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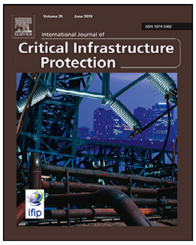

Quality function deployment-based framework for improving the resilience of critical infrastructure systems

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ABSTRACT

Critical infrastructure systems (CISs), increasingly suffering from various hazards in recent decades, are in urgent need of improving their resilience. So far few approaches for CISs resilience improvement have recognized that different resilience improvement efforts could have synergetic or conflicting correlations between them. There lack systemic approaches for transforming resilience improvement requirements into coordinated and implementable measures. To address this gap, the current study proposes a quality function deployment (QFD)-based framework for strengthening the resilience of CISs. The proposed framework involves different stages of the CISs lifecycle, and takes into consideration the correlations between resilience improvement efforts at these stages. It can transform resilience criteria into system properties, component characteristics, implementation processes and controlling factors successively, which is facilitated with a series of houses of quality (HoQs). Using a case study of electric power system, we demonstrated the feasibility of the proposed framework with detailed explanations of the design and implementation of the first HoQ. The results of the case study showed that the proposed framework could identify the trade-offs between resilience improvement efforts at different stages of the CISs lifecycle, and take into account their relationships with resilience criteria and the correlations among them to work out optimized solutions for improved CISs resilience.

1. Introduction

Critical infrastructure systems (CISs), defined as networks of manmade facilities for delivering essential goods or services [1], have been increasingly suffering from various natural and manmade hazards, especially in urban regions where the high density and complexity of CISs significantly increase the risk of large-scale failures. Further adding to the severity of the challenge is the fact that large-impact natural hazards have become more frequent in the past decade, for which many researchers argue that global climate change is responsible [2–6], and the hazards are causing increasingly more physical and functional CISs damages and associated economic losses [7]. For instance, Puerto Rico, among the most severely impacted regions hit by Hurricane Maria in September 2017, suffered from a complete power outage and breakdown of water supplies and telecommunication [8], with roughly half of

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the population lacking electric power three months after the hurricanes [9]. Similarly, Gulf of Mexico and inland Texas had more than 20% of the oil and gas production affected, due to the hit of Hurricane Harvey in August 2017 [10]. The closure of oil refineries ahead of Hurricane Harvey created a fuel shortage that even forced gas stations to shut down due to rush lines [11]. Large areas of Texas were still trying to recover about four months after the hurricane [12]. Those disasters have highlighted the urgent needs of disaster risk management in CISs.

To address the needs, the concept of resilience provides a new perspective. Resilience refers to the ability of a system to resist, adapt to and recover from disturbances, emphasizing the maintenance of system functionality during the whole disaster lifecycle, including particularly the system recovery stage. This is based on the notion that under many circumstances transitory functionality losses may be acceptable as long as the recovery is efficient and fast [13]. Resilient CISs are believed to have the ability to reduce their functionality losses or recovery time within restraints of resources. Different ways are available to improve the resilience of CISs, which focus on different stages of the CISs lifecycle. For instance, some prior studies proposed to improve the CISs resilience during the planning and design stages, by measures such as enhancing the component redundancy or global connectivity of the CISs network [14–16]. Some other studies focused on the operation stage, aiming to mitigate the functionality losses from disasters by monitoring and remote control [17–19]. In addition, restoration management approaches have also been studied to reduce the recovery time and cost through optimal restoration schedule and resources allocation [20–23]. Although focusing on distinct stages of the CISs lifecycle, these mitigation efforts, however, are not independent on each other, for there are potential correlations, such as synergies, conflicts and trade-offs, among them [24]. For example, power redistribution operations in case of partial grid breakdown require pre-existing connections between substations; if failed facilities are initially designed and constructed in such a way that they require fewer efforts to be restored, post-disaster restoration process would be less resource-intensive and more efficient. Therefore, improving CISs resilience requires a systematic approach that takes into account various scenarios at different stages of the CISs lifecycle.

To address this need, this paper aims to propose a quality function deployment (QFD)-based framework for improving the resilience of CISs. Originated from and widely adopted in the manufacturing domain, the QFD method is used to transform the voice of customers into measureable design targets and drive them from the assembly level down through the sub-assembly, component and production process levels [25–28]. It has the potential capability to integrate different stages of the CISs lifecycle and deal with synergies and conflicts between these stages [28–30]. The proposed framework is designed to identify various resilience criteria for CISs resilience, and transform these criteria into actionable system requirements to be achieved at different stages of the CISs lifecycle. More specifically, the transformation takes place from resilience criteria successively into system properties, component characteristics, implementation processes, and controlling parameters. The main contribution of this study is to build a novel framework for improving the CISs resilience, which integrates various efforts during the whole lifecycle of CISs and takes in consideration complex correlations between these efforts. Each transformation step in the framework can be used at the corresponding stage of the lifecycle of CISs and thus contribute to the enhancement of their overall resilience. To demonstrate the feasibility of implementing the proposed framework in practice, the first transformation in the framework, from resilience criteria into system properties, is explained in detail and then implemented in a case study involving an electric power system. The results of the case study and their practical implications are discussed in the paper.

2. Related work

2.1. *Approaches for improving CISs resilience*

Various approaches for improving CISs resilience have been proposed in prior studies, which focused on different stages of CISs' lifecycle, including planning, design, operation, and post-disaster restoration.

For the planning stage, a number of principles, advocated to support the resilient CISs planning, are considered fundamental to the resilience of CISs; by strengthening these principles the improvement of CISs resilience can be achieved. For instance, Foster [31] proposed thirty-one planning principles for achieving the resilience of a generic system, relating to physical, social, economic and environmental aspects. Godschalk [32] adapted these resilience planning principles, and applied them to urban hazard mitigation. Similarly, Sharifi and Yamagata [33,34] proposed principles for improving the resilience of urban energy systems, and related them to various CISs components. Jackson [35] proposed a list of forty principles, among which fourteen were considered top-level principles and the others sub-principles [36]. The challenges with these principles, however, include the lack of quantitative relationships between expected performance of CISs and these principles, and the failure to account for various synergies, conflicts and trade-offs between different resilience principles [34].

For the design stage, different reliability- and- risk- management methods have been applied to discover all possible ways the CISs could fail and identify the critical and vulnerable parts which should be strengthened. These methods include, for example, failure modes and effect analysis (FMEA), fault and event trees, and Bayesian belief networks. FMEA can be used to identify various modes of component failure and analyze the effect of failures on system-level functionality [14,37,38]. The fault and event trees method employs a logic diagram to show both how a system failure can be generated by component failures and how initial component failures can propagate and result in a system failure [16,39]. Bayesian belief network considers the failure possibility of each component based on the fault and event trees method [40–42]. All of the above methods assume that CISs are already designed or constructed, and suggest that reliable components should replace critical and vulnerable ones. [14]. While the above methods have been proven effective in addressing vulnerability issues in CIS design, they bear two limitations. Firstly, instead of being inherently embedded to enable resilience-oriented system design, they can only be applied to assess and adjust system designs after they are developed by traditional methods. Secondly, they mostly focus on vulnerability issues of systems and thus have ignored other important attributes of resilient CISs such as their recoverability and adaptability.

Meanwhile, a number of studies aim to enhance the resilience of CISs by improving their operations [17,43]. For instance, Alderson et al. [17] modeled operations of CISs when they are attacked by disturbances, and proposed a number of resilience improvement measures that target at system operations. Liu et al. [44] proposed a resilience analysis framework for interdependent CISs, and identified a set of operation parameters that should be enhanced to improve the CISs resilience. Ishfaq [45] developed a logistic strategy to improve the resilience of supply chains, by enhancing the operational flexibility of the system for responding to transportation disturbances. Similarly, Salmeron et al. [19] developed an electric power distribution model, which aims to minimize unmet user demands during grid breakdown by reconfiguring all operational generators, substations and transmission lines in the system. While resilience-oriented system operations are important to disaster risk reduction, Ishfaq [45] pointed out that they should be considered in connection with the planning and design of CISs during which most system attributes are determined. The synergies between the operation stage and other stages of the CISs lifecycle are yet to be addressed in the literature.

In addition, the recoverability of CISs has also been widely studied in the literature, with focuses on post-disaster restoration plans, scheduling and resources allocation to minimize restoration time, costs and unmet user demands. For instance, a few studies [20,21] proposed models for optimizing restoration-task scheduling in electric grids during power outage, by minimizing the average time that every grid user is left without power. Several other studies [22,46] explored the problem of optimizing the schedule of road recovery tasks, by maximizing the accessibility of road network. To improve resource allocation, Yao and Min [47] developed a model for efficient allocation of repair units to support restoration of multiple power transmission lines. To prepare and pre-place restoration resources in electric power system, Wang et al. [48] proposed a decision-making model to determine the optimal number and location of depots and the optimal number of repair crews for each depot, by minimizing the transportation time and cost associated with restoration operation. Despite these prior studies, one challenge to improve the recoverability of CISs that remains to be addressed is that the recoverability is highly dependent on various system attributes, such as topological structure and geographical contexts, which are determined at earlier stages of the CISs lifecycle. Measures to account for possible restoration scenarios at these stages are needed to further enhance the overall resilience of CISs against potential hazards.

2.2. *Quality function deployment*

Quality function deployment (QFD) is a process and set of tools used to effectively define customer requirements and convert them into detailed engineering specifications and plans to produce the products or projects that fulfill those requirements. It is configured to transform ‘whats’ into ‘hows’, specifically from customer desires into successively technical descriptions, component characteristics, process steps and control factors. It keeps high consistency between various stakeholders during the transforming process that involves all stages of product development – planning, design, operation and control. House of quality (HoQ), as the core construct of QFD, is a matrix, closed at the top with a triangular “roof” that illustrates the relationship between technical factors at two successive stages. It is used to implement the transformation step between these two stages. In addition, HoQ can also take into consideration correlations between technical factors at the same stage to avoid design conflicts and their implementation difficulty, which ensures high operability of solutions developed by this method in reality.

The QFD method has been applied in a range of industries. Manufacturing is the first industry to adopt QFD, where it has been widely used to analyze customer needs and transform them into product attributes [27,29]. Other typical applications of QFD in the manufacturing industry include production process improvement by matching production technologies with product design [49,50], material selection by matching product attributes with correlated material properties [51], and supply chain resilience enhancement by analyzing the relationship between resilience capabilities of the supply chain and resilience enhancement measures [52,53].

Service industry also widely adopts QFD as a customer-oriented quality management tool. For instance, it has been applied to improve the government service quality or support policy strategies development, by transforming the expectations of citizens into specific technical requirements [54,55]. The quality of transportation service, such as airline [56], railway [57] and highway bus [58], could also be improved by using QFD to transform customer needs into technical requirements. Moreover, QFD has been integrated with other management theories and techniques, such as fuzzy logic, Kano model and analytic hierarchy process (AHP), to address various needs for service quality improvement in different domains including healthcare [59–61], hotel [62–64] and education [65–68].

The QFD method has also been adopted by the construction industry. For instance, it was applied to analyze and coordinate the conflicting demands from various stakeholders so as to reduce design changes in construction projects [69,70]. It was also used to integrate end-user demands into the design of public facilities [71–73], and citizen demands into the planning and investment of infrastructure projects [74,75]. In addition, QFD was applied to support the selection of design-build firms in the bidding process [76], and analyze the effectiveness of accident prevention measures at construction sites [77,78].

The above applications of QFD are summarized in Table 1, which compares their differences and similitudes. These applications, especially those related to civil and infrastructure projects, suggest that this method has significant potential to be applied to address the aforementioned challenges in CISs resilience improvement. Specifically, QFD has demonstrated notable strength in analyzing the demands from various stakeholders, transforming these demands into technical

Table 1 – Comparison of QFD applications in different industries.

Industry	Application domain	Whats	Hows	Stakeholder	Correlation between ‘hows’
Manufacturing	• Product planning [27,29]	Customer demands	Product attributes	Multiple	Yes
	• Product design [51]	Product attributes	Design parameters	Single	Yes
	• Production process [49,50]	Design parameters	Production technologies	Single	No
	• Supply chain [52,53]	Resilience capabilities	Resilience measures	Multiple	Yes
Service	• Government service [54,55]	Citizen expectations	Administrative procedures	Single	No
	• Transportation service [56–58]	Passenger demands	Facilities and schedules	Single	No
	• Healthcare service [59–61]	Patient needs	Facilities and procedures	Single	No
	• Hotel service [62–64]	Customer demands	Facilities and standards	Single	No
	• Education service [65–68]	Industry demands	Curriculum system	Multiple	Yes
Construction	• Project design [71–73]	End-user demands	Design parameters	Multiple	Yes
	• Stakeholder management [69,70]	Stakeholder demands	Design parameters	Multiple	Yes
	• Infrastructure investment [74,75]	Citizen demands	Investment plans	Multiple	Yes
	• Project bidding [76]	Bidding requirements	Firm capabilities	Single	No
	• Safety and health [77,78]	Reduced accidents	Protection measures	Single	No

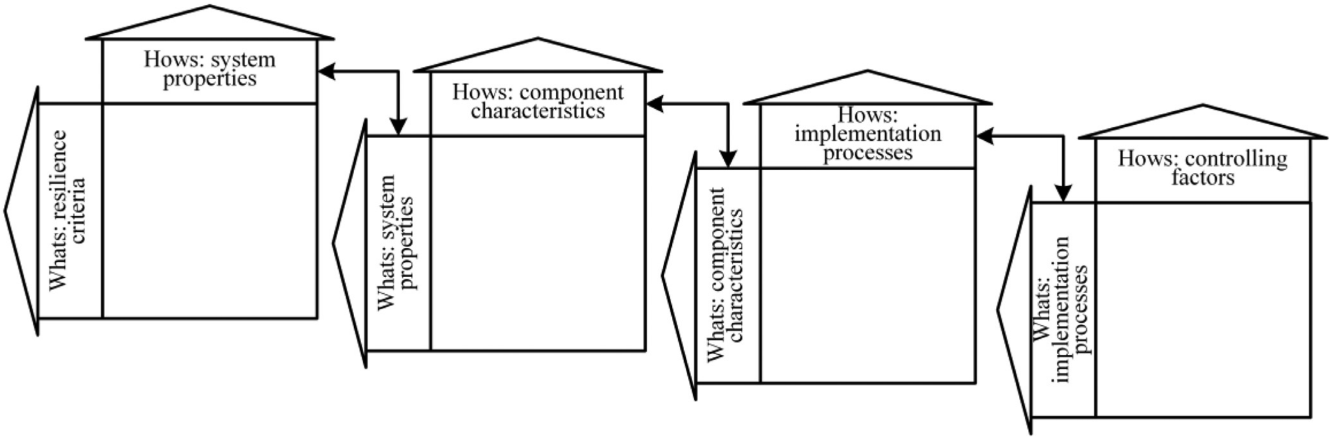


Fig. 1 – The proposed QFD-based framework for improving the CIS resilience.

parameters, and accounting for the correlations among different parameters. In addition to these benefits, this study will also explore the possibility of using QFD to identify and coordinate the trade-offs between resilience improvement efforts at different stages of the CIS lifecycle. By extending QFD to this new application domain, this study aims to provide an alternative and hopefully better way to improve the resilience of CISs.

3. Quality function deployment-based framework

3.1. *General process*

The proposed framework aims to transform the conceptually expected performance of CISs in response to hazards (e.g., reducing the recovery time of power outage) into actionable technical requirements at certain stages of the CISs lifecycle (e.g., increasing the capacity redundancy of CIS components at the design stage, or enhancing the ability of remote sensing and control at the operation stage). The transformation processes, as illustrated in Fig. 1, can be decomposed into four steps, from a macroscopic scale to a microcosmic one, and specifically from resilience criteria into system properties, and successively into component characteristics, implementation processes, and controlling parameters. Each step transforms ‘whats’ into ‘hows’, and the ‘hows’ at the previous step automatically become ‘whats’ at the next step. These ‘whats’ or ‘hows’ are explained in detail in Table 2. Specifically, two variables associated with ‘whats’ and ‘hows’ are transformed in each step. The first variable is improvement requirement, describing which and to what extent ‘hows’ should be improved given the expected levels of ‘whats’. These improvement requirements of ‘hows’ at each step become the expected levels of ‘whats’ at the next step, and are further transformed to improvement requirements of ‘hows’ at the same step. The other variable to be transformed is importance weight, evaluating the priorities of different resilience improvement efforts when simultaneously meeting all resilience criteria is unlikely, due to such reasons as limited resources. Importance weights of resilience criteria are measured first and further transformed to importance weights of ‘hows’ at each step.

Table 2 – Definitions of 'whats' and 'hows' during the transformation processes in the proposed framework.

'Whats'/'Hows'	Definition	Example
Resilience criterion	Expected performance of resilient CISs in different aspects when responding to disturbances [13]	Reduced failure consequence; reduced recovery time
System property	Technical parameters considered at the system level, which could directly affect the resilience criteria [79]	Network connectivity of electric substations; ability of remote sensing and controlling
Component characteristic	Technical parameters considered at the component level, which determine the system properties [79]	Number of links of one substation to others; location of sensors
Implementation process	Critical processes to implement the component characteristics [79]	Flow distribution calculation; communication simulation
Controlling factor	Factors controlled at each implementation process [79]	Transmission line capacity; sensing range

To conduct the transformation processes, the proposed framework first evaluates the relationships between 'whats' and 'hows' at each step (e.g., between resilience criteria and system properties at the first step). The relationships hereby refer to the effects of 'hows' on 'whats', where the values of relationships denote the strength of such effects. Taking 'whats' as rows and 'hows' as columns, respectively, the values of relationships between them form an interrelationship matrix, which is the core of a HoQ and the bridge to transform the two variables, namely importance weights and improvement requirements.

The overall resilience level of CISs could be affected by all stages of the CISs lifecycle [44]. For example, an effective way to reduce the recovery time, is either to design components in a way that they can be easily restored after they fail, or to prepare and allocate sufficient restoration resources during operation and maintenance. Therefore, during the transformation processes, the proposed framework considers different stages of the CISs lifecycle simultaneously, compares alternative measures for improving CISs resilience, and identifies the most effective and efficient measures to achieve expected resilience goals. Specifically, at each transformation step, the framework considers envisioned efforts to be made at all later stages. For example, at the first transformation step focusing on system planning, the system properties taken into consideration include the connectivity of components concerned at the planning stage, the ability of remote sensing and controlling concerned at the operation stage, and the allocation of restoration resources concerned at the maintenance stage. Then the results of this transformation step would suggest what measures should be taken and at what stages of CISs lifecycle.

At each transformation step, the framework also evaluates the correlations between 'hows' to avoid conflicting ones or enhance synergetic ones. For example, in electric power system, adequate capacity redundancy of substations and transmission lines and robust connections between substations are both needed to conduct electric flow redistribution to meet unmet demand in case of partial grid breakdown. Thus, there is synergy between the measures that improve capacity redundancy and connectivity of system components. To the contrary, a conflicting instance could occur between increasing connectivity and reducing independency, both of which are measures to improve system resilience. Improving the connections between CIS components may lead to additional interactions between the components and hence increase their interdependencies. Due to these synergies and conflicts, among all possible solutions, which prescribe certain measures that should be acted upon 'hows' in order to achieve expected levels of 'whats', the proposed framework only considers as feasible solutions the ones that promote synergies and avoid conflicts.

All feasible solutions are then evaluated and compared to identify the optimal one. The criterion for the evaluation is the implementation difficulty. The framework first evaluates the difficulty of implementing each 'how', by considering various relevant factors, such as costs, technical feasibility and public policy. Then, the overall implementation difficulty of a solution is determined based on the implementation difficulty of each 'how' and the improvement requirements of 'hows' involved in the solution. The optimal solution, according to the proposed framework, is the one with the lowest difficulty to implement and desirable consistency between 'hows'. Meanwhile, the improvement requirements of 'hows' in this solution become the expected levels of 'whats' at the next transformation step and are further transformed to improvements requirements of later 'hows'.

3.2. *First house of quality for planning*

Based on the above general introduction of the proposed framework, this subsection takes the first transformation step as an example to further demonstrate the detailed elements as well as possible approaches to fully implement the framework. The first transformation step is completed in the first HoQ, mainly focusing on the planning stage of CISs. It aims to transform various resilience criteria into associated system properties. The detailed elements included in the first HoQ are shown in Fig. 2. The process to implement these elements is illustrated in Fig. 3, and explained step-by-step as follows. All other HoQs in the proposed QFD-based framework can be implemented similarly.

3.2.1. *Identification of resilience criteria*

Resilience criteria, located at the second left column of the HoQ in Fig. 2, refer to the expected or desirable performance of resilient CISs in different aspects when responding to disturbances. Identification of the resilience criteria sets the targets for CISs resilience improvement. There are several approaches to conducting this task. Individual interviews and

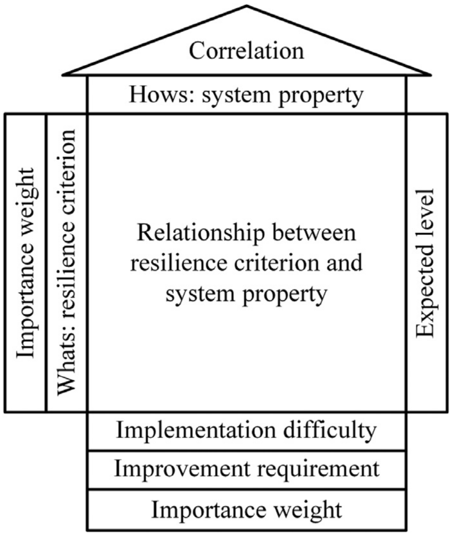


Fig. 2 – Detailed elements in the first HoQ of the proposed framework.

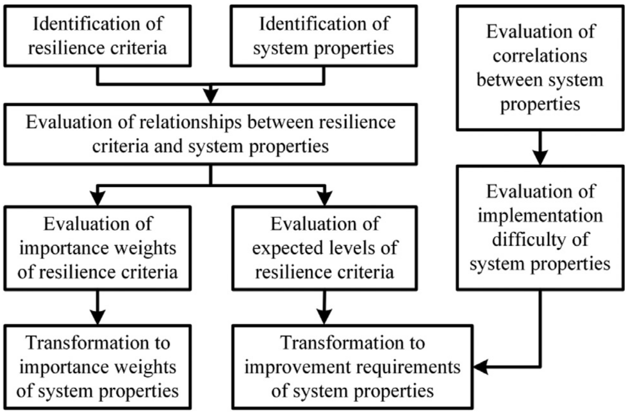


Fig. 3 – General process to implement the first HoQ in the proposed framework.

focus groups are usually applied to identify these resilience criteria from different stakeholders, such government agencies, CIS operators, and citizens. Alternatively, various criteria and metrics have been developed in the literature to define or assess the resilience of CIS [13,80,81]. Hence, conducting a thorough literature review is another approach to identifying resilience criteria.

3.2.2. *Identification of system properties*

System properties, located at the top row of the HoQ in Fig. 2, refer to those technical parameters that are considered at the system level and highly related to the resilience criteria. Examples include system redundancy, adaptability, and resourcefulness. Identification of system properties determines whether all resilience criteria would be adequately transformed and satisfied. Similar to the identification of resilience criteria, individual interviews and focus groups, and review of the existing literature are common approaches to compiling a list of system properties.

3.2.3. *Evaluation of the relationships between resilience criteria and system properties*

The relationships, located at the central body of the HoQ in Fig. 2, refer to the effects of system properties on resilience criteria, where the values denote the strength of such effects. The relationships are the core of the transformation in HoQ, as they build a connection between resilience criteria and system properties. Taking resilience criteria and system properties as rows and columns, respectively, the relationships between them form a matrix, and each element in the matrix denotes the value of relationship between the corresponding resilience criterion and system property. The values of relationships can be measured as an integer at a scale of 0–9, where 9 represents the extremely significant relationship [52,53,70]. There are several approaches to evaluating these relationships. It is a common approach to conduct a focus group of relevant stakeholders to evaluate the relationships [28,69]. Conducting a questionnaire survey is another experience-based approach [53,71]. When rich data about CIS construction and operation are available, data mining can be an alternative approach to evaluating the relationships. Sometimes simulation is also used as an experiment-based approach to measuring the relationships.

It is noteworthy that the results of the previous two steps should be revisited if the results of relationship evaluation meet the following situations. First, each resilience criterion should have significant relationship with at least one system property. Otherwise, it would indicate that the identification of system properties is not thorough and needs to be revisited. Second, when two columns in the relationship matrix appear to be highly similar, it would indicate that two system properties have similar effects on the same set of resilience criteria, and these system properties should be revisited and possibly merged. Likewise, when two resilience criteria appear to be similarly affected by the same set of system properties, they should be revisited and possibly merged.

3.2.4. *Evaluation of importance weights of resilience criteria*

Importance weights of resilience criteria, located at the first left column of the HoQ in Fig. 2, measure the priorities of resilience criteria to be satisfied. For it is not always possible to satisfy all resilience criteria due to reasons such as limited resources, it is important to support decision-making on the prioritization of resilience criteria to be satisfied. Evaluation of importance weights can be conducted based on focus groups or surveys. The importance weights should be normalized with a sum equal to 1 for convenience of comparison.

3.2.5. *Transformation to importance weights of system properties*

Similar with resilience criteria, importance weights of system properties measure the priorities of system properties to be improved. However, unlike resilience criteria, importance weights of system properties are transformed from importance weights of resilience criteria, based on the relationships between resilience criteria and system properties, as described in the following equation [52,53,70]:

$$Pw_j = \sum_{i=1}^{n} Dw_i A_{ij} \quad (1)$$

where Dw_i and Pw_j denote respectively the importance weights of resilience criterion i and system property j, n denotes the total number of resilience criteria, and A_{ij} denotes the relationship between resilience criterion i and system property j. The importance weights of system properties should also be normalized for convenience of comparison. The above equation indicates that the system properties with higher effects on resilience criteria should be assigned with higher importance weights.

3.2.6. *Evaluation of expected levels of resilience criteria*

The expected levels of resilience criteria, located at the right column of the HoQ in Fig. 2, refer to the performance level, assessed based on the resilience criteria, that stakeholders expect the CIS to satisfy. They can be derived mainly by comparing the disaster response performance of CISs in similar cities or learning from local historical disasters. For example, a city may want to reduce its recovery time to some extent if recovery time has been a major problem in past disasters.

3.2.7. *Evaluation of correlations between system properties*

The correlations, located at the top triangle of the HoQ in Fig. 2, refer to the synergies or conflicts between different system properties. Evaluation of these correlations could help avoid solutions that require simultaneous implementation of conflicting measures, and prioritize solutions that require simultaneous implementation of synergetic measures. The evaluation of correlations can be carried out by conducting focus groups or surveys. The results can be expressed as an integer value at a scale of −2 to 2, where values −2 and −1 denote strong and weak conflicts, respectively, values 2 and 1 denote strong and weak synergies, respectively, and value 0 denotes that no correlation exists [82].

3.2.8. *Evaluation of implementation difficulty of system properties*

Implementation difficulty, located at the third bottom row of the HoQ in Fig. 2, refers to the difficulty to improve one system property based on the assessment of all relevant factors, such as cost and budget, available technologies, public and corporate policies, and so on. It sets the basis for identifying optimal solutions. The evaluation of implementation difficulty can be carried out by conducting focus groups or surveys. The results can be expressed as an integer value at a scale of 1–5, where 5 denotes the highest difficulty.

3.2.9. *Transformation to improvement requirements of system properties*

The improvement requirements of system properties, located at the bottom row of the HoQ in Fig. 2, refer to the extent to which the system properties should be improved in order to meet the expected levels of resilience criteria. Improvement requirements are transformed from the expected levels of resilience criteria based on the relationships between resilience criteria and system properties. It can be done by solving the following optimization problem:

$$min \sum_{j=1}^{m} Pr_j Id_j \tag{2}$$

$$\sum_{j=1}^{m} Pr_j A_{ij}/9 \geq De_i \tag{3}$$

$$\begin{cases} \frac{1}{2} \leq \frac{Pr_i}{Pr_j} \leq 2 \text{ or } Pr_i = Pr_j = 0, & \text{if correlation } \left(Pr_i,\ Pr_j\right) = 2 \\ Pr_i \cdot Pr_j > 0 \text{ or } Pr_i = Pr_j = 0, & \text{if correlation } \left(Pr_i,\ Pr_j\right) = 1 \\ Pr_i \cdot Pr_j < 0 \text{ or } Pr_i = Pr_j = 0, & \text{if correlation} \left(Pr_i,\ Pr_j\right) = -1 \\ -\frac{1}{2} \leq \frac{Pr_i}{Pr_j} \leq -2 \text{ or } Pr_i = Pr_j = 0, & \text{if correlation } \left(Pr_i,\ Pr_j\right) = -2 \end{cases} \tag{4}$$

where De_i and Pr_j denote, respectively, the expected levels of resilience criterion i and the improvement requirements of system property j, Id_j denotes the implementation difficulty of system property j, m denotes the number of system properties, and A_{ij} denotes the relationships between resilience criterion i and system property j. Eq. (3) indicates the possible solutions about improvement requirements of system properties should meet the expected levels of resilience criteria based on the relationships. Eq. (4) suggests how the correlations between system properties work. If there is a strongly positive correlation between two system properties, the improvement requirement of one system property should be at least half of the improvement requirement of the other one. If there is a weakly positive correlation between two system properties, their improvement should be simultaneous but there is no constraint on the values of their improvement requirements. It is the same to the negative correlations. Eq. (4) helps select those possible solutions where synergetic system properties are improved simultaneously and conflicting ones are avoided. Eq. (2) indicates that the optimal solution is a set of improvement requirements of system properties with the lowest implementation difficulty among possible ones.

4. **Case study**

To demonstrate the implementation of the proposed framework, this paper takes the electric power system as a case. The case study focuses on the first HoQ for the planning of resilient electric power system. It intends to identify the expected resilience performance of the system and transform it to system-level technical parameters at different stages of the system lifecycle.

We firstly conducted a thorough literature review to identify the resilience criteria and system properties for typical electric power systems. Then, we designed a survey to evaluate various elements in the HoQ. Specifically, the survey included six parts that were presented to survey respondents in the following order: (1) questions that identify the effects of system properties on resilience criteria; (2) questions that assess the relative importance between different resilience criteria; (3) questions that assess the implementation difficulty of each system property; (4) questions that assess the significance of effects of system properties on resilience criteria; (5) questions that identify the correlations between different system properties; and (6) questions that are related to background information of the respondents, including gender, age, job responsibility, work experience, and profession. The design of these questions is explained in further detail in the following subsections. After the survey was initially designed, it went through four rounds of piloting and revision, by incorporating inputs and feedback from three experts in statistics, who commented on overall structure of the questionnaire and design of specific questions, and two electric grid planning and operation professionals with over five years of work experience, who commented on the questions and options, and grading scales.

The survey was conducted between May 24 and June 14, 2018. An electronic survey link was distributed to practitioners working on planning of electric power system in several regions in China. A total of 48 responses were received, and after filtering incomplete responses or those from apparently unexperienced professionals, a total of 41 valid responses were collected. A response number within the range of 30–50 was considered sufficient for paired samples t-tests [83], which was applied to analyze the responses in order to evaluate the relationships in the HoQ. The values of Cronbach α for the responses in six parts of the survey were 0.922, 0.683, 0.763, 0.965, 0.977 and 0.730 respectively, which indicated high statistical reliability. Among these 41 respondents, 31 of them were male and 10 were female. More than 95% of them had at least 2 years of relevant work experience, and more than 75% of them had at least 5 years of work experience. The majority of them (over 85%) were planners or engineers. The respondents were mainly from four provinces in China, including Sichuan, Zhejiang, Jiangsu and Beijing, where the electric power systems all suffered from major disasters such as earthquakes and extreme weather events within the past ten years.

Based on literature review, survey, and QFD transformation operations, the HoQ was developed for the case study, as shown in Fig. 3. The results are explained in detail in the remainder of this section.

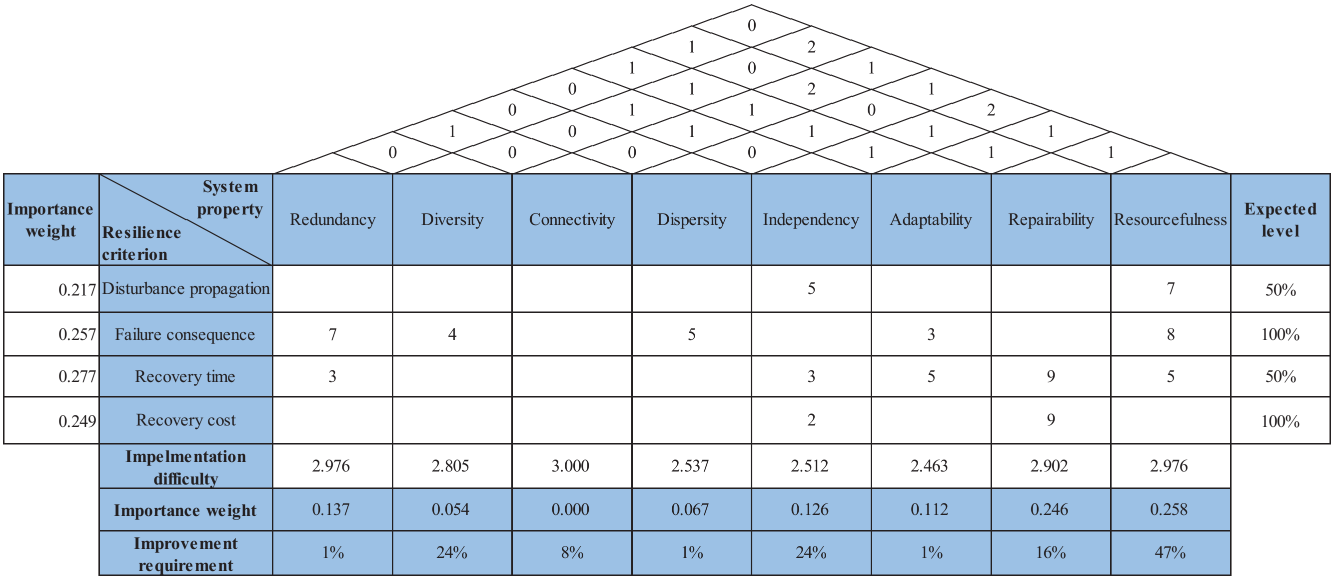
4.1. *Identification of resilience criteria and system properties*

A review of existing literature on resilience criteria or metrics was conducted for the case study to identify resilience criteria. Keywords of 'infrastructure', 'resilience', and 'criteria or metric or quantification' were used to search publications in the core collection on Web of Science. The search returned a total of 34 publications. Each of these publications was carefully reviewed to determine whether it included any original propositions of resilience criteria. Based on this criterion, 14 publications were selected, from which six resilience criteria were initially identified. These criteria described the expected performance of resilient CISs in different aspects when responding to major hazards. However, there were overlaps between these criteria according to their definitions. Specifically, 'failure consequence' and 'recovery time' can be altogether represented by 'total performance losses'. To avoid overlaps while capturing all major aspects of CISs resilience, four resilience criteria were selected. These were 'reduced disturbance propagation', 'reduced failure consequence', 'reduced recovery time', and 'reduced recovery cost'. The definitions of these four resilience criteria are summarized below, including citations to their sources:

- Disturbance propagation [84]: the situation where the failure of one component can result in failures of other components, such as fault-trips propagation in electric power and failure of water supply due to power outage. Disturbance propagation measures the risk of cascading failures, which is critical in the resilience assessment;
- Failure consequence [13,85–88]: the decrease of flow or service of CISs, such as reductions in power supplies. Failure consequence measures the functionality losses of CISs in the aftermath of disturbances;
- Recovery time [80,89–91]: the time taken from the beginning of disturbance to full recovery of system functionality. Since CISs are fundamental to the city functionality, the shorter recovery time is, the fewer losses the city endures;
- Recovery cost [81,92,93]: the cost to restore components and recover system functionality. Recovery cost reflects the severity of damage and the difficulty of recovery.

Similarly, the keywords of 'infrastructure', 'resilience', and 'planning or design' were used to search in the core collection on Web of Science, which retuned a total of 64 publications. Each of these publications was carefully reviewed to determine whether it included any original propositions of system properties related to resilience. Based on this criterion, 16 publications were selected, from which a total of 12 system properties that had clear and direct effects on resilience criteria were initially identified. Overlaps between these system properties were then assessed. For example, 'adaptability' and 'feedback correction' both refer to the ability of a system to adjust its status in order to maintain normal functionality. Based on their definitions, some system properties were excluded if they had the same meanings as others or they could be entirely determined by others. A total of eight system properties were finally selected. These were 'redundancy', 'diversity', 'connectivity', 'dispersity', 'independency', 'adaptability', 'repairability', and 'resourcefulness'. The definitions of these system properties are summarized below, including citations to their sources:

- Redundancy [32,94–97]: the extra components or the additional capacity of a component compared to the normal working level. If the system has high redundancy, the functionality of failure components can be easily replaced by others, which benefits to decreasing the functionality losses. For example, the power plant has the capacity to produce more power than normal level and the transmission lines have standby ones.
- Diversity [94–101]: the system has components working differently to protect itself against various types of disturbances. For example, the electric power system has diverse power sources of fuel, nuclear, hydraulic or the transportation system has various types of roads, trains, airlines.
- Connectivity [14,94–101]: the components are well connected to each other, and can potentially support or substitute each other in case of disturbances.
- Dispersity [102]: the components are geographically distributed dispersedly rather than centrally to avoid the failure of all components when hazards attack on a spot.
- Independency [33,34]: the components can maintain a minimum acceptable level of functioning when influenced



Importance weight	System property / Resilience criterion	Redundancy	Diversity	Connectivity	Dispersity	Independency	Adaptability	Repairability	Resourcefulness	Expected level
0.217	Disturbance propagation					5			7	50%
0.257	Failure consequence	7	4		5		3		8	100%
0.277	Recovery time	3				3	5	9	5	50%
0.249	Recovery cost					2		9		100%
	Impelmentation difficulty	2.976	2.805	3.000	2.537	2.512	2.463	2.902	2.976	
	Importance weight	0.137	0.054	0.000	0.067	0.126	0.112	0.246	0.258	
	Improvement requirement	1%	24%	8%	1%	24%	1%	16%	47%	

Fig. 4 – HoQ developed in the case study.

by disturbance. It can greatly decrease the possibility of disturbance propagation. For example, a backup power can ensure the functionality of a water pump in case of a power outage.

- Adaptability [36,103,104]: the system can automatically adjust running status of components in order to meet as much demand as possible. It can help decrease the functionality losses.
- Repairability [36,96,104]: physically failed components can be easily restored. It can greatly shorten the recovery time and reduce the recovery cost.
- Resourcefulness [13,33,34]: the system has adequate maintenance resources and complete emergency plans. It is of great importance to the post-hazard recovery and maintaining the functionality.

4.2. *Relationship between resilience criteria and system properties*

The evaluation of relationships between resilience criteria and system properties was conducted based on the survey responses. In the survey, respondents were firstly asked to assess whether there exists an effect of each system property on each resilience criterion. If the answer was yes, the respondents would be asked two follow-up questions. They would read descriptions of two different situations with the system property being at high level and low level, respectively. They would then be asked to assess the performance level based on that resilience criterion under each situation. For example, if the respondents indicated there was an effect between redundancy and disturbance propagation, they would be asked to assess the level of disturbance propagation, when the electric power system had either high redundancy or low redundancy, respectively. A paired *t*-test was applied to all responses, to determine whether there was a significant difference between paired answers under high and low levels of the system property. If paired answers had statistically significant difference, assessed at the 95% confidence level, it indicated that the corresponding system properties had significant effects on the associated system criterion. The values of these significant effects were then assessed, by calculating the mean differences between paired answers under high and low levels of system properties in all responses. Next, all resulting values of the relationships were scaled to 0–9 points using linear interpolation, where the maximum and minimum values were assigned as 9 points and 0 point, respectively. Points 1–3 denote slight relationships, 4–6 denote medium relationships, and 7–9 denote high relationships. The final results are shown in Fig. 4, as the central matrix in the HoQ, whose rows are resilience criteria and columns are system properties.

4.3. *Importance weights of resilience criteria and system properties*

Based on the survey responses, the importance weights of resilience criteria in the case study were measured using the Analytic Hierarchy Process (AHP) method [105]. In the survey, respondents were asked to select a score at scale 1–5 to assess the relative importance between every possible pairs of resilience criteria (an example is shown in Fig. 5). The final values of relative importance are determined by the geometric average of all responses [106], which are presented in a judgment matrix, as shown in Table 3. Based on the judgment matrix, the normalized importance weights of all resilience criteria were derived, by calculating the eigenvector of maximum eigenvalue and normalizing it, according to the following equations:

$$(\lambda_{max}E - R)x = 0 \tag{5}$$

$$\bar{x} = \frac{x}{\sum_1^n x_i} \tag{6}$$

<<< --------------------- More important ------------------|------------------More important---------------------- >>>

	Extremely	Strongly	Moderately	Slightly	Equally	Slightly	Moderately	Strongly	Extremely	
	5	4	3	2	1	2	3	4	5	
Disturbance propagation	________	________	________	________	________	________	________	________	________	**Failure consequence**

Fig. 5 – Example question in the survey to assess relative importance of resilience criteria.

Table 3 – Judgment matrix in resilience criteria assessment.

	Disturbance propagation	Failure consequence	Recovery time	Recovery cost
Disturbance propagation	1.00	0.77	0.76	0.99
Failure consequence	1.30	1.00	0.90	0.96
Recovery time	1.31	1.11	1.00	1.06
Recovery cost	1.01	1.04	0.94	1.00

Fig. 6 – Importance weights of resilience criteria.

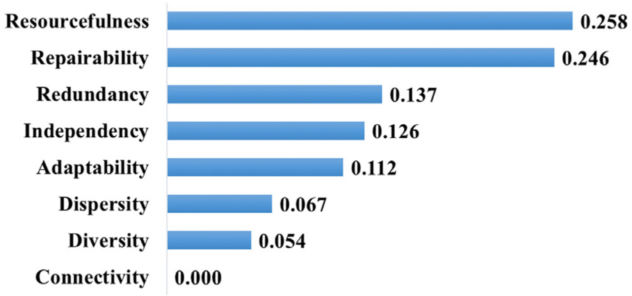


Fig. 7 – Importance weights of system properties.

where λ_{max} and x denote the maximum eigenvalue and its eigenvector, E and R denote unit matrix and judgement matrix, $\bar{x}$ denotes the normalized importance weights, and x_i denotes the ith element of vector x. The results of normalized importance weights of resilience criteria are illustrated in Fig. 6 as well as the left column in Fig. 4. The consistency level [105] of the results was calculated to be 0.0028, which was below a threshold of 0.09 (when four items were in comparison) [105], indicating that the results had high reliability. The results showed that 'recovery time' was the most concerned in electric power system, closely followed by the other three resilience criteria.

Next, based on the above relationships between resilience criteria and system properties and importance weights of resilience criteria, the importance weights of system properties were calculated according to Eq. (1). The normalized importance weights of system properties are shown in Fig. 7. The results showed that system properties differed notably in terms of their importance, where 'resourcefulness' and 'repairability' had high importance weights, 'redundancy', 'independency' and 'adaptability' had medium importance weights, and 'dispersity' and 'diversity' had low importance weights. 'Connectivity' had zero importance weight, since survey responses indicated that it had no effect on any of the resilience criteria.

4.4. *Correlations between system properties*

Respondents were asked to select a score between −2 and 2 to assess the correlation between all possible pairs of system properties. The arithmetic average of all responses was calculated for the correlation of each pair. The results all fell between a range between 0 and 1. To distinguish the correlations, their values were re-scaled as 0, 1 or 2 according to the following equation [107]:

$$\mathrm{Co}_{ij,\,\mathrm{new}} = \begin{cases} 0, \ if \ \dfrac{\mathrm{Co}_{ij,\,\mathrm{old}} - min(\mathrm{Co}_{ij,\,\mathrm{old}})}{max(\mathrm{Co}_{ij,\,\mathrm{old}}) - min(\mathrm{Co}_{ij,\,\mathrm{old}})} \in \left[0,\ \frac{1}{3}\right) \\ 1, \ if \ \dfrac{\mathrm{Co}_{ij,\,\mathrm{old}} - min(\mathrm{Co}_{ij,\,\mathrm{old}})}{max(\mathrm{Co}_{ij,\,\mathrm{old}}) - min(\mathrm{Co}_{ij,\,\mathrm{old}})} \in \left[\frac{1}{3},\ \frac{2}{3}\right) \\ 2, \ if \ \dfrac{\mathrm{Co}_{ij,\,\mathrm{old}} - min(\mathrm{Co}_{ij,\,\mathrm{old}})}{max(\mathrm{Co}_{ij,\,\mathrm{old}}) - min(\mathrm{Co}_{ij,\,\mathrm{old}})} \in \left[\frac{2}{3},\ 1\right) \end{cases} \tag{7}$$

where $Co_{ij,\,old}$ and $\mathrm{Co}_{ij,\,\mathrm{new}}$ denote the values of the correlation between system properties i and j before and after the re-scaling, respectively. The final correlations between system properties are shown in the top triangle in Fig. 3.

4.5. *Difficulty of improving system properties*

Respondents were asked to select a score of 1–5 (1-extremely easy and 5-extremly difficult) to estimate the difficulty of improving each system property, based on their knowledge and experience in the planning and operation of electric power infrastructures. The arithmetic average of all responses was calculated and used to assess the level of difficulty. The results are illustrated as the third row from the bottom in Fig. 4. The difficulty values were all between 2 and 3 and close to each other. Moreover, a t-test was conducted, at the confidence level of 95%, for every possible pair of system properties to assess whether there was significant difference between their difficulty values. The results showed that it was more difficult to improve 'redundancy', 'connectivity', 'repairability' and 'resourcefulness', while improving 'dispersity', 'independency' and 'adaptability' was relatively easier.

4.6. *Expected levels of resilience criteria and improvement requirements of system properties*

Since the case study was not based on any electric power system in a particular city or region, the expected levels of resilience criteria were arbitrarily given for the purpose of demonstrating the QFD transformation. Specifically, it was assumed that the 'disturbance propagation' and 'recovery time' were expected to be reduced by 50%, while other resilience criteria could remain at their current levels. Then, based on Eqs. (2)–(4), the improvement requirements of system properties were calculated. The results, as illustrated in the bottom row in Fig. 4, showed that 'resourcefulness', 'independency' and 'repairabilty' needed to be improved in order to meet the expected levels of disturbance propagation and recovery time. Due to strongly positive correlations with the above three system properties, an additional two system properties, including 'diversity' and 'connectivity', would also be significantly improved, although they had no direct effects on disturbance propagation and recovery time. Other system properties barely required any improvement.

5. Discussions and conclusions

This study proposed a QFD-based framework for improving the resilience of CISs by identifying various resilience criteria for CISs resilience and transforming these criteria into actionable system requirements to be achieved at different stages of the CISs lifecycle. The proposed QFD-based framework, specifically the first HoQ in the framework, was demonstrated in a case study. This section summarizes major findings and implications of the case study, overviews the feasibility of the proposed framework demonstrated in the case study, and discusses the limitations and future research.

5.1. *Findings and implications of the case study*

Several findings related to the relationships between resilience criteria and system properties were new and interesting in the case study. At the system planning stages, 'disturbance propagation' and 'failure consequence' are more affected by 'resourcefulness' than other system properties such as 'redundancy', 'diversity', 'dispersity'. The reason could be that emergency resources can be used at the early post-hazard stage for preventing disturbance propagation and further failures, suggesting that efforts at operation and restoration stages should be considered early on to reduce vulnerability of the CISs. Similarly, 'repairability', which is mainly determined at the planning and design stages, has the highest effects on the 'recovery time' and 'recovery cost'. This implies that in order to reduce 'recovery time' it is more efficient to design the electric power components with high 'repairability' than to prepare emergency resources. Comparing the effects of 'repairability' and 'resourcefulness' on resilience criteria, it can be derived that the resilience criteria are affected by system properties at different stages of the CISs lifecycle, therefore they require comprehensive and systematic consideration, which could be facilitated by using the proposed framework.

In addition, no significant effect of 'connectivity' on any resilience criterion was found in the case study. One possible explanation could be that 'connectivity' was understood differently among the respondents. Some respondent may have based on their response on the notion that higher 'connectivity' meant more spare connections between components, which could improve the 'redundancy' of transmission lines and hence mitigate possible failure consequence; others may have thought that higher 'connectivity' could lead to more interdependencies between components, which would then aggravate possible failure consequence [43]. The respondents may have reported conflicting effects of 'connectivity' due to such different understandings, resulting in insignificant overall effect of 'connectivity' based on all responses.

5.2. *Feasibility of the proposed framework*

The case study, which focuses on the design and implementation of the first HoQ, has demonstrated in several aspects the main features, functions and capabilities of the proposed QFD-based framework, and the feasibility of implementing it in practice.

Firstly, the results of relationships evaluation indicated that each resilience criterion could be affected by multiple system properties at different stages of the CISs lifecycle. For example, 'failure consequence' could be affected by 'redundancy' at the planning and design stages, 'adaptability' at the operation stage, and 'resourcefulness' at the restoration stage; In order to reduce 'disturbance propagation' and 'recovery time', measures could be taken to towards system properties such as 'diversity' at the planning stage, 'independency' at the operation stage and 'resourcefulness' at the restoration stage. This highlights the importance of the capability of the proposed framework in involving system properties at different stages of the CISs lifecycle, and associating them with various resilience criteria, so that the enhancement of system resilience can be achieved by coordinating various measures that are to be implemented at different stages of the CISs lifecycle.

Secondly, the case study demonstrated that the capability of the proposed framework to transform resilience criteria of CISs into system properties. This is done by properly prioritizing the measures, which in turn depends on proper prioritization of resilience criteria. When applied to massive new CIS projects, the framework can be used to identify measures that would act upon the most critical resilience criteria prioritized by stakeholders; when applied to CISs expansion projects, the framework can be used to identify measures that would have the most effective resilience enhancement outcomes given the conditions of existing CISs.

Thirdly, the case study demonstrated that trade-offs between different system properties could be identified and applied to support the assessment of competing resilience-enhancement solutions. For instance, in the case study, reducing 'recovery time' can be achieved by improving either 'repairability' or 'resourcefulness'. While 'repairability' has more significant effect on 'recovery time' than 'resourcefulness', its improvement requirement assessed by the proposed framework is relatively lower, because improving 'resourcefulness' can also contribute to the reduction of 'disturbance propagation' to its required level. By considering such trade-offs between system properties, the proposed framework avoids excessive concentration on one system property and achieves higher effectiveness and efficiency by diversifying the improvement efforts.

Last but not the least, the case study also demonstrated that the proposed framework could reveal and analyze the synergies between system properties, and use them to support the transformation process. For instance, in the case study, since 'independency' and 'resourcefulness' are highly synergetic, 'independency' could be improved simultaneously by measures that act upon 'resourcefulness'. Due to such improvement of 'independency' and the relationship between 'independency' and 'recovery time', it needs fewer efforts to improve other system properties for satisfying the expect level of reduced 'recovery time'. If such synergies are not taken into consideration at the planning stage, improvement requirements of system properties such as 'repairability' would be overestimated, which would be wasteful and inefficient. It needs to be noted that, with such synergies some system properties having no direct effects on resilience criteria, such as 'connectivity', would also be improved by the recommended solution. There were no conflicting correlations between system properties in the case study. According to Eq. (4), if there existed such conflicts, they would also be taken into account to balance different improvement requirements of the system properties so as to work out an optimized solution.

5.3. *Limitations and future study*

This study bears several limitations that are noteworthy. Firstly, the relationships between resilience criteria and system properties could vary with disaster scenarios. For instance, physical properties such as 'redundancy' may be prioritized in small-impact disturbances to prevent system failures, while external efforts such as 'resourcefulness' may be more critical in large-impact disturbances when system failures are inevitable. Secondly, certain types of correlations between system properties may be unidirectional and hence may require the top triangle in the HoQ to be redesigned to process such correlations. Moreover, there are interdependencies between different CISs. Resilience improvement of one system may depend on efforts done to other systems, therefore cross-system coordination should be considered. The authors plan to further advance this line of research to address the above limitations in future research, and continuously improve the proposed framework to support resilience enhancement of interconnected CISs under different disturbance scenarios.

Conflict of interest

The authors declare no conflict of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijcip.2019.100304.

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