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Towards Resilient Civil Infrastructure Asset Management: An Information Elicitation and Analytical Framework

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Abstract: It is rather difficult for the stakeholders to understand and implement the resilience concept and principles in the infrastructure asset management paradigm, as it demands quality data, holistic information integration and competent data analytics capabilities to identify infrastructure vulnerabilities, evaluate and predict infrastructure adaptabilities to different hazards, as well as to make damage restoration and resilience improvement strategies and plans. To meet the stakeholder's urgent needs, this paper proposes an information elicitation and analytical framework for resilient infrastructure asset management. The framework is devised by leveraging the best practices and processes of integrated infrastructure asset management and resilience management in the literature, synergizing the common elements and critical concepts of the two paradigms, ingesting the state-of-the-art interconnected infrastructure systems resilience analytical approaches, and eliciting expert judgments to iteratively improve the derived framework. To facilitate the stakeholders in implementing the framework, two use case studies are given in this paper, depicting the detailed workflow for information integration and resilience analytics in infrastructure asset management. The derived framework is expected to provide an operational basis to the quantitative resilience management of civil infrastructure assets, which could also be used to enhance community resilience.

Keywords: resilience management; infrastructure asset management; information elicitation; analytical framework

1. Introduction

Currently, civil infrastructure systems are facing unprecedented challenges ranging from ageing assets, limited maintenance budget, surging facility usage to society's outcry for quality services and natural hazards due to climate change [1]. The growing interdependencies and interconnectedness have exacerbated the difficulties and complexities of managing and operating these systems, risk governances, and particularly of improving their capacity, reliability, and sustainability against climate change, natural disaster, adverse events, or man-made threats. There have been myriad theories, models, tools, processes and frameworks related to infrastructure asset management (IAM), resilience management (RM), system reliability and vulnerability analysis, risk management, and emergency and disaster management [2,3]. However, it is still a daunting task for the stakeholders to use them effectively in making resilience improvement strategy, developing tactical and operational plans, monitoring execution, and optimizing performance. There is an urgent need for a synthesized framework for integrated resilient IAM, as existing research and practices mainly focus on coping with limited specified hazards and processes, and using them in an isolated manner by decision-makers from different disciplines could lead to unintended and inconsistent results. The framework needs to be capable of articulating the explicit inputs for the resilience analysis of infrastructure systems under different adverse event scenarios (e.g., acute service disruptions, chronic stress like ageing issues, and uncertain natural hazards); supporting different RM processes (e.g., pre-event mitigation and post-event recovery), incorporating good engineering practices (e.g., resilience engineering by Hollnagel and others) [4,5]; and integrating with various quantitative modeling approaches and qualitative analysis methods, such as a system-theoretic accident model and process (STAMP), functional resonance analysis method (FRAM), and resilience analysis grid (RAG) methods.

In response, this paper develops an information elicitation and analytical framework for resilient inter-networked infrastructure asset management (RIAM). The framework comprises two components: Asset information elicitation and resilience analytical workflow. The asset information elicitation describes what types of data are required for RM, e.g., infrastructure asset configuration and condition data, community characteristics, hazards and disruption profiles, and infrastructure performance metrics. The resilience analytical workflow depicts the detailed steps for analyzing the resistant and absorptive capacity, adaptive capacity, and recoverability of interdependent infrastructure systems. The framework is designed in a modular manner; different stakeholders can reuse, replace, or implement any of its sub processes according to their data availability, analytics capability, and unique business objectives. Two general cases are presented to illustrate the applicability of the proposed framework, which can guide soliciting and organizing information and for analyzing the resilience of community infrastructures by a community manager. The framework is effective in assembling and aggregating the fragmented and diverse infrastructure data source. Besides, flexible decision-making analysis models can also be configured, integrated, or developed to carry out resilience analyses at different temporal and spatial scales and in corresponding real or speculated hazard scenarios. The study contributes to the integration of domain knowledge from diverse disciplines to make maximum use of existing theories, models, and frameworks to facilitate RIAM, and provides an operational approach to the RM of civil infrastructure systems, which could also be used to enhance community resilience.

The remainder of this paper is organized as follows: Section 2 reviews core data source and analytical capabilities in IAM, RM related concepts, theories, and processes, and investigates the synergy between IAM and RM. Section 3 briefly introduces the methodology adopted in this research. Section 4 details the information elicitation and the analytical framework. A brief validation is presented in Section 5. Two typical use cases are presented in Section 6. Finally, conclusions, the study's implications, and directions for future research are given in Section 7.

2. Background

2.1. Core Data Sources and Analytical Capabilities in Infrastructure Asset Management (IAM)

Infrastructure asset management (IAM) is defined as a series of coordinated activities in organizations to achieve the predefined level of services through cost-effectively managing their infrastructure assets. Great efforts have been made to standardize the IAM process in terms of information and process integration, and cross-sector coordination to avoid functionality fragmentation and information "silos", which would affect the effectiveness of communication and coordination across different infrastructure system owners or operators when joint decisions pertinent to sustainable and resilient infrastructure are made. Notably, the authors have devised an integrated infrastructure asset management framework to structure associated sub-processes such as asset inventory management, condition monitoring, performance assessment, criticality identification/vulnerability analysis and rehabilitation, and renewal and capital improvement to facilitate consistent and effective IAM practice within and between organizations [6].

Emerging information and communication technologies (ICT) serve as important catalysts to transform the practices of infrastructure asset management (IAM) since a large amount of timely data would enable informed decision-making. Ironically, adopting cutting-edge technologies has led agencies to collect abundant data and create vast databases, which have not always been useful or necessary for supporting the decision-making process. This implies that in many cases, the data collection activities have not been designed specifically to support the decision process inherent in asset management. It is thus both effective and pragmatic to link data collection policies, standards, and practices to their asset management decision-making processes, especially for project selection. Ideally, analytical capabilities of infrastructure asset management should be elaborated and predefined in advance of data collecting practice. Figure 1 outlines the core data sources, enabling tools and mainly analytical capabilities proposed for IAM, which follows an "Input–Process–Output" principle. "Input" denotes the core asset data used for further analysis by enabling tools. "Output" indicates the expected outcomes for strategic decision-making encompassing identified needs and solutions, evaluated options and investment versus performance tradeoff results. "Process" represents detailed analytical capabilities IAM may equip with. The peripheral portion of "Analytical capabilities for IIAM" modules in Figure 1 constitutes performance tradeoffs within programs for different investment levels. While the inner parts of the analysis module represent those performance tradeoffs across programs for different investment levels. Regardless of within- and across-program analysis, all the analytical functions accommodate the two convergent characteristics of IAM analytics: 1) Measure the level of "performance enhancement" when asset management improvement strategies are implemented; 2) tradeoff analysis when allocating limited funds. Further analytics should be well suited to helping with decisions that cross the boundaries of asset types (e.g., pavement versus bridge), mode (e.g., highway versus transit), work class (e.g., maintenance, operations, or capital), and objective (e.g., safety, quality, preservation, or mobility). It is worth noting that since different programs adopt different objectives and performance measures, thus formulating common measures for comparison is imperative.

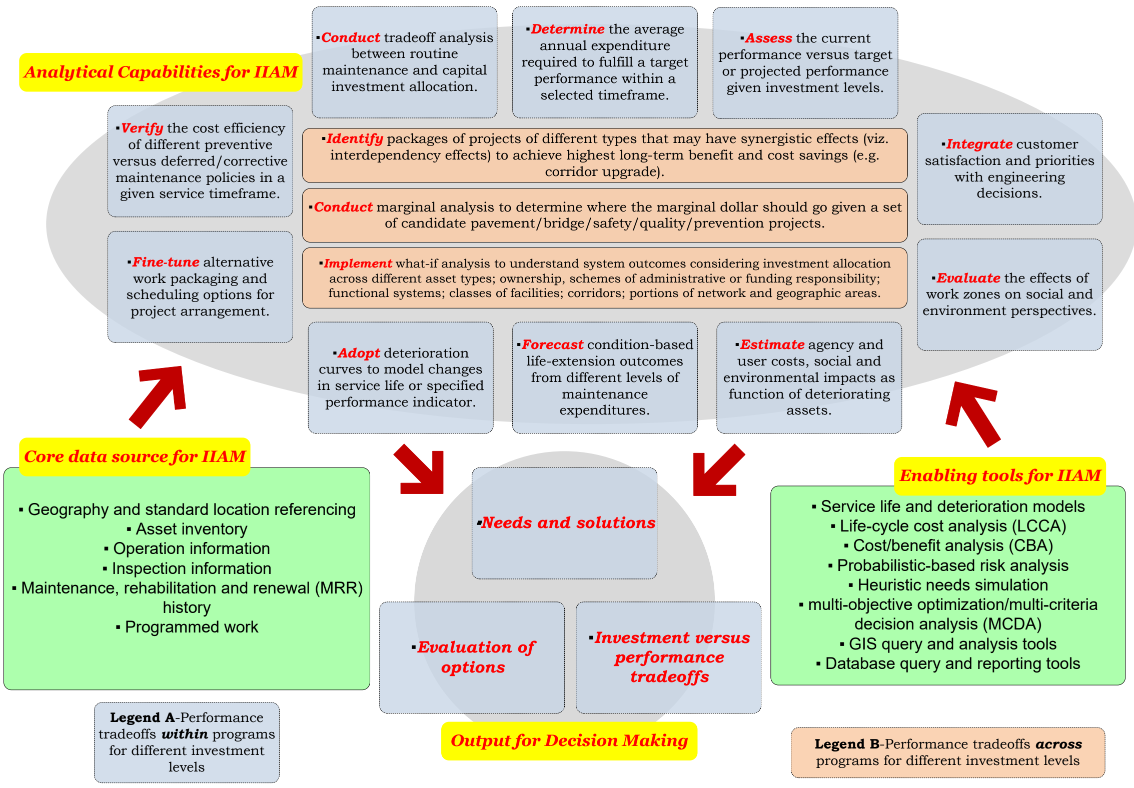

Figure 1. Core data sources, enabling tools and analytical capabilities for infrastructure asset management (IAM), summarized by the authors with reference to the IAM standards and specifications listed in our previous work [6].

2.2. Resilience Related Concepts

Resilience-related concepts and practices appear to be imperative recently since ageing problems, and frequent and severe natural hazards as well as antagonistic man-made accidents collectively stress the infrastructure systems in both the short- and long-term timeframe. Resilience received its first fundamental definition in the ecological domain, thus called ecological resilience [7], concentrating on the dynamic attribute of system equilibrium rather than the sole steady state. This type of resilience could potentially apply to socio-economic systems. Comparably, engineering resilience emphasizes stability near one equilibrium state, in which capabilities of resistance to disturbance and speed of return are adopted to measure resilience property [8]. Besides ecological resilience versus engineering resilience, static resilience vs. dynamic resilience is another pairwise of concepts worthy to be distinguished. Static resilience is the ability of a system to maintain function when shocked, which focuses on the resistance capability of a certain system. While dynamic resilience considers speeding up the recovery process to re-attain the desired state, which highlight the restoration capacity of one system [9]. The above two pairs of concepts (viz. ecological vs. engineering resilience and static vs. dynamic resilience) are the most elementary and acceptable that many subsequent derivative definitions could be found [10]. It is inevitable that overlaps would exist when so many resilience-related concepts prevail in research, so it would be beneficial and indispensable to draw relatively identifiable boundaries between concepts such as risk, reliability, vulnerability, robustness, resilience, etc.

Table 1 summarizes the main attributes of these resilience related concepts.

Table 1. Clarification of resilience-related concepts.

Concepts	Main Attributes
Risk	- Four typical questions: "What can happen? How likely is that? What are the consequences? What can be done with it?"
	- Risk scenario as a "triplet": A scenario description, the probability, and the consequences (measure of damage) [11]
	- Risk is conceptualized as all the set of possible such as the "triplet" [12]
	- Typically focus on identifying hazards or threats to the system and the likelihood of scenarios occurring
Reliability	-"The probability of a device performing its purpose adequately for a timeframe intended under the operating conditions encountered" [13], with no focus on the inherent ability to survive and recover from failure [14]
	- Appropriate for high frequency–low impact events [15]
	- Applicable to component level, system level, and "system of systems" level
Vulnerability	-"The susceptibility of the system or any of its constituents to harmful external pressures" [16,17]
	- Appropriate for low frequency–high impact events
	- Vulnerability analysis focus on the consequences that arise given system failures and not on the likelihood of the various hazardous events [18]
Robustness	- "No performance loss is allowed in the case of robustness" [14,19,20]
	- Appropriate for high (or medium) frequency–moderate impact events
	- Normally treat as an alternative mitigation strategy when vulnerability is regarded as unacceptable

Table 1. *Cont.*

Concepts	Main Attributes
Resilience	- Ecological resilience [7] vs. engineering resilience [8]
	- Static resilience vs. dynamic resilience [9,21]
	-"Emphasize response of system, its elasticity or capacity to rebound after a shock, indicated by the degree of flexibility, persistence of key functions, or ability to transform" [16,22]
	-"A resilient system may permit a (sometimes temporary) performance loss in "bouncing back" from the adverse event" [14,19]
	- Appropriate for low frequency–high impact events
	- More appropriate for system and "system of systems" level - Normally treat as an alternative mitigation strategy when vulnerability is regarded as unacceptable

For specific clarification, Figure 2a illustrates schematically the distinction between reliability and vulnerability. The horizontal axis represents the increasing severity of consequence and the vertical axis indicates the cumulative probability of scenarios with consequence greater than a predefined level. In the occurrence of "low frequency–high impact" events, vulnerability theory is more appropriate to be leveraged for further decision-making. While when encountering "high frequency–low impact" events, reliability theory is more suitable since we base it on statistical estimates with abundant empirical data about frequencies and consequences. Additionally, antagonistic attacks are genuinely challenging to predict both with respect to frequency and location as compared to natural threats and technical and human-error failures for which it is possible to collect statistics that are beneficial for prediction and prevention [23]. Figure 2b outlines the relationship between vulnerability, robustness, and resilience. The curve shape depends on ex ante mitigation, which leads to reduced loss of function and on ex post adaptation, which generates a rapid recovery procedure. The residual system function after disruption indicates the level of robustness. The area between the dotted lines that respectively corresponds to the target performance and reduced performance after shock denotes conditional vulnerability [23,24].

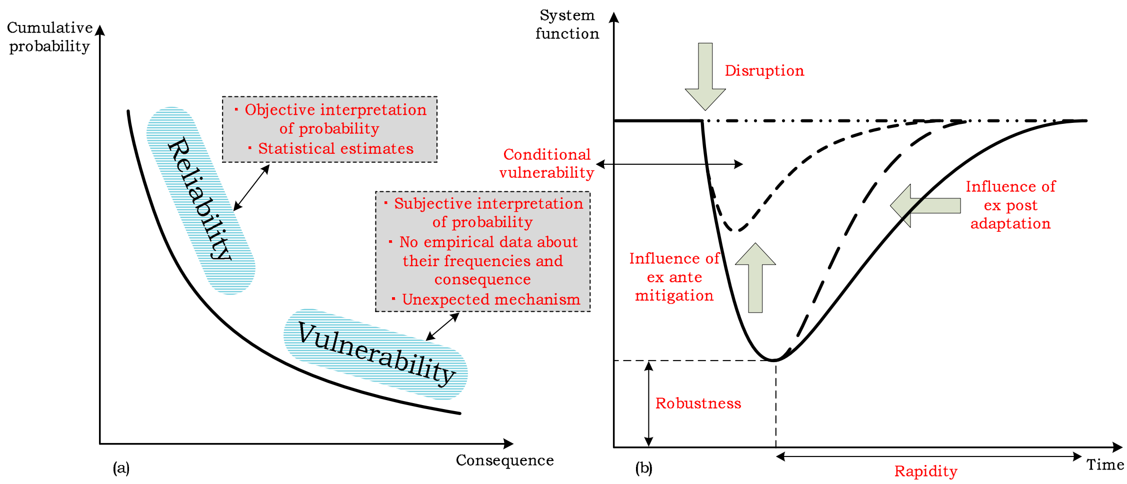

Figure 2. (**a**) Risk curve illustrating the distinction between reliability and vulnerability, by courtesy of [23]; and the (**b**) resilience curve and effects of ex ante mitigation and ex post adaptation, by courtesy of [23,24].

2.3. Infrastructure Resilience Analysis Frameworks Against Natural Disasters

The ability (of an asset, a system, or an organization) to withstand, adapt to, and recover from a disruption is generally referred to as resilience [19,25]. It is crucial to quantify resilience systematically through the lens of comparing system performance of interrelated disaster management sub-processes, viz. mitigation, preparedness, response, and recovery. Current resilience management (RM) research has moved forward from the conceptual debate to operational paradigms. In response, many resilience assessment frameworks and toolkits have emerged with representative studies encompassing the system-theoretic accident model and process (STAMP), functional resonance analysis method (FRAM), and resilience analysis grid (RAG) methods by Hollnagel, Woods, and others [4,5,26,27], 4R model [28], four-cornerstone model [4,29], three-stage resilience analysis framework [30], compositional demand/supply framework (Re-CoDes) [31], and physics-based framework [32] in order to enlighten the resilience assessment of urban infrastructure systems while the disaster resilience scorecard for cites [33], baseline resilience indicators for communities (BRIC) [34], and PEOPLES resilience framework [35] mainly address the community or regional-level disaster resilience analysis. These frameworks can explain how people deal successfully with unexpected and unforeseen events, highlighting the steps from work-as-imagined to work-as-done resilience and even promoting more strategic and tactical control within daily operations. The common characteristics in terms of representative infrastructure resilience assessment frameworks pertains to that they address the constrained infrastructure system functionality degradation and rapid recovery process after the disruption. Detailed analytical sub-processes in these frameworks involve hazard characterization, infrastructure component fragility modeling, adverse consequences propagating between interdependent infrastructure systems, restoration strategies planning, etc. These frameworks are of value to be investigated as we can identify and tease out the themes and processes emphasized in each framework, which facilitates the reconfiguration of these selected processes in our derived RIAM framework to reveal the potential interactions between IAM and RM analytical capabilities.

2.4. Synergy of the IAM Process, Resilience Analysis, and Disaster Management

Traditional IAM primarily focuses on the practices of asset operations, asset condition monitoring and assessment, maintenance and rehabilitation, and capital improvement planning, which generally assume that the infrastructure systems function as expected under normal conditions. Currently, a number of regulations and guidelines governing climate change mitigation, natural disasters, and prevention of man-made incidents have posed new expectations. A broad range of theories and approaches have been developed for meeting such expectations, including risk management, reliability engineering, vulnerability system analysis, and system robustness tests [14,22]. The most popular recent resilience engineering treats infrastructures as systems of systems, considering the effect of component failures on the performance of interdependent systems or networks. This transforms IAM from an asset inventory-centric focus to a higher systematic-level discipline-resilient IAM (RIAM) [11,36,37], where interdependency has become the nexus of IAM and RM due to the growing interconnectedness of infrastructure systems. From an IAM perspective, failing to understand the interdependency between and among infrastructure systems can lead to the disarrangement of resources, ineffective responses and inadequate coordination between agencies and decision-makers. While from a resilience perspective, interdependency is practically demonstrated by tangible and physical interactions between systems, which could result in knock-on or ripple effects even from minor component failures.

Ultimately, a synergized holistic landscape of RIAM, as shown in Figure 3, could demystify their intricate relationships and assemble diverse processes (IAM, risk and reliability analysis, vulnerability analysis, resilience assessment, and even disaster management). The landscape includes both pre-disaster processes (e.g., risk and vulnerability analysis) and post-disaster processes (e.g., response and recovery). Underpinned by these process models, it is possible to identify which concepts (viz. risk, reliability, vulnerability, and robustness) contribute to which resilience sub-processes. In IAM, once a large amount of statistical data is accumulated, a risk-based and reliability analysis can be used for decision-making to deal with certain types of natural hazards [38]. Complementarily, vulnerability analysis is suitable for less-frequent hazards. Figure 3e articulates the resilience analysis framework's three core elements, formulated based on the landscape for resistant, absorptive, and restorative capability [30,39].

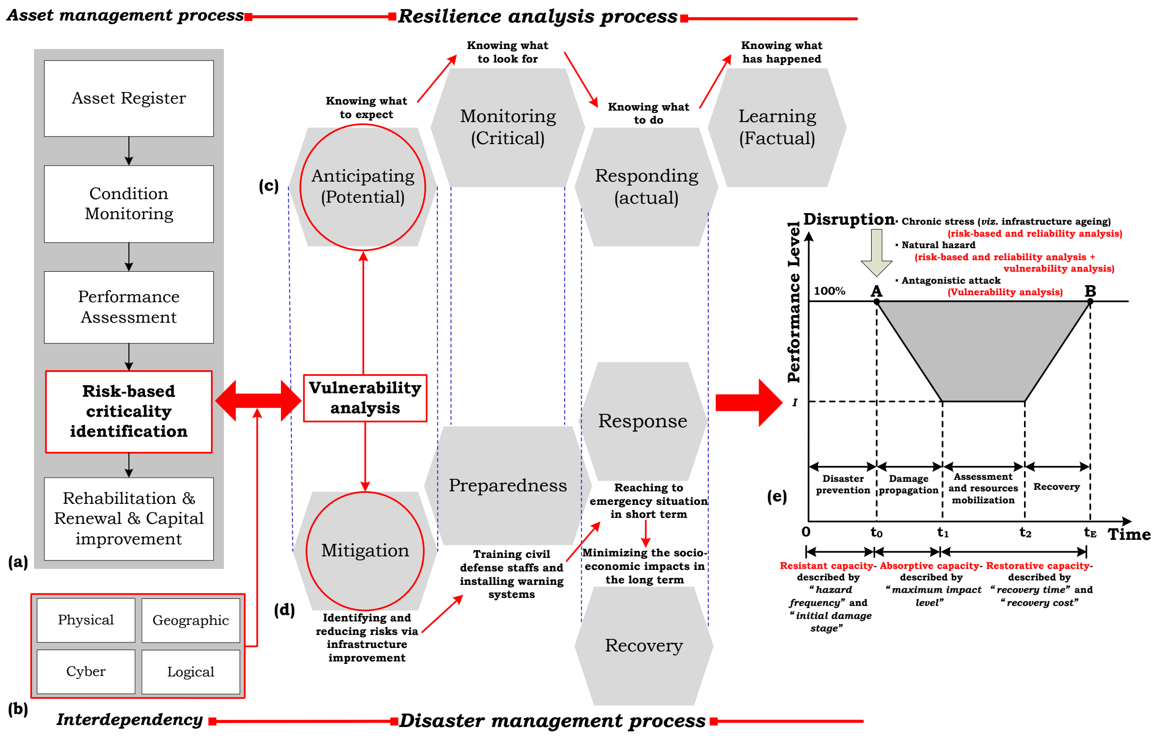

Figure 3. Alignment of the IAM, resilience analysis, and disaster management processes, with (**a**) the IAM process; (**b**) interdependency; (**c**) resilience analysis process (viz. four cornerstones model), by courtesy of [5]; (**d**) disaster management process, by the courtesy of [40]; and (**e**) different stages and corresponding capacities of resilience assessment (viz. three-stage resilience analysis framework), by courtesy of [30].

A comprehensive literature review reveals a lack of harmonized framework for the resilient asset management of interdependent infrastructure systems due to the broadness of the resilience related concepts and discrepancies between the emphasis in IAM and RM analytical processes. Therefore, to cope with the growing complexity of infrastructure systems and uncertain adverse events/hazards, a multi-disciplinary synergistic approach that addresses and coordinates both IAM and RM analytical requirements is clearly needed for informed decision-making.

3. Research Methodology

Owing to the exploratory and interpretive nature of this study, qualitative approaches are adopted to investigate the literature and current practices of both the IAM processes and RM analysis, which could inform the derivation of the framework. Conforming to the principles of grounded theory, which is a "code-concept-category-theory" based, hierarchical, and inductive research paradigm, code source is primarily determinant to validity and authenticity of the formulated framework [41]. Apart from soliciting from the literature, expert judgments are also posited as code sources to complement and refine the information solicited through literature review process. We referred to the four linked sequential phases suggested by [42] to elicit the constitutes that experts recommend to be involved in the induced framework: (1) Structuring and conditioning, in which we develop ways to structure the expert judgments, according to background knowledge that pertains to required information and processes for RIAM that we have prepared through literature content analysis; (2) expert interviews, in which we introduce the basic concepts summarized from literature to the selected experts, and identify from their remarks in each selected themes the key categories to be addressed in the framework; (3) data synthesis, in which we assemble the results of individual interviews into preliminary checklists and diagrams; (4) information sharing, feedback, and revision, in which a workshop is conducted to allow information sharing among the interviewees, clarify the vagueness and build the consensus, and update the preliminary results.

It is noteworthy that in the step of structuring and conditioning, related IAM guidelines and reports, pioneer RM frameworks presented in peer-reviewed journals were examined prior to interviews to identify preliminary information and analytical requirements. Based on our previous work in [6], we scrutinized the listed representative IAM standards and specifications to identify the hints for resilience expectations in these IAM-specific documents. On the other hands, existing resilience assessment frameworks were also investigated and we rethought the opportunities to incorporate IAM features in our formulated RIAM framework. This resulted in five themes of interview being designed to obtain insights into the requested information and analytical capabilities from the perspective of practitioners, of:

(i) The role of IAM in RIAM, including such sub-topics as asset inventory, condition grading, criticality identification, and interdependency considerations;

(ii) Vulnerability analysis in infrastructure systems, constituting the network topology, functioning mechanism, strategies to identify component fragility, system performance degradation, and societal consequence due to service disruption;

(iii) Delineation of hazards or disruptions, consisting of the frequent hazards encountered by the community and identified hazard prone areas;

(iv) Restoration of failed components of infrastructure systems, encompassing emergency management, project scheduling, and strategies for resource prioritization;

(v) Performance metrics for assessing infrastructure resilience, investigating the participants' opinions concerning the suitable and multi-dimensional selection of performance metrics to evaluate infrastructure resilience.

Twelve participants were selected by convenience and snowball sampling [43]. Individuals selected for the interviews were organizational specialists on infrastructure engineering and system performance or emergency response, or both. Table 2 summarizes their widespread range of profiles—ensuring the interview results would be representative, generalizable, and referenceable. The interview participants were asked to highlight the information required for decision-making under each of the five themes. We asked questions about how the infrastructure systems plan for extreme events, what source of hazards to be investigated, how to accommodate infrastructure component conditions during the resilience assessment process, what types of information need to be solicited and aggregated, about ways to reduce regional vulnerability to interdependencies among infrastructures. Following [44], valid remarks were then identified from the recorded transcripts and further classified into key findings. Excerpts of the remarks and key findings are summarized in Table 3. These key findings were developed into broad patterns, theories, or generalizations to complement the existing literature and are also addressed in the framework [45].

Table 2. Profiles of the interview participants.

Code	Infrastructure Sector	Institution	Position	Experience (Work Years)
1	Water-related	Government department	Assistant Director	>10
2	Water-related	Government department	Senior Engineer	>5
3	Water-related	Government department	Senior Engineer	>5
4	Road	Government department	Chief Engineer	>10
5	Road	Government department	Senior O&M Engineer	>5
6	Road	Government department	Senior O&M Engineer	>5
7	Electricity	Service provider	Senior Operation Engineer	>5
8	Electricity	Service provider	Senior Operation Manager	>5
9	Railway	Service provider	Senior Electrical and Mechanical Engineer	>5
10	Railway	Service provider	Senior Electrical and Mechanical Engineer	>5
11	Utilities	Consultancy	Senior Engineer	>10
12	Utilities	Consultancy	Engineer	>3

Based on the comments in Table 2, the framework was aimed at addressing the following eight issues: (i) Integrating condition-based IAM with RM; (ii) combining topology-based and flow-based analysis paradigm in RIAM; (iii) operationalizing interdependency in vulnerability analysis; (iv) conducting hazard map delineation to identify hazard prone areas; (v) treating ageing components in the infrastructure system as a special type of hazard; (vi) treating restoration decision as an optimization issue with available resources as a constraint; (vii) identifying priorities (e.g., special technical and societal considerations) in the restoration process; and (viii) selecting performance metrics from a multi-dimensional standpoint. Afterwards, a workshop was held to invite the interviewed experts and the purpose was to (1) provide all participates with an overview of interview findings, (2) entitle opportunities for feedback and revisions, and (3) develop a consensus perspective on the information and analytical requirements in the RIAM framework. In such a way, the framework was validated and modified based on the feedback from the current and future implementers of IAM and resilient practices. Case studies were further conducted for illustrative purposes—one focusing on information aggregation practices, and the other to elaborate the RIAM analytical processes. The proposed RIAM framework in this research is developed through the overall research procedures summarized in Figure 4.

Table 3. Excerpts from the interview participants' remarks on the selected themes.

Selected Themes	Participant Remarks	Identified Key Findings
The role of resilient IAM	○ " . . . it is necessary to incorporate infrastructure asset condition grading in resilience assessment since the ageing problem besets the community . . . " ○ " . . . we can reap the benefit of integrating condition assessment with network analysis . . . " ○ " . . . from an asset management perspective, we are accustomed to allocating maintenance and rehabilitation resources based on condition assessment results, with insufficient consideration of the network level, while from a system engineering standpoint, they usually conduct network analysis regardless of the different default conditions of the system components . . . thus it is really a good opportunity to merge these two paradigms . . . " ○ " . . . if you want to conduct risk analysis at the network level, you should tease out the required information as inputs; broad information stored in an asset management system, especially that on the operational side, can lend you a great hand . . . "	(i) Integrate condition-based IAM in resilient IAM
Vulnerability analysis of infrastructure systems	○ " . . . vulnerability analysis should be conducted in a comparative manner, since we have limited resources and we should allocate resources firstly to the most vulnerable components . . . " ○ " . . . we also have the process of vulnerability assessment in our IAM platform, but it is condition-based . . . if we complement this analysis with topological and functional information, the results can be totally different . . . " ○ " . . . we are interested in how to combine the different vulnerability analysis models to facilitate decision making . . . " ○ " . . . we have noticed that some of the problems in our infrastructure system are not induced by vulnerabilities within our system scope, but the unexpected events outside our system boundary, which are out of our control . . . what is worse, we seldom conduct this kind of vulnerability analysis that transcends two different systems . . . "	(ii) Combine thetopology-based and flow-based analysis paradigms in resilient IAM (iii) Operationalize interdependency in vulnerability analysis
Hazard or disruption delineation	○ " . . . our department has the delineation of a landslide-prone area in our system . . . and as I know the highway department uses this information to make traffic-regulation decisions during heavy rain . . . " ○ " . . . we have a hotpot of flooding in our system . . . which is based on empirical data collected over the years . . . " ○ " . . . it is valuable to analyze the potential hazard . . . essentially, you need to identify the most frequent hazard encountered by our community since different communities have different concerns about hazards . . . " ○ " . . . the chronic stress in IAM is ageing components, which could be treated as a special hazard threatening the community . . . "	(iv) Conduct hazard map delineation to identify the hazard prone areas (v) Treat the problem of ageing components in infrastructure system also as a special type of hazard

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Restoration of failed components in infrastructure systems	○ " . . . restoration work is much more related to the emergency plan enacted by each authorized agency . . . " ○ "... the responsible agency should have a detailed recovery plan when service disruption occurs . . . and priorities should be identified . . . so to some degree, the restoration can be treated as an optimization problem . . . " ○ " . . . we usually choose to recover the critical nodes and lines first because of their dominance in the network . . . moreover, we usually choose to recover the node connected to other systems first . . . and nodes that serve a special group of community members (e.g., disadvantaged groups) are presumed to be recovered first . . . " ○ " . . . we can have different recovery strategies in the decision pool and choose the one with the most rapid recovery process of infrastructure performance . . . "	(vi) Treat restoration decision making as an optimization issue with the constraint of available resources (vii) Identify priorities in the restoration process
Performance metrics for assessing infrastructure resilience	○ " . . . it is necessary to choose suitable performance metrics to measure the dynamics . . . " ○ " . . . you should have your own preference when selecting the performance metrics . . . for example, you can select the connectivity metrics on the technical side, and you can also select the proportion of the users with recovery service on the social side . . . " ○ " . . . you can refer to the available performance metrics in each infrastructure sector rather than devising new ones . . . and I think each infrastructure sector have their generally used performance metrics . . . " ○ " . . . it is reasonable to investigate performance recovery from multiple dimensions and to make the trade-off between different dimensions . . . "	(viii) Select performance metrics from a multi-dimensional perspective

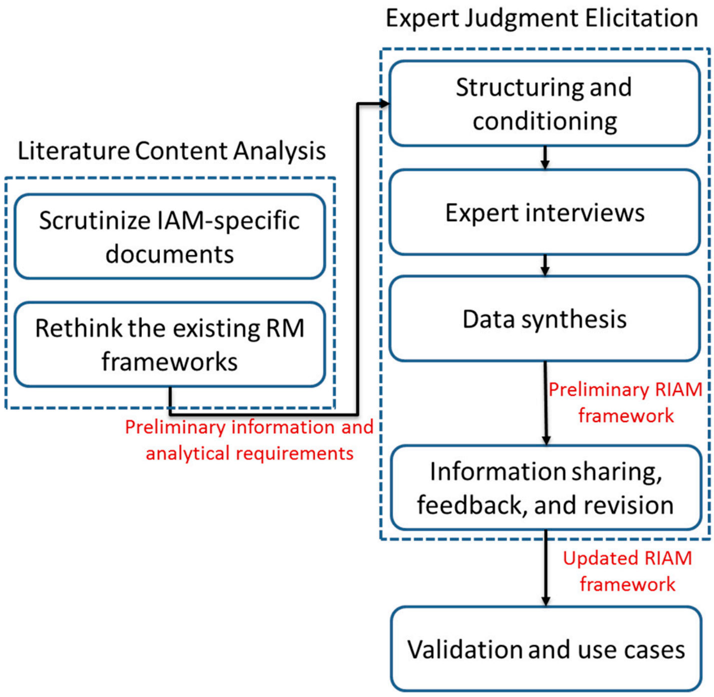

Figure 4. The overall research procedure to develop the resilient civil infrastructure asset management (RIAM) framework.

4. The Resilient Civil Infrastructure Asset Management (RIAM) Framework

The framework comprises of two parts: The information aggregation process and resilience analytical workflow. The information aggregation process describes what types of data (e.g., asset location and condition data, community characteristics, hazards and disruption models, and infrastructure performance metrics) are required for RM. Resilience analytical workflow, on the other hand, depicts the detailed steps for analyzing the absorptive capacity, adaptive capacity, and recoverability of interdependent infrastructure systems. The information aggregation process outputs and results can be used as inputs for some steps in the resilience analytical workflow. Deep and seamless integration of infrastructure asset data with resilience analysis can complement the risk management practices adopted in the traditional IAM, and support comprehensive resilience decision making for cross-sector integrated infrastructure operation and management.

4.1. RIAM Information Elicitation

The initial step to operationalize the resilience-related theories and concepts is an information model. The model's elements can be materialized from four dimensions: (i) Data pertaining to IAM; (ii) information characterizing community members and their needs; (iii) information for specified disruptions; and (iv) performance metrics. Note that (i) and (ii) are not exhaustive because of the complexities and diversities of the services, configurations, operations, and management of different infrastructure systems. Therefore, only a generic information model is provided, which can be customized based on the stakeholders' unique organizational characteristics, distinctive management granularities, and diverse business objectives.

4.1.1. Information Pertaining to IAM

A global unique identifier (GUID) is designated to identify an individual asset entity in the infrastructure asset encoding system [46] for linking the static and dynamic data of an entity. The static data comprises spatial and non-spatial data. Location information including latitude and longitude can be used to depict the absolute location of an asset unit in the global coordinate system, while connectivity and adjacent data provide its relative location. Non-spatial data, such as geometric and physical information, provide a rudimentary boundary representation of an asset. Such myriad asset attributes as material type, condition, functional properties, ownership, construction, and installation dates also need to be embedded for maintenance and rehabilitation purposes [47]. Maintenance and rehabilitation records are tracked mainly for condition assessment. Cost information is needed for conducting a tradeoff analysis since cost is the main determinant of project selection. This information, together with as-built drawings (e.g., building information models) and operation specifications are critical for risk management and RIAM. For example, the technical specifications could include the statistical profile of response and repair times for different categories of components facing different hazards with varying intensities.

Mature and standard data models have already been adopted and deployed by a wide range of municipalities and utility companies for municipal IAM. Representative examples include the Federal Geographic Data Committee (FGDC) data standard; Spatial Data Standards for facilities, infrastructure, and environment (SDSFIE); Environmental Systems Research Institute (ESRI) data models; LandXML; Municipal Infrastructure Data Standard (MIDS); Pipeline Open Data Standard (PODS); and an ongoing endeavor called 'IFC (viz. Industrial Foundation Classes) for GIS'. For pipeline information, these standards define the detailed physical parameters involved, including the pipe location, material, diameter and depth, exterior coating, joint type, lining type, roughness, date of installation, type of pressurization, type of value, and work order administration [48]. Some standards have their own emphasis. For example, LandXML is dedicated to describing the hydraulic properties of pipelines, such as pipe flow, maximum flow levels, and hydraulic grade attributes [49]; the PODS data standard elaborates asset inspection and condition [50].

4.1.2. Information Characterizing Community Members and Their Needs

Communities comprising different races, cultures, income and education levels, and demographics may have different resilience capabilities and be affected differently by similar infrastructure disruptions, so their recoverability and adaptability may be unique given their socio-economic characteristics. Many empirical studies show that hazard and disaster risks differ between communities [51]. Improving community resilience involves incorporating infrastructure network resilience with other social capital for the allocation of pre-disaster resources and aiding post-disaster recovery and priorities. The potentially influential characteristics affecting community infrastructure investment decisions include (i) such demographic data as age, gender, and education level, (ii) the geographic locations of disaster-prone areas, (iii) social vulnerabilities and inequities within the population (e.g., proportion of special needs groups within the community), (iv) diversity of community members' needs, (v) community economic profile (e.g., employment rate), and (vi) insurance coverage [34,52,53]. Moreover, the user costs of intervention strategies can be crucial for some maintenance and rehabilitation projects. For example, the user costs due to the partial or full loss of transportation assets (e.g., lane and bridge closures) should be well documented since they determine the effect of transportation construction projects on a community scale. Furthermore, the impact of infrastructure component damage and its service condition, as well as the socio-economic benefit of prompt recovery, are necessarily measured by user cost at the community level [54].

4.1.3. Information for Specific Disruption

Identifying and understanding all hazards (e.g., hazard types, frequencies, patterns, magnitude and potential intensity, duration, and estimated spatial extent of impact) that a community has experienced or could experience is necessary for analyzing and managing infrastructure and community resilience. For example, areas along the U.S.'s Southeast Gulf Coast are more susceptible to hurricanes [55], Japan's coastal cities experience more earthquakes and induced tsunamis [56], and riverine cities in Queensland, Australia need to handle flooding and inundation issues [57]. With hazard information and the delineated hazard maps, communities can make informed decisions for pre-event prevention and mitigation. By monitoring the evolution of such hazards as tidal, precipitation, tropical cyclone paths, and intensity, governments can produce specified hazard delineation maps to display liquefaction zones, seismic faults, subsidence areas, floodplains and landslide prone areas, etc. Integrated with the geospatial information of infrastructure asset entities, stakeholders can identify the parts and locations of infrastructure systems that are prone to fail, which provide the input for further vulnerability and resilience analysis of whole networks/systems.

4.1.4. Performance Metrics

The performance metrics of infrastructure assets and systems provide another type of fundamental information for resilience analysis and RM. These can relate to both an operationalization perspective, in terms of the operational performance of its constituting physical components and their interdependencies, and a system and network perspective. The network metrics, for example, include the node degree, characteristic path length, cycle length distribution, average clustering coefficient, node average betweenness, centralization, meshedness, system modularity, degree of assortativeness, and network efficiency [58,59].

The framework proposed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER), on the other hand, suggests quantifying infrastructure system resilience from four interrelated dimensions, i.e., technical, organizational, social, and economic dimensions [28,60], from which metrics for each dimension can be introduced. Utility agencies in each infrastructure sector can obtain their system performance measures for daily operation. For instance, the Transportation Research Board of the National Academies in US has proposed performance measures for asset management ranging from preservation of assets, operation and maintenance, mobility and accessibility to the safety category [61]. The Water Research Foundation has also formulated system performance indicators encompassing reliability, efficiency, adequacy, and water quality dimensions [62]. Virtually all these performance indicators could be adopted and leveraged to derive measures for quantifying system resilience.

By obtaining quality data according to the proposed data aggregation model, RM and analysis can be conducted to support decision-making. [63] defines three types of resilience analytics, namely descriptive, predictive, and prescriptive analytics. Descriptive analytics depicts the statistical characteristics of the performance of interdependent infrastructure systems before, during, and after disruptions; while predictive analytics focuses on quantifying the likelihood of future adverse events and their effects; while prescriptive analytics aims to identify a feasible course of interventions and strategies to best achieve the systems' resilient objectives. The next section elaborates the formulation of these analytics.

4.2. RIAM Analytical Workflow

A modularized workflow is proposed to provide a comprehensive and consistent RIAM analytics methodology. As delineated in Figure 5, this entails four parts: (i) A preparatory process; (ii) resilience curve-resistant and absorptive capacity analysis; (iii) resilience curve-restorative capacity analysis; and (iv) considerations for long-term improvement. In accordance with the theoretical basis, the workflow encompasses not only the core elements originating from IAM, but it also incorporates the methodologies for topology- and flow-based network analysis. It articulates absorptive, resistant, and restorative capacities, which are the main characteristics of the resilience concept and interdependent infrastructure asset systems. Considering the changing nature of infrastructure systems, the workflow also stresses the long-term prospects for improvement. Detailed sub-processes are interpreted as follows.

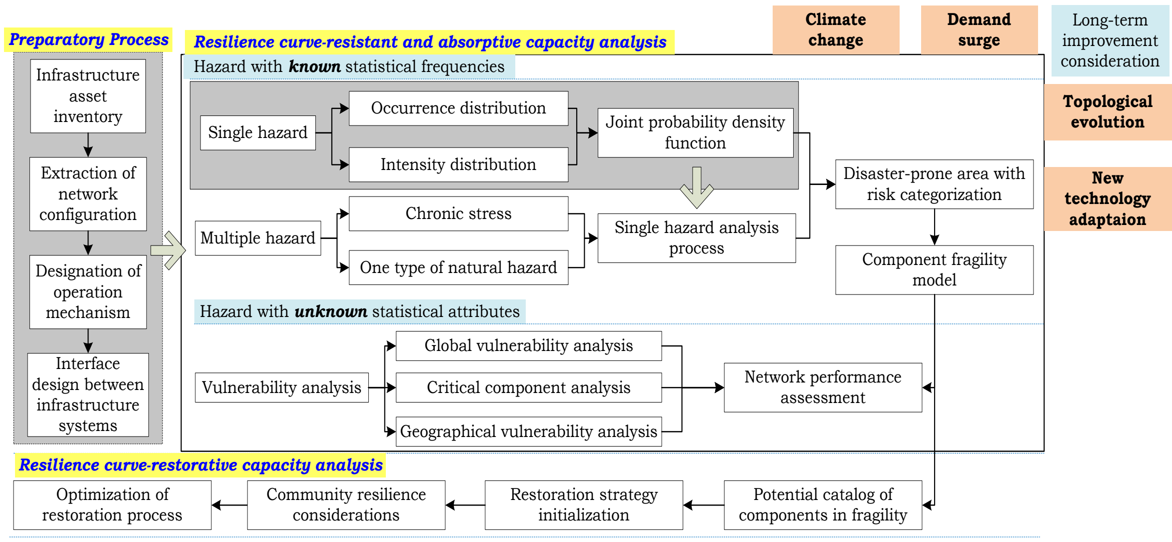

Figure 5. Analytical workflow for RIAM.

4.2.1. Preparatory Process

The preparatory process involves four steps.

1. Representative infrastructure assets are selected from an inventory.

2. Supported by the basic attributes bundled with tangible infrastructure assets, the network configuration is extracted to provide the connectivity information between infrastructure elements needed to initialize topological properties.

3. The operation mechanism, which is also described as the flow-based information, is designated for different infrastructure systems as it dominates their functional performance. To do this, domain knowledge (e.g., the electricity system cascading effects and water pipeline system hydraulic analysis) is requested to depict the system's operating state. There are several types of such domain knowledge, including a generalized betweenness centrality model [64] harnessed in water supply systems; a DC power flow model [65], recursive load redistribution algorithm [66], and a complex network betweenness model [58] leveraged in electric power transmission and distribution systems; and a gas delivery model [65] and maximum network flow model [67] exploited in natural gas supply systems.

4. The interdependency concept, the interface design between two different systems, is materialized to reveal the interaction between infrastructure systems [64,68]. In addition to the binary and deterministic connections between components within different systems, interdependent strength is introduced to mirror connection intensity by probabilistic means [65].

4.2.2. Resistant and Absorptive Capacity Analysis

For resistant and absorptive capacity analysis, two scenarios—the capacity of systems against known and unknown hazards—need to be studied using different underlying theories and modeling procedures. For known and foreseeable single hazards delineated by statistical frequencies, a Poisson process may furnish a good fit for the distribution of the occurrence time and interval between two consecutive hazards [69]. To capture the uncertainty and variations in hazard intensity, a specific distribution, such as the Gaussian [70] or power law [30], is embedded in the modeling. Consequently, a joint probability density function can be generated. A Poisson pulse process may be suitable when considering hazards in one timeframe. Owing to the spatial distribution of infrastructure systems, the hazard exposure delineation of different infrastructure components needs to vary to differentiate areas of possible unequal hazard and associated risk categorization [71,72]. For example, spatial differences of flooding are not only due to rainfall distribution and storm duration, but also local terrain features, roughness coefficients, stage boundary conditions, and hydraulic timing.

Usually, multiple scales of known hazards also need to be investigated simultaneously. In the daily operation and maintenance of infrastructure assets, regular failures of certain components occur due to ageing, human errors, or abrupt events (outlined in Figure 3 as chronic stress) can also be assumed to comply with specific possibility distributions. When combined with the distribution rules of a specific natural hazard, a joint distribution can be deduced to describe a synthesized hazard. The identical procedure of single hazard modeling can then be referred to as embodying both hazard occurrence time and intensity. In summary, a disaster-prone area with risk categorization is regarded as an elementary input for component fragility modeling, which, enabled by probabilistic reliability theory, elaborates component functioning state with due consideration of such environmental properties as local hazard intensity, terrain, vegetation, and other spatial factors. In this way, a catalogue of potentially disrupted components can be obtained, endorsed by the component fragility model, and the resilience performance metric ultimately re-measured based on the updated topological structure and renewed flow-based information.

For unknown hazards without significant statistical characteristics, vulnerability analysis is more suitable. This uses stochastic simulation to assess system performance in the presence of numerous hypothetical combinations of disrupted components [36]. Global vulnerability analysis can provide a reference for condition-based component failure sequences; degree-based and load-based attack strategies can be used to simulate system performance when criticalities are malfunctioned; while geographical vulnerability analysis can concentrate more on the characteristics of neighborhood community since a relatively less critical component in a topological dimension may serve a population with sensitive demographics. Using such risk-based, reliability and vulnerability analyses, the absorptive capacity of infrastructure systems can be practically revealed by simulating the performance losses involved.

4.2.3. Restorative Capacity Analysis

The restoration process, involving mobilizing resources and arranging projects to minimize recovery time under resource constraints, is more pertinent to the organizational capability and available resources of the utilities responsible. Different restoration strategies can be formulated by adjusting the parameter settings in the simulation process. Based on node betweenness, the characteristic path length, or relative criticality of damaged facilities, etc. [60], a suitable component restoration sequence can be identified. This enables the efficiency and effectiveness of different restoration strategies to be evaluated within, and under, a joint restoration strategy across system boundaries [73,74]. In addition, it will help accentuate the community vulnerability index's role in the restoration process [75], and track its dynamic features to help quantify and qualify the recovery capacity with respect to the baseline condition, and complement the evaluation of the restoration strategies [76].

4.2.4. Consideration of Long-Term and Continuous Resilience Improvement

RM and the analysis of infrastructure systems need to be carried out continuously across different temporal and spatial scales. A long-term resilience strategy can help tackle the occurrence of more frequent and severe chronic stresses and natural hazards caused by climate change; meet the surging demand with diverse use patterns; improve reliability; and adapt to the changes arising from the adoption of new technology, reconfiguration, and reengineering of topological structures and operation mechanisms, etc. These future expected improvements could be simulated by simply changing the related parameters in the simulation model. Such parameters in the joint hazard distribution probability function as the return period and average intensity would be altered to mimic scenarios of natural hazards becoming more frequent and severe. Likewise, the demand-of-load node in the infrastructure network can also be adjusted to mirror increasing demand scenarios. Technically, the topological configuration can be changed, e.g., by introducing redundant capacity into a node to allow buffer time when disrupted, or modifying the operating mechanism to imitate the outcome of adopting new technology [77]. In this way, the dynamic process of resilience can be demonstrated, and potential strategies to improve future system resilience can be identified through comparative studies.

5. Validation

Given the circumstance that one cannot validate the RIAM framework in terms of outcomes, it is nevertheless important to consider validation in terms of the process employed to obtain the judgments. The RIAM framework is formulated by adopting the methodological approach proposed and tested in expert judgment elicitation in terms of infrastructure resilience performance (i.e., robustness and recovery rapidity) against extreme events [42]. Besides, the method is iterative and consensus-based thus improving the judgment forecasting, as is the Delphi approach. Based on the judgment validation strategies suggested in traditional probability elicitation methods, convergence can be realized by asking the same questions multiple times, both in individual interview process and the subsequent workshop. All basic themes solicited from literatures are clearly defined and explained to the experts, ensuring that the interviewees have the identical scenarios in mind when providing the judgments. Besides, since the preliminary information and analytical requirements of the RIAM framework is provided to interview participants as the background preparation for the survey and workshop, it is convinced that such data sources are partially verified to illuminate the judgment elicitation from experts. Obviously, the expert judgment-based RIAM framework cannot be completely validated unless it could be applied and demonstrated effectiveness in real cases. To this end, we further devised two use cases in the following section to strengthen the claim that RIAM framework would provide structured information and knowledge needed to conduct further quantitative analyses.

6. Use Cases

Two case studies from actual industry practice were presented in this section to demonstrate the framework's applicability and practicality. The first case concerned the information orchestration by the unified modeling language (UML) class diagram, while the second exhibited the analytical process of generic resilience assessment adopted by a community IAM agency.

6.1. Information Orchestration by UML Class Diagram

Figure 6 shows an excerpt of the unified modeling language (UML) class diagrams of the Water Research Foundation's infrastructure resilience analysis data model, with two representative asset entities, namely the *WaterLine* and *PavementSegment*, from the water supply and roadway pavement systems respectively. Generally, the attributes of the classes and class relationships can be inherited from the geography markup language (GML) profile, which is essentially the type of extensible markup language (XML) encoding for modeling and exchanging spatial and non-spatial attributes of infrastructure assets. New attributes representing infrastructure lifecycle data (e.g., *WaterInspectionRecord, ConditionAssessmentRecord, WaterLineBreakRecord,* and *WaterLineMaintenanceRecord*), community (e.g., *CommunityUnit*), and hazard (e.g., *Hazard, HazardOccuranceParameter, HazardIntensityParameter*) were defined. A confluent class *AnalysisUnit* was added for further resilience analysis. Class definitions include the elements describing the relationship with other interdependent infrastructure systems, while relationship classes can be defined between different objects. For example, the *WaterLine* class has a 0..* association relationship with the *PavementSegment* class. The *HazardIntensityParameters* class is expected to be associated with both the *WaterLineRiskParameters* class and *CommunityUnit* class, demonstrating that the hazards would affect both the infrastructure systems and communities. The confluent *AnalysisUnit* class has a 1..* association relationship with the *PerformanceMetrics* class, indicating that infrastructure resilience can be analyzed from multi-dimensional (e.g., technical, social, organizational, and economical) perspectives. The UML class diagrams can be easily mapped onto the XML schema for sharing data across different IAM applications.

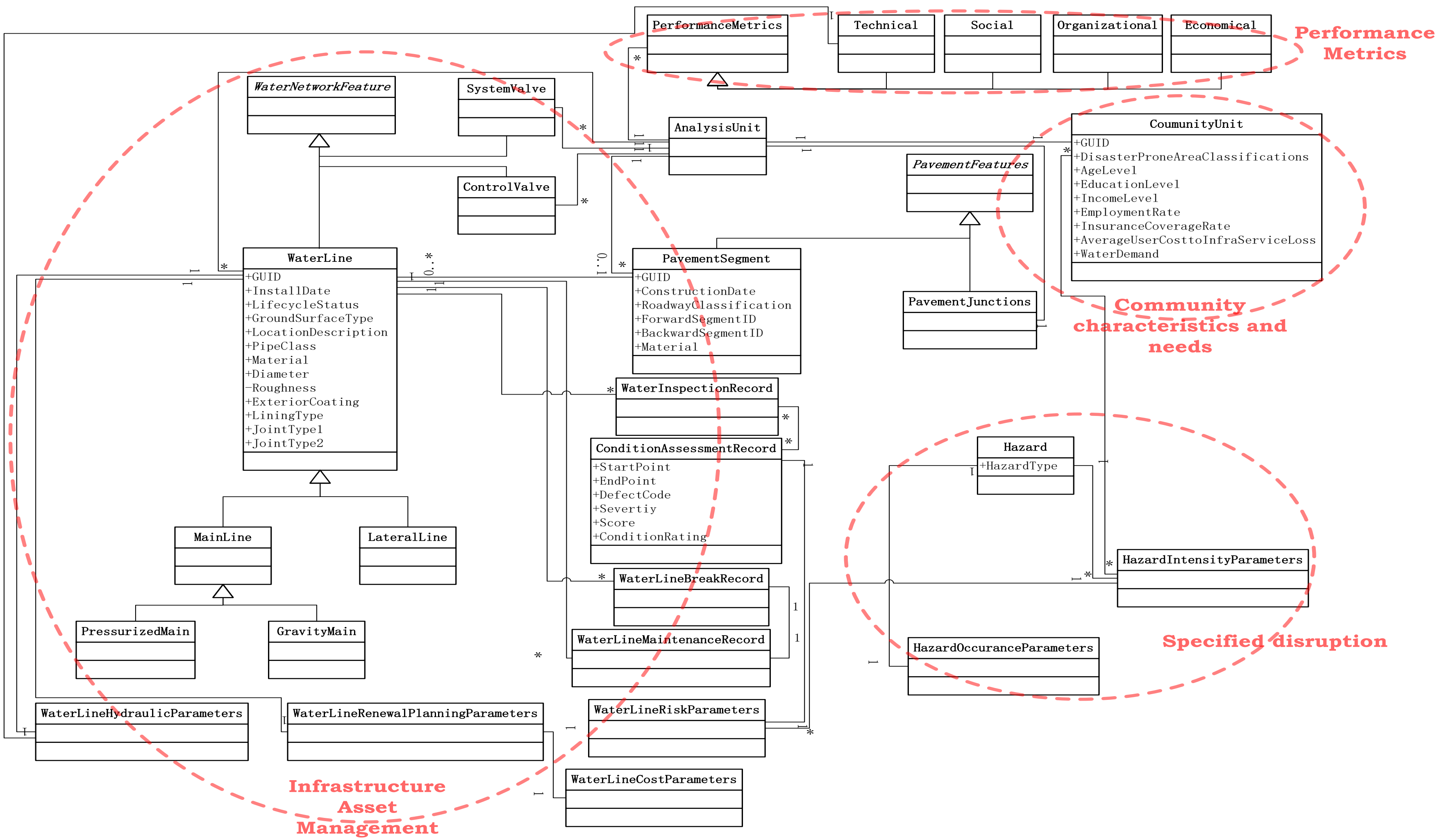

Figure 6. Excerpt of the unified modeling language (UML) indicating the classes and relationships of sources of information for RIAM.

6.2. Infrastructure Resilience-to-Earthquakes Analysis Processes

This case demonstrated the analytics workflow formulated with the framework to assess the resilience of the water utility network of Shelby County (in southeast U.S.) to an earthquake hazard, as well as to examine the interdependency between the water system and the county's electric power utility network (The scenario is based on the tutorials provided by the open source tool Ergo v4.0.0 (https://opensource.ncsa.illinois.edu/confluence/display/ERGO/Ergo+Home)). The workflow consists of the nine steps illustrated in Figure 7, as follows:

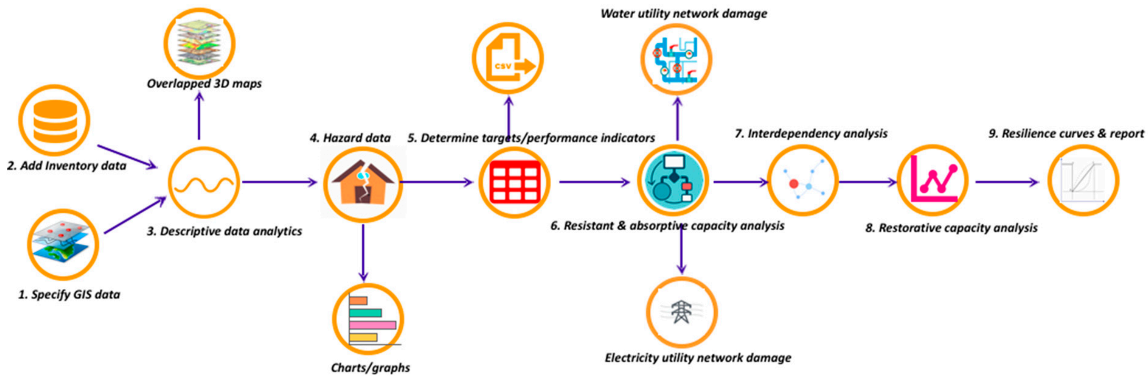

Figure 7. Infrastructure resilience analysis workflow against earthquake hazard.

(1) Specify the GIS data of Shelby County. The GIS data is fundamental to conduct damage, resilience, and interdependency analysis. The data can be used to superimpose and layer the spatial, property, and condition information of the county's water and electric power utility networks, and provide end users with a friendly frontend interface to visualize the aggregated hazard impacts on the networks.

(2) Solicit the inventory data of the water and electric power utility networks. Sample inventory data attributes include the network node IDs, linking edges, pipe types, pipe length and diameter, joint types, soil types, and pipe and cable capacity. This data can be extracted, transformed, and cleansed from sector specific IAM systems according to the RIAM information model, and then imported into such a resilience and risk analysis tool as Ergo to carry out further detailed investigation.

(3) Conduct a descriptive data analysis on the ingested water utility and electric power utility inventory. The statistical features of the inventory data set and the network structure of the utilities can be explored graphically using a variety of statistics and visualization techniques, such as the mean, standard deviation, sampling, missing value processing, principal component analysis, association analysis, and clustering analysis. This step assists end users to select target variables (e.g., performance indicators), and suitable simulation and prediction models for further resilience and interdependency analysis.

(4) Import or generate the earthquake hazard data. The required general seismic data includes the period, depth, peak ground acceleration, attenuation factor, latitude, longitude, and magnitude. The information can be obtained from past earthquake events or evaluated/generated through site characterization techniques, scenario-based, and probabilistic ground shaking hazard models based on historical and current data of surface and subsurface geometry, soil and rock properties, and groundwater conditions of the site.

(5) Determine the performance indicators as the target attributes for resistant and absorptive capacity analysis. In this case study, such indicators as water pipe breakage and leakage rate, number of power facility breakdowns, service flow reduction rate, and connectivity loss of water and electricity networks are selected to estimate the earthquake's damage and cascading effects on the water and power utilities.

(6) Perform resistant and absorptive capacity analysis with suitable models and model parameters. Sector-specific performance and hazard evaluation models for water utility and power networks and

appropriate algorithm parameters need to be configured to carry out the analysis. Domain knowledge is required to select an appropriate configuration from a variety of probabilistic and statistical models, graph theory tools, complex network-based techniques, etc.; the models developed in Hazus-MH 4.0 provide a good reference. The other advanced modeling parameters set for this analysis include buried pipe fragility curves, potable water fragility mapping, Hazus electric power fragility graphs, and hazard uncertainty and liquefaction probabilities.

(7) Conduct interdependency analysis. Geographic and physical interdependency between the water and electric power utility networks is employed to estimate the earthquake's cascading damages. The input parameters include the water and electric power network damage from step 6, network interdependency table, number of simulation runs, and homogeneous interconnectedness level; while the analysis results include the connection loss and service flow reduction of the two networks.

(8) Perform restorative capacity analysis to generate strategies and plans for recovering from the damage. Various types of decision-making analysis techniques can be exploited to determine the optimal restoration solution corresponding to available resources and the target objective of minimizing recovery time or cost. The techniques include such traditional approaches as the cost–benefit analysis, cost-effective analysis, multi-criteria analysis, multi-attribute utility analysis, and risk-based decision making methods, as well as emerging deep learning-enabled prediction tools.

(9) Generate the resilience curves and output a customized resilience analysis report. The report presents the details of the above analysis steps, the aggregated vulnerability hotspot map, damage and breakdown charts, and decision-making graphs.

The open source tool Ergo 4.0 does not implement all these functions, although the workflow is developed by leveraging the software suite. Researchers, developers, emergency managers, and community infrastructure managers could employ and integrate different software tools to carry out the resilience analysis tasks on-demand by referring the framework. Stakeholders are encouraged to contribute knowledge and expertise to refine the framework and enrich the functions of Ergo 4.0. A software system that integrates easy-to-use data processing tools and diverse modeling algorithms will also be developed to facilitate the resilience analysis of user-customized scenarios.

7. Conclusions and Future Work

This paper proposed a RIAM information elicitation and analytical framework that aimed to facilitate infrastructure stakeholders to operationalize resilience principles and practices into their existing asset management processes and systems. The framework was developed using a devised qualitative research methodology. Theoretical foundations in terms of IAM and RM integration were first built through a thorough content analysis of IAM guidelines and worldwide practices, RM related concepts and frameworks. The hints of both incorporating resilience considerations in IAM and encapsulating IAM features in resilience analysis were identified and justified theoretically. This also resulted in candidate themes for further interviews to obtain insights of our proposed RIAM framework from the perspective of practitioners. The research findings were validated and refined through interviews with different stakeholders from selected infrastructure sectors in Hong Kong and Mainland China. Two case studies were presented to demonstrate the applicability of the proposed framework, which could be leveraged to conduct interdependency and resilience analysis of infrastructure systems and utility networks. This alignment contributes to the integration of domain knowledge from diverse disciplines to make maximum use of existing theories, models, and frameworks to facilitate RIAM. Practically, the framework further stimulates quantitative operationalization of the basic concepts involved (e.g., interdependency and resilience) and the assessment of diverse strategies from both IAM and RM perspectives.

The framework has a valuable potential for aligning the understanding and practice of different sectors in implementing RIAM. Based on the framework, fragmented and diverse infrastructure data could be assembled and aggregated, and explicit and beforehand information inputs for conducting the RIAM analysis would inform and improve the accuracy and efficiency of stakeholders' data collection practices. The analytical workflow for RIAM articulates the procedure of infrastructure system resilience with IAM considerations (e.g., involving component conditions in resilience analyses). Stakeholders would reference to the procedure meanwhile considering the local contexts and requirements. The flexible decision-making analysis models can be configured, integrated, or developed to carry out resilience analyses at different temporal and spatial scales and in corresponding real or speculated hazard scenarios. Moreover, two different paradigms entitle the decision makers to choose either risk-based or vulnerability-based analysis according to the hazards facing the community. The infrastructure ageing problem is also involved in the RIAM workflow through either abstracting the ageing problem as chronic hazard delineated by specified hazards curves or manipulating physical parameters to represent the component deteriorating effects when modeling the infrastructure systems. Due to its versatility and flexibility, the framework can therefore be adopted by cities and communities of varying sizes to enhance community and urban infrastructure resilience. Moreover, municipalities can hone and customize the framework into their smart and sustainable city technology plans. For future research, a suite of built environment-oriented resilience indicators, a set of data integrated adaptors, a hybrid of resilience evaluation models, and a 'big data'-enabled resilience analysis service platform prototype need to be developed to refine and enrich the framework. More case studies also need to be devised to further validate the framework and demonstrate its use to enhance the resilience and sustainability of community infrastructures.

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