by representing real-world variabilities and highlighting their system-wide impacts (Saurin et al., 2016; Safi et al., 2023).

In construction, the FRAM has also been applied to model variability propagation in the Last Planner System (Hamerski et al., 2021), to model a chain of wastes in an airport terminal expansion (Fireman & Saurin, 2020), and to model concrete structure activities with the aim of improving safety performance (Pardo-Ferreira et al., 2020). In turn, this study uses the FRAM at the societal level to analyze CI interdependences in the context of the 2024 floods, while adopting lean principles as an analytical lens for interpreting system performance. By doing so, the study moves beyond descriptive modelling of interdependences and provides insights into how lean thinking can support resilient performance during EWEs.

FUNCTIONAL RESONANCE ANALYSIS METHOD

The FRAM was conceived as a method for modelling variability propagation among the functions of complex sociotechnical systems (Hollnagel, 2012). The method provides a representation of work-as-done in reality, which tends to be different from the work-as-imagined in formal procedures (e.g., flood contingency plans). According to Hollnagel (2012), the FRAM is based on four principles:

- **The equivalence of successes and failures:** this principle considers that success and failure have the same causes. However, the outcome depends on how individuals and organizations adapt to expected and unexpected circumstances.
- **Approximate adjustments:** work is continuously adjusted to match existing conditions (e.g., scarce resources, time pressure, or underspecified plans). These adjustments are approximate rather than perfect, and therefore variability is always present in everyday work in sociotechnical systems.
- **Emergence:** this principle acknowledges that variability stemming from different functions can combine in unexpected ways and lead to nonlinear effects. Thus, both success and failure are emergent, rather than a resulting phenomenon, as they cannot be attributed or explained solely based on the functioning or non-functioning of specific components.
- **Functional resonance:** the aggregation of variability across multiple functions can create functional resonance, thereby producing unexpected results. Functional resonance is the detectable variability (e.g., system disruption) that otherwise would remain hidden in everyday work.

The FRAM application involves five steps (Hollnagel, 2012):

1. To define the purpose of the FRAM analysis: the FRAM is commonly employed for accident investigation, risk assessment, and evaluation of design changes.
2. To identify and describe the functions: the functions have to fall within the defined boundaries of the system under analysis. The functions are described by six aspects, namely input, output, precondition, resources, control, and time. It is not necessary to describe all the six aspects.
3. To identify the potential variability: the analysis of the potential variability accounts for what is reasonable to expect from each function. It concerns the variability of the functions' outputs in terms of time (too early, on time, too late, not at all) and precision (precise, acceptable, imprecise).
4. The aggregation of variability: regards the assessment of whether the actual variability of the output of a function affects the aspects of other functions.
5. To identify consequences of the analysis: to propose recommendations to manage the functional resonance identified in the previous steps.

LEAN PRINCIPLES

The flow principles proposed by Koskela (2000) and adopted as a basis for addressing the research question are presented in Table 1. These principles capture key concerns of lean construction thinking and have also been used by other studies, such as identifying interactions between lean and building information modelling (Sacks et al., 2010), applying lean to the modular building industry (Innella et al., 2019), and analyzing the application of artificial intelligence in lean construction (Dumrak & Zarghami, 2023).

Table 1: Flow management principles. Adapted from Koskela (2000).

Principles	Relevance	Exemplar implementation approaches
Shorten the lead time	Faster delivery, quicker detection and correction of errors, decrease of disruptions	Eliminating non-value-adding time
Reduce undesired variability	Undesired variability is embedded in production flows, and it can hinder system outcomes	Preventive maintenance, reducing set-up times, and improving quality control
Simplify	Cost reduction and higher reliability	Reducing the number of steps in a process or service
Increase flexibility	Increases the variety of products or services in face of changing operational conditions	Developing a multi-skilled workforce
Increase transparency	Making processes directly observable	Using visual devices to share information on process operational status

METHOD

RESEARCH DESIGN

A case study was adopted to address the research question, permitting a deep understanding of the context in which the CI were exposed to the flood (Flyvbjerg 2011). The research design comprised two stages, namely: (I) selection and functional description of the CIs; and (II) modelling of the CI interdependences through the FRAM. In Stage I, 20 CIs were selected either because their service provision was disrupted during the flood or because they had to be set up to mitigate the flood consequences. This set of CIs defines the functional boundaries of

the system under analysis. Each function was described based on its functional purpose, which refers to the expected outputs of the CI. The purpose of the FRAM model developed in Stage II was to understand CI interdependences during the flood. In this model, each CI was represented as a function. In the final FRAM step, consequences of the analysis, opportunities for improving the CI resilient performance were discussed by using the five lean construction principles previously presented as a lens. In addition to the lean principles, these opportunities were guided by two premises: each CI has two major customers, namely the final customer (e.g., community, businesses), and other downstream CIs; and focus on system-wide improvements rather than only on individual CI.

CASE STUDY SCENARIO

The study encompassed CIs affected in Porto Alegre, the capital city of the state of Rio Grande do Sul, Brazil. The city has a flood defense system built in the 1970's as a response to what was then the largest ever recorded flood that occurred in 1941. The system is composed of levees, pumping stations, floodwalls, and flood gates along two major river shores. Porto Alegre experienced a slow-moving and lingering flood that peaked at 535 cm at its central area on May 5, 2024. Several failures in the flood defense system exposed these areas to flooding, affecting CIs across the city and its vicinities. The Porto Alegre municipality keeps an online repository⁴ with flood data, such as affected CI, maps of the flood extent and three-dimensional representations of the affected areas.

DATA COLLECTION AND ANALYSIS

Data collection was conducted by the first author using multiple sources of evidence to allow triangulation⁵: semi-structured interviews, document analysis, and site visits. Semi-structured interviews were carried out with 27 professionals representing 20 CI. Participants were selected through purposive sampling, targeting individuals with leadership roles and/or active direct involvement in supporting essential service continuity during the floods. The research team contacted CI managers, and they recruited one or two representatives from each organization. The diversity of interviewees allowed to explore the event from different perspectives. Recruitment was concluded when the research team judged the interviews provided sufficient coverage of the phenomena within the predefined system boundary and thus additional interviews would be unlikely to affect the FRAM modelling. The interviewees' average time of experience was 24 years in the CI they represented. The interview guide was composed of 15 questions that covered the periods before, during, and after the event. The average duration of interviews was 1 hour, and all interviews were audio recorded and transcribed verbatim. Documents consulted included, but were not limited to, the Porto Alegre contingency plan for civil defense in effect before the flood and reports released by the municipal, state and federal governments stating the status of the CI operations as the event unfolded (around 290 pages). Four site visits (approximately two hours each) were conducted in CI organizations that granted access to the researchers, namely: municipal civil defense facilities; the state civil defense headquarters; the municipal public security headquarters; and the municipal water management department. Site visits consisted of guided tours to the facilities, including control rooms, and informal conversations with staff. During the visits, the first author took notes on a field diary.

A deductive thematic analysis was conducted to identify instantiations of interdependences between the CI based on textual data from the interviews' transcripts, documents and field notes (160,000 words) following the steps proposed by Pope et al. (2000). Familiarization consisted of reading the dataset several times. Next, the concept of CI interdependence presented in the introduction was imposed as a theme to the dataset. Then, excerpts of text associated with the

⁴ <https://prefeitura.poa.br/inundacoes/>

⁵ The data are available from the authors upon request.

theme were identified and coded. Each code corresponds to an instantiation of CI interdependence. Table 2 presents examples of coding. In this step, a 20x20 matrix was drawn to tabulate the interdependences and to calculate the number of upstream couplings (NUC) and the number of downstream couplings (NDC) of each CI. To reduce potential bias from individual researchers, the data were analyzed through iterative discussions among the research team. After identifying the interdependences between CIs, the functions and couplings were modelled following the FRAM steps. Opportunities for applying the lean principles to improve system resilience were guided by the premises presented earlier.

The study was approved by the Federal University of Rio Grande do Sul (UFRGS) research ethic committee (CAEE number 88015625.6.0000.5347).

Table 2: Examples of coding and FRAM representation. Note: input (I), time (T), control (C), precondition (P), resource (R), and output (O).

Excerpts of interviews	Interdependence identification (codes)	Interdependence representation on FRAM instantiation
“Our major difficulty was supplying food to the city of Porto Alegre as there was only one route accessible by road”. (State food distribution hub manager) “In the first days, healthcare workers could not reach the city. The commute took four hours each way”. (Municipal primary care department director)	<State road network> – <State food distribution hub> <State road network> – <Primary care facilities>	

RESULTS

CHARACTERIZATION OF THE CRITICAL INFRASTRUCTURES

The selected CIs and their functional purposes are presented in Table 3. The set comprehends diverse sectors, such as transportation, healthcare, civil defense, public security, education, and urban services.

FRAM INSTANTIATION

Figure 1 presents the instantiation of the FRAM for the scenario under analysis. Table 3 presents the NUC and NDC of each CI. <Power distribution network> and <Flood defense systems> obtained the highest NDC (15). This means that 15 CIs depended directly on the outputs of these functions. Functions with high NDC have high potential for downstream variability propagation. In turn, <Temporary shelter> presented the highest NUC (11), followed by the <Municipal civil defense> (9). This makes sense as temporary shelters were recipients of the services provided by other CIs. The NUC obtained by the municipal civil defense is justified by its bridging role between several CIs in the city. Functions with high NUC are particularly vulnerable to upstream variability.

Table 3: Functional purposes of the CIs.

CIs	Functional purpose	NUC	NDC
Municipal civil defense	To prevent and reduce the effects of disasters and restore normal social conditions in coordination with other municipal CIs	9	11
State civil defense	To coordinate disaster prevention, response, and reconstruction efforts in collaboration with municipal civil defense units and partners	7	8
State firefighting department	To prevent and combat fires, conduct search and rescue operations, and perform civil defense actions	6	3
Porto Alegre international airport	To provide airway mobility for passengers and cargo transportation	5	0
State road network	To promote road mobility integrated to other modes of transport	5	12
Municipal bus station	To manage the intermunicipal passenger transport system	3	0
Metropolitan train	To promote intermunicipal mobility in the metropolitan region of Porto Alegre	6	3
State food distribution hub	To regulate, facilitate, and promote the commercialization of horticultural products by connecting producers, traders, and consumers	7	1
Temporary shelter	To provide temporary shelter and immediate protection for people displaced or affected by disasters and emergencies	11	1
Tertiary care facility	To provide high quality tertiary healthcare	6	1
Primary care facilities	To provide comprehensive healthcare through integrated actions of promotion, prevention, protection, diagnosis, treatment, rehabilitation, harm reduction, palliative care, and health surveillance	7	1
Municipal solid waste department	To promote urban cleaning and manage urban solid waste	3	3
State data center	To develop and provide high value-added technological solutions	6	5
State public schools	To provide education that contributes to the State development	4	1
Universities	To promote teaching, research, and extension, aiming at improving quality of life in society, and articulating response actions with partners	3	6
Telecommunications network	To promote mobile connectivity	3	4
Municipal public security department	To plan, coordinate, and manage societal security and violence prevention policies	4	8
Power distribution network	To distribute electrical energy	3	15
Water catchment, treatment plants and distribution network	To provide public services of water supply, sanitation, and urban drainage	5	9
Flood defense systems	To protect the city of Porto Alegre from floods through an integrated flood protection system composed of levees, floodwalls, gates, and pumping stations	4	15

All functions in the FRAM instantiation displayed output variability. Table 4 exemplifies these variabilities and their implications to other functions. Figure 1 highlights the five examples (A)–(E) among the couplings.

Table 4: Examples of variability propagation across functions.

Example	Upstream function	Output	Variability of the output	Downstream function	Aspect of the downstream function
(A)	<Tertiary care facilities>	Healthcare professionals	Time: on time – healthcare teams were assigned in the early hours of the shelter operation Precision: acceptable – the teams were able to address the main demands of the shelter	<Temporary shelter>	Resource
(B)	<Telecom. network>	Internet connection	Time: too late – disruption was observed for days before connectivity was restored Precision: acceptable – customers affected were supplied by competitor companies in most cases	<State civil defense>	Resource
(C)	<Power distribution network>	Power supply	Time: not at all – power supply was shut down for most water pumping stations Precision: imprecise – lack of power supply led to officials seeking alternatives to reactivate pumping stations	<Flood defense systems>	Resource
(D)	<State road network>	Accessible roads for transportation	Time: too late – flooded roads closed the access to the city's landfill Precision: imprecise – it took several weeks for capacity to meet demand for the transportation of solid waste to the landfill	<Municipal solid waste department>	Precondition
(E)	<Municipal civil defense>	Notification to assist rescue activities	Time: on time – teams respond to the notification after receiving it Precision: imprecise – due to the vast area where victims were distributed, there was imprecision regarding location, clarity of the tasks and availability of resources	<State firefighting department>	Control

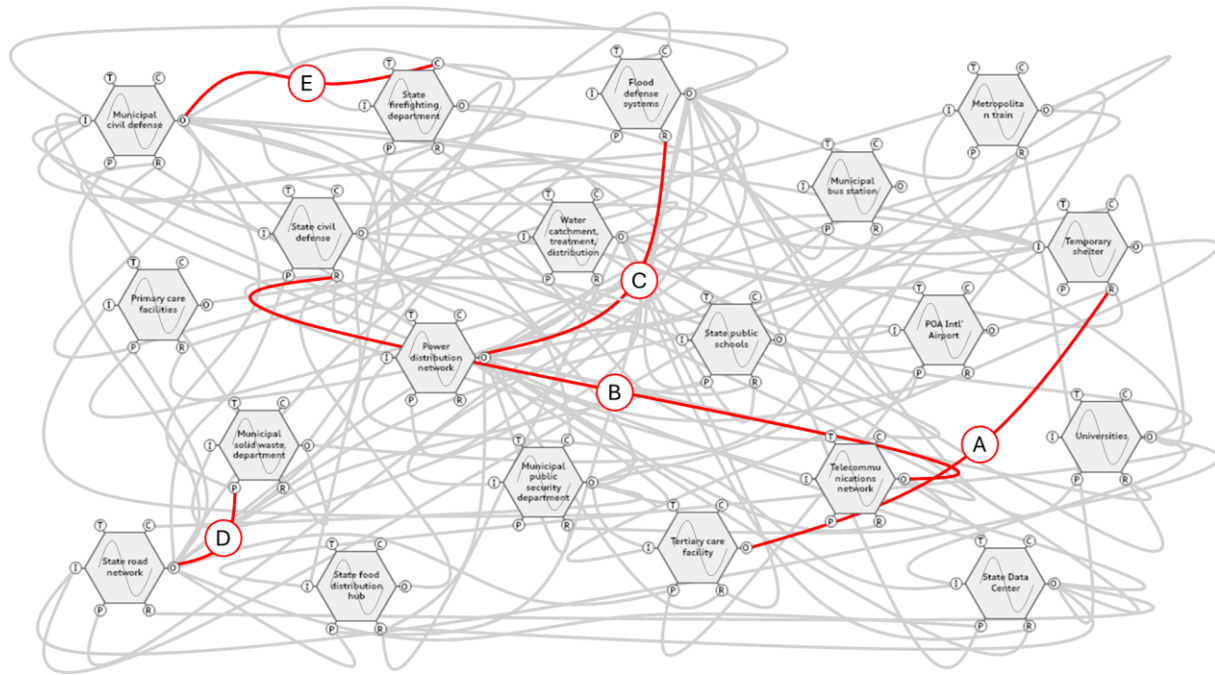


Figure 1: Instantiation of the FRAM.

OPPORTUNITIES FOR THE APPLICATION OF LEAN CONSTRUCTION PRINCIPLES

Table 5 presents a summary of the lean principles' perspective on CI interdependences. Each perspective draws upon the examples (A)–(E) (Table 4).

Table 5: Summary of the application of the lean principles to CI interdependences

Principles	Example	Application
Shorten the lead time	(A)	Reducing patient lead time in shelters.
Reduce undesired variability	(B)	Reducing disruptions in connectivity.
Simplify	(C)	Making CI loosely coupled by dual electricity supply.
Increase flexibility	(D)	Repurposing CI operations to the continuous provision of services and using slack resources.
Increase transparency	(E)	Making the CI operational status visible, enhancing coordination, and incorporating interdependence models to contingency plans.

Shorten the lead time: the <Tertiary care facilities> interdependence with <Temporary shelter> conveys that many healthcare professionals (e.g., nurses, dentists, physicians) were allocated by tertiary care facilities to shelters to provide services to the affected population. This was a patient-centered arrangement that reduced the lead time of patient consultation and the temporal propagation of variability. Other approaches that supported the shelter operation included layout studies to reduce walking distances, multidisciplinary healthcare teams, and volunteers for all the activities performed in the shelter. These approaches also represent manifestations of resilient performance displayed to cope with limited resources and time pressure.

Reduce undesired variability: internet connection was disrupted to different degrees throughout the state. The <Telecommunications network> regulator triggered a national roaming agreement with the main mobile providers in the country in order to reduce signal

variability. The roaming agreement supported the <State civil defense> efforts to rescue and assist the affected people. Rescues were more effective both when civil defense teams were able to communicate with partners (municipal civil defenses, firefighting departments) and when the affected people were able to contact them for help. The roaming agreement reduced the undesired variability stemming from poor connectivity.

Simplify: CI operations can be made simpler either by reducing interdependences or making them loosely coupled. This can be done by the design of slack resources and strategies. For instance, the water pumping stations, part of the <Flood defense systems> were supplied by single electrical connections from the <Power distribution network>. Flooding in protected areas could be reduced if the coupling between the two functions was loosened by adopting redundancies, such as dual electricity supply.

Increase flexibility: due to disruptions in the <State road network>, the road access to the landfill was closed for several days, and the <Municipal solid waste department> had no alternative route to reach the final disposal destination. To continue addressing the regular demand for waste disposal, the department borrowed spare pieces of land from public and private partners throughout the city for waste transshipment. This example shows how the use of slack resources in the form of space can support continuous service provision and prevent the escalation of variability.

Increase transparency: this principle can be observed in the coupling between the <Municipal civil defense> and <State firefighting department>, through which notifications to assist evacuation and rescue operations were sent. Transparency is crucial to reduce coordination delays, especially recognizing that the CI are managed by diverse organizations, such as public and private stakeholders. Another approach for increasing transparency among the functions' interdependences is by incorporating the interdependence models in contingency plans for EWEs, which also assists identifying manifestations of waste that degrade flow.

DISCUSSION

This study used the FRAM as a modelling tool to understand how lean principles can be applied to enhance the resilient performance of CI interdependences during EWEs. Compared with lean construction practices, which do not provide equivalent tools for this purpose, the FRAM enables more realistic modelling of functional interdependences in complex systems. Understanding CI interdependences is relevant for construction and infrastructure systems, where projects are embedded within wider sociotechnical networks. In fact, most CIs presented in the study consist of physical infrastructure assets (e.g., the airport, tertiary care facilities), requiring that they be designed for resilient performance under EWEs in both construction and operation phases. The findings contribute to advancing a systemic perspective of CIs, highlighting how variability propagates beyond the built asset boundaries and how lean principles can be leveraged to manage such complexity in disaster contexts. By analogy, construction sites also require water, energy, waste disposal, staff transportation, and resource logistics to operate, meaning that the study of interdependences is highly relevant for lean construction.

There is a growing body of knowledge on the positive effects of applying lean to enhance resilient performance in sociotechnical systems, such as networks of CIs. In fact, lean production is suitable to tackle complexity stemming from these systems (Saurin et al. 2013). For instance, Hussain et al. (2022) argue for the suitability of lean tools to improve resilient performance in disaster response scenarios through identifying waste, fostering stakeholder collaboration and improving cost-effectiveness. Moreover, the joint effect of adopting lean and resilience might be more beneficial than adopting each perspective in isolation (Brikie 2016). A conflict might exist in the perspectives of resilience and lean on slack, which tends to be regarded as waste by the latter. However, lean acknowledges that designing the right amount

of slack is necessary to avoid disruptions in daily operations, contributing to the complementary view of lean and resilience (Tortorella et al. 2025). An example of slack that is beneficial is the maintenance of dual electricity supply for flood defense systems; whereas an example of slack that would be too costly to maintain is keeping spare pieces of land inside the city for waste transshipment. In addition, slack resources in excess can increase system complexity by amplifying potential interactions and creating emergent risks (Marley et al. 2014). This is exemplified by the need for transporting waste from transshipment areas to the landfill after road conditions were restored, which increased costs and created emergent functions.

Since lean and resilience can be complementary, the examples might indicate an appropriate mix between the two approaches. The high complexity setting in which interdependent CIs operate during EWEs might determine the predominant use of the resilience perspective, while lean plays a secondary role for specific process improvements that aim at reducing waste and unnecessary complexity (Rosso & Saurin, 2018). For example, the shelter operated without meeting preconditions usually found in healthcare settings, which required healthcare professionals to display resilient performance. Lean principles could gradually be applied as a means to enhance value for the patient through the removal of waste (Bharsakade et al., 2021).

Overall, the development of a comprehensive CI interdependence model that enhances transparency also permits CIs to search for best practices developed by others. During the flood reported in this study, distinct CIs presented similar manifestations of resilient performance to operate under degraded conditions, meaning the rationale for adaptation might be similar while practices vary. Furthermore, the occurrence of EWE such as the one described in this investigation should trigger the revision of contingency plans emphasizing failures in CI interdependences in sake of pursuing continuous improvement. Depending on the type and magnitude of the event, the FRAM instantiation could be tailored to include a varying number of CIs. A systemic representation of the network of CIs could enhance the design of future lean interventions in the different phases of an EWE.

CONCLUSIONS

The FRAM was used to explore the application of lean principles to enhance resilient performance of CI interdependences, adopting a systemic perspective. A FRAM instantiation was developed encompassing 20 CIs affected during the 2024 floods in Brazil. The study shows the applicability of five lean principles to manage CI interdependences, namely: shorten the lead time, reduce undesired variability, simplify, increase flexibility, and increase transparency. One limitation of the study is its application to a single case study regarding a single city and a single EWE. Another limitation regards the FRAM model being developed at a higher abstraction level with low granularity. In this respect, future studies could investigate the applicability of the lean principles (i) to other contextual settings and EWE, and (ii) to develop FRAM models that represent CIs with higher granularity. Further opportunities regard (iii) taking advantage of CI interdependence modelling to propose system redesign based on the lean principles, and (iv) applying the FRAM to make sense of CI interdependences in construction processes.

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