Quality Function Deployment Based Conceptual Framework for Designing Resilient Urban Infrastructure System of Systems

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Abstract. The frequent natural hazards and their significant impacts in recent years have repeatedly highlighted the vulnerability of urban infrastructure systems and their lack of system resilience. The ever increasing interdependencies between urban infrastructure systems have further complicated the situation, causing considerable risks of failure propagation. Considering that the properties of urban infrastructure systems including their level of resilience are mainly determined at the design stage, the authors aim to propose a Quality Function Deployment (QFD) based conceptual framework for designing resilient urban infrastructure system of systems (SoS). As a preliminary effort towards this goal, this paper mainly focuses on developing the first matrix in the QFD based framework. Steps to identify resilience criteria and principles are presented, the questionnaire-based method to determine the main body of the first matrix is described, and the approach to work out practical design schemes is explained. Lastly, this paper summarizes the main strength of the proposed framework as well as its limitations, and discusses directions for future research.

Keywords: Infrastructure · System of systems · Resilience criteria
Resilience principle · Quality Function Deployment

1 Introduction

Last year was significant in terms of natural hazards. In ten weeks from August to October in 2017, a 124-year-old record was matched with ten consecutive Atlantic storms reaching hurricane strength [1] and causing more than four hundred deaths. Moreover, two devastating earthquakes of magnitude 8.1 and 7.1 hit Mexico City in just two weeks, resulting in over three hundred deaths and massive destruction of buildings [2]. These disasters have highlighted the increasing exposure of urban assets to high-density, large-impact hazards that have caused enormous economic losses reaching hundreds of billions US dollars annually, most of which are in cities with large population [3].

In these situations, urban infrastructure systems (e.g. electric power system, water supply system, transportation system), which provide various services to support fundamental functions of cities, are also becoming quite vulnerable to these hazards. When

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studied in all their complexity, urban infrastructure systems can be modeled as a system of systems (SoS) since different infrastructure systems work interactively and interdependently to support the various fundamental functions of urban systems [4]. Within the SoS, the increasing interactions and interdependencies between their different components or facility assets (e.g. substations, water plants) can lead to significant risks of cascading failures. Propagating through these interdependencies, local disaster impacts can grow to become regional ones in a city or global ones in a country. For example, after Hurricane Maria hit Puerto Rico, a complete power outage in the island resulted in the failure of telecommunications and water supplies [5]. In place of electric power, fuel was required for generators to power critical buildings such as hospitals [6]. The competition for fuels made it difficult for trucks to deliver food, water and medicines, which made the situation even worse [6].

These lessons have repeatedly highlighted the lack of resilience in urban infrastructure systems. In this paper, resilience refers to the ability of a system to absorb, adapt to and recover from changes and adverse impacts in the system. Given that urban expansion is expected to continue in the coming decades, building more resilient urban infrastructure systems is a major challenge that urban planners, developers, policy makers and citizens alike are faced with.

The properties of urban infrastructure systems including their level of resilience are mainly determined at the design stage where operation planning and risk management are included [7]. Thus, this paper proposes a conceptual framework for designing resilient urban infrastructure system of systems. It needs to be noted that, given that most cities already exist and will not be designed from scratch, the concept of designing resilience into urban infrastructure systems mostly focuses on new infrastructure development during urban expansion and urban renewal processes, and examines its impact on the resilience level of the entire infrastructure systems including the existing infrastructure components.

2 Related Work

2.1 Approaches for Resilient Urban Infrastructure Systems Design

Various methods or tools have been proposed and developed to support the design of resilient infrastructure systems. Based on traditional reliability and risk assessment techniques, methods used for identifying the weakness of infrastructure systems include failure modes and effects analysis (FMEA) [8], fault and event trees [9] and Bayesian belief networks [10]. These methods can identify and characterize all the risks that could cause a failure, and further identify the failure-critical components. However, the traditional reliability and risk assessment methods regard infrastructure systems as a simple compound of components rather than a SoS. For example, these methods normally regard an electric power system as a network of hardware, with external support such as supervisory control and data acquisition (SCADA), maintenance and emergency management. Such a perspective fails to recognize the electric power system as an integrated and interdependent system composed of not only hardware but various resources and supporting agents, and overlooks the interplays between these system components.

This could be inefficient in resilience design, because most of these methods assume that a system design has existed and suggest using infrastructure components with higher robustness or redundancy to improve the overall resilience [8]. Alternatively, there could be a more efficient design, which achieves improved resilience of the integrated systems by optimizing the interactions between infrastructure systems in a SoS perspective [8].

Another method to design resilient infrastructure systems proposed by Bruneau et al. [11] is to "create" resilience. It measures system resilience based on different properties including robustness, redundancy, resourcefulness and recoverability, and decomposes each single infrastructure system into subsystems on physical, cyber, social and institutional dimensions. Then, the method relates the characteristics (e.g. component capacity) of these subsystems to each property of resilience. Thus, it implies what characteristics can be enhanced to achieve resilience [11, 12]. A significant number of research studies have followed this method and proposed various resilience principles that each single infrastructure system design should meet [12–15]. This method helps transform the complex resilience concept into subsystem characteristics and makes it operable. However, it depends largely on the experience of designers. Without knowing the priority of these characteristics as well as the correlations between them, it is difficult to use this method to support city governments in the allocation of limited resources for building resilience into urban infrastructure systems.

Other methods using high-fidelity simulations have also been proposed for designing resilient infrastructure systems. These methods allow for the investigation of failure propagation and evaluation of different recovery strategies [16]. Each single infrastructure system would be modeled as a system of interactive components by considering their interdependencies. With the resilience assessment metrics such as reduced system performance losses or reduced time of recovery, a trial-and-error process can be conducted to optimize the design scheme by varying infrastructure component characteristics. These methods regard infrastructure systems as a system of systems, and propose an optimized and efficient design scheme for improving resilience. However, it is difficult to set the quantitative mechanism of all interactions between different infrastructure systems with this method since some interdependencies are not well identified or measured (e.g. interdependency between telecommunication system and transportation system). Meanwhile, it is difficult to analyze the correlations that could be synergistic or inhibiting between optimization approaches. This limitation could lead to the impractical design scheme.

2.2 Quality Function Deployment

An approach that has the potential to capture the advantages of all these above methods based on reliability and risk assessment, resilience decomposition and simulation is the QFD. The QFD was developed in Japan in 1966 as a method to transform qualitative customer desires into quantitative engineering parameters that can be controlled [17]. It is an iterative process of transforming customer desires into technical descriptions, successively into component characteristics, process steps and control factors. Thus, it can take into consideration all the stages of development including planning, design, operation and control, and can engage various stakeholders involved in the design and development of complex systems.

House of Quality (HoQ) is the core of QFD as a series of matrices. HoQ can measure the effect of each engineering parameter on each customer desire, or the “relationship” between them, even if they are in separate subsystems. Meanwhile, HoQ can also take the “correlation” that could be synergistic or inhibiting between two engineering parameters into consideration. Based on a specific case study, a self-assessment of customer desires in the existing system can be conducted as well as the expected level of those desires. Based on the gap between these two levels of customer desires, QFD can calculate the specific improvement requirement of given engineering parameters by also taking their implementation difficulty into consideration. This function of QFD method is quite useful to infrastructure systems design.

QFD has been applied in a wide variety of services [18, 19]. For example, it is applied to improve the efficiency and effectiveness of the design of consumer products by transforming customer desires into engineering characteristics and control factors [20, 21]. It is also applied in construction management to support buildable design decision making by analyzing the relationships between client requirements and characteristics of building components [22]. When applied to urban planning, it is used to improve the design of public space by transforming citizen needs into alternative engineering parameters [23].

3 Proposed Conceptual Framework

This section introduces how QFD can be applied into the resilient infrastructure systems design by describing the core concepts, critical steps and main methods in the proposed framework.

3.1 Goals and Core Concepts of the Framework

The main goal of the proposed framework is to decompose the multi-criteria of resilience into a number of engineering parameters, whose relative importance is assessed, during the planning, design, operating and control stages of the lifecycle of infrastructure systems, by using a combination of analysis and simulation methods. The proposed framework also aims to identify factors that have impact on the implementation of engineering parameters, and measure the difficulty of their implementation. Ultimately, the framework can identify the gap between current and expected levels of resilience of the system, and support the decision-making with respect to the investment levels and sequencing of the engineering parameters.

This paper takes the first QoH of QFD (shown in Fig. 1) as an instance to demonstrate the development and implementation process of the proposed framework. The first HoQ mainly focuses on the planning stage of resilient urban infrastructure systems, which concerns the process of transforming customer desires of resilience into engineering parameters considered at the planning stage. The HoQ is composed of a room surrounded by walls on the left and right sides, floor and foundation at the bottom, and ceiling on the top. In addition, there is a triangular roof attached to both the left wall and the ceiling.

Specifically, as shown in Fig. 1, the left "wall" of the HoQ illustrates a list of resilience criteria with their relative importance, while the left "roof" illustrates the correlation between these criteria. Resilience criteria refer to the expected performance of infrastructure systems when responding to extreme events by stakeholders. One examples of resilience criteria is reduced failure consequences of urban infrastructure systems when responding to extreme events. The right "wall" illustrates both the expected and self-assessment levels of each resilience criterion. The "ceiling" illustrates a list of resilience principles, and the top "roof" shows the correlation between these principles. Resilience principles, which are engineering parameters involved at the planning stage, correspond to general system properties such as redundancy and diversity. The "room" illustrates a relationship matrix whose elements reflect the effect of each resilience principle on each resilience criterion. Lastly, the "floor" illustrates the relative importance between resilience principles, and the "foundation" illustrates the implementation difficulty and to what levels each resilience principle should be improved in order to meet the expected resilience level.

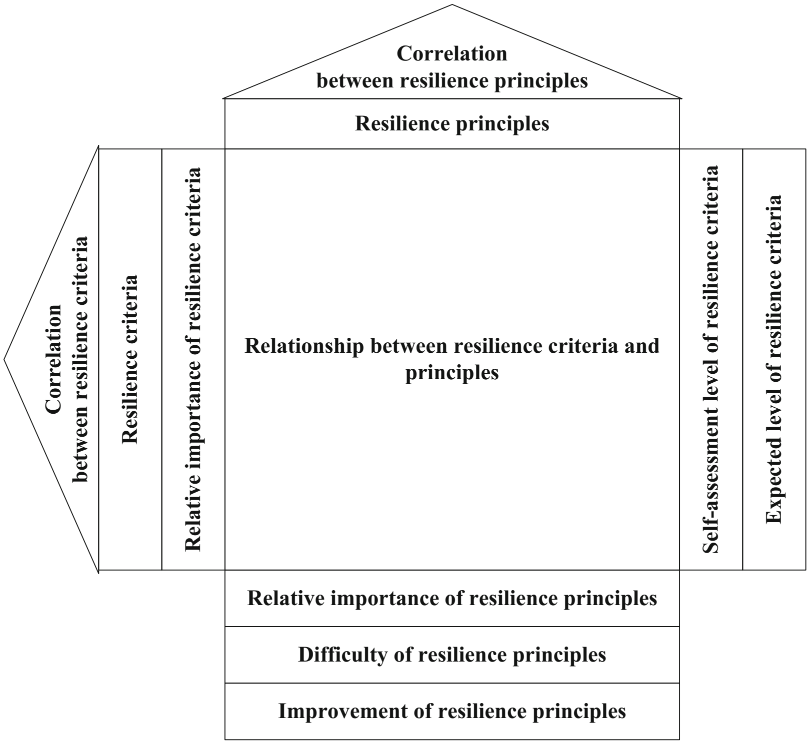

Fig. 1. The first HoQ of the proposed framework for designing resilient infrastructure systems

When the relative importance of resilience criteria and the relationship between resilience criteria and principles are provided (e.g. by survey), this HoQ is able to assess the relative importance of resilience principles. Moreover, when the correlation between resilience principles and the implementation difficulty are provided (e.g. by survey), the matrix is also able to assess the level of improvement of each resilience principle that is needed to achieve the expected level of each of the resilience criteria. The following subsections explains in further detail how the proposed framework can be implemented in resilient urban infrastructure systems planning practices.

3.2 Identification of Resilience Criteria and Principles

Urban infrastructure systems are expected to perform to meet certain criteria when responding to extreme events. A review of existing literature was conducted to identify specific infrastructure systems resilience criteria adopted in prior research or practice. According to the definition of each criterion, this paper reduces the number of resilience criteria from six to four, in order to avoid overlap or repetition. For example, failure probabilities and its consequences are so similar that they can vary in the same ways. Meanwhile, the consequences, referring to the decrease of flow or service provided by each single infrastructure system, are more palpable and measurable. Besides, according to the definition, the total performance losses are directly determined by the consequences from failures and recovery time. It could be repetitive to keep them all as separate resilience criteria. Therefore, this paper narrows down the list of resilience criteria into the following: disturbance propagation, consequences from failures, time to recovery, cost to recovery. A list of these criteria with their definitions and sources is presented in Table 1.

Table 1. Resilience criteria, references and examples

Criteria	Definition and references	Examples
Disturbance propagation	Failure propagation due to interdependencies between components of one or several infrastructure systems [24]	Fault-trips propagation in electric power
Consequence from failures	The decrease of flow or service of infrastructure systems [11, 25–34]	Massive black out
Time to recovery	The time from the beginning of disruptive event to full recovery of system functions [11, 24–34]	Time for power system to fully recover from failure
Cost to recovery	The economic cost to restore components and recover system functions [27, 29, 35]	Cost for repairing failed power facilities

Drawing on the application of QFD in other domains, engineering parameters at the planning stage are how a product should be designed as a whole. Based on the existing literature on infrastructure systems resilience design, resilience principles were identified. Resilience principles refer to what resilient infrastructure systems should be designed as. These resilience principles are listed in Table 2 with the source references. Different terms sometimes mean essentially the same principle, and are therefore combined in this paper. For example, adaptability, flexibility, self-regulation, foresight and feedback correction all mean the ability of a system to adapt to changing conditions and undergo a safe failure by changing its configuration. Also, repairability and resourcefulness both mean having adequate resources and personnel to restore the primary failed components directly due to attacks.

Table 2. Resilience principles, references and examples

Principles	Definition and references	Examples
Redundancy	With a number of functionally similar components so that the entire system does not fail when one component fails [8, 11–13, 15, 36–43]	Multiple plants in electric grids; standby pipelines
Diversity	With a number of functionally different components in order to protect the system against various threats [13–15, 36–40, 42–44]	Diverse energy sources; multiple transportation routes
Connectivity	With system components connected so that they support each other [8, 13–15, 36–40, 42–45]	Connected substations; high density of road network
Adaptability	A system should have the ability to "adapt to changing conditions" and undergo a safe failure by changing its configuration [8, 12, 13, 15, 36–42, 44, 45]	Power redistribution responding to disturbances; preparedness based on emergency forecast
Repairability	Ensure availability of adequate resources and personnel to restore the primary failed components directly due to attacks [8, 11–13, 15, 39, 41]	Technical maintenance teams; repairable or replaceable facilities
Independency	A resilient system should possess a "certain degree of self-reliance" that gives it the ability to maintain a minimum acceptable level of functioning (without external support) when influenced by disturbance [13, 15]	Backup power; independent communication channels

3.3 Relative Importance of Resilience Criteria

Following the identification of resilience criteria, it is significant to weight the relative importance between them to support decision-making. The main method used is customer ranking by surveys. In the field of urban planning, the customers should not be limited to end-users but also any stakeholders whose benefits are affected by the outcomes of infrastructure projects and need to be engaged in the decision-making process. Stakeholders involved in resilient infrastructure systems design can be citizens, economic institutions (companies and factories), infrastructure operating institutions and city managers.

The relative importance score between each two resilience criteria is from 1–9 based on Analytic Hierarchy Process (AHP) method [46] (a sample in Fig. 2). The relative importance can be determined by the geometric average of scores from various experts. The number of experts should be more than three and odd [46]. In order to deal with differences of scores between experts, the number of experts is set as three times of score levels, which should be fifty-seven. Finally, based on the judgment matrix, each element of which represents the relative importance between two resilience criteria (see an example in Table 3), the normalized relative importance can be computed by calculating the eigenvector of maximum eigenvalue and normalizing it, respectively based on Eqs. (1) and (2):

$$\left(\lambda_{max}E - R\right)x = 0 \tag{1}$$

$$\bar{x} = \frac{x}{\sum_{1}^{n} x_i} \tag{2}$$

where λ_{max}, x respectively denote the maximum eigenvalue and its eigenvector, E, R denote unit matrix and judgement matrix, $\bar{x}$ denotes the normalized importance weights, and x_i denotes the i-th element of vector x. In the judgment matrix, there could be a contradictory situation where relative importance between several items is not consistent. In such case, an approach termed consistency test is used to ensure the reliability of the results [46]. It estimates the consistency level of different relative importance in the judgment matrix by comparing maximum eigenvalue with matrix dimensions.

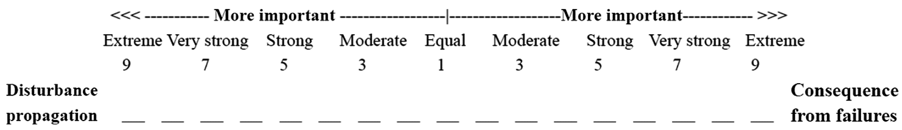

Fig. 2. Example of relative importance measurement of resilience criteria

Table 3. Example of judgment matrix of resilience criteria

	Disturbance propagation	Consequence from failures	Cost to recovery	Time to recovery
Disturbance propagation	1	1/3	5	1/2
Consequence from failures	3	1	7	1/3
Cost to recovery	1/5	1/7	1	1/9
Time to recovery	2	3	9	1

3.4 Relationship Between Resilience Criteria and Principles

The main strength of QFD is to transform the customer desires into engineering parameters that can be controlled based on the relationship between them. In the proposed framework, each resilience principle can have an effect on certain resilience criteria. For example, redundancy (resilience principle) could reduce the consequences from failure (resilience criterion). The relationship matrix reflects the strength of such effect. The strength can be weighted on a scale of: 9 (extremely strong), 5 (very strong), 1 (weak), and 0 (no relationship) following works in other applications of QFD [17, 47]. The identification of the relationship and its specific score can be determined by several methods [48]:

- Brainstorming based on technical knowledge;
- Expert scoring including different stakeholders;
- Design experiments;
- Historical product data analysis.

The method of simulation or experiments is difficult to implement due to the large-scale and complexity of urban infrastructure systems. This paper proposes three approaches to reveal the relationship between resilience criteria and principles. Firstly, the relationship is identified based on literature review and brainstorming based on technical knowledge. The results (shown in Table 4) are qualitative and can be used to validate the results of the latter two methods.

The second approach is based on the direct score of the relationship by experts in a survey. Given the explanation of each principle and criterion, experts are asked to provide an assessment (9-strong, 5-moderate, 1-weak or 0-no) to estimate the effect of each principle on each criterion based on their experience in the infrastructure domain. The reliability of results is ensured by consistence test using Kappa coefficient [49] and the validity can be ensured by comparing the results from different stakeholders.

The third approach, which is also survey-based, uses questions developed based on actual cases and data to decrease the dependence of results on experts' experiences and avoid subjectivity. The survey lists a number of typical existing infrastructure investment/design/construction projects. Experts are asked to select those projects that they ever participated in or are familiar with, and estimate the implementation level (1–5 scale) of each resilience principle in these selected projects (e.g. they are asked "how much redundancy do you think the single infrastructure system has in this project"). They are also asked to estimate the extent to which each resilience criterion is achieved in these projects (e.g. they are asked "how severe do you think the consequences from failures in this project were during past hazard events or would be during a virtual hazard event"). To decrease the subjectivity of these assessments, all survey respondents are presented with the same descriptions of these projects and hazard events. To yield statistically reliable results, the number of experts should be five to ten times the number of questions [50]. Given that there are four resilience criteria and six resilience principles to be assessed in the survey, a total of 50–100 responses are needed for each project included in the survey. Then a structure equation model (SEM) can be built to analyze the survey data. SEM is a statistical framework for analyzing the relationships among a collection of variables simultaneously in one model with a diverse set of mathematical models, computing algorithms, and statistical methods [51]. Exploratory factor analysis can be conducted to test the validity of each item in resilience criteria or principles. Meanwhile, path analysis can be conducted to reveal the relationship between each resilience criterion and principle in a quantitative way. To be used in QFD, the strength of relationship should then be transformed to a scale of 1–9.

Table 4. Identification of relationship between resilience criteria and principles

	Disturbance propagation	Consequence from failures	Time to recovery	Cost to recovery
Redundancy	Redundancy can provide backup goods or service to avoid the disturbance propagation caused by lacking power or service	Redundancy can provide backup goods or service to mitigate the impact of failures	No relationship	Fewer failures mean less cost
Diversity	Diversity can provide backup goods or service to avoid the disturbance propagation caused by lacking power or service	Diversity can provide backup goods or service to mitigate the impact of failures	Diversity can provide diverse ways to make the restoration work more efficient	Fewer failures mean less cost
Connectivity	Connectivity can aggravate the situation due to the interaction	Connectivity can aggravate the disturbance propagation due to the interaction	Connectivity can provide diverse ways to make the restoration work more efficient	Fewer failures mean less cost
Adaptability	Adaptability can mitigate the disturbance propagation by adjustments and self-regulation	Adaptability can mitigate the consequences by adjustments and self-regulation	Adaptability can accelerate the restoration work by adjustments and self-regulation	Fewer failures mean less cost
Repairability	No relationship	No relationship	Repairability can reduce the restoration time with adequate resources	
Independency	Independency can make subsystem not influenced by external failures	No relationship	No relationship	Fewer failures mean less cost

3.5 Relative Importance of Resilience Principles

Based on the function of QFD, the relative importance of resilience principles is worked out with the relative importance of resilience criteria and the relationship between resilience criteria and principles, which can be described as Eq. (3):

$$p_j = \sum_{i=1}^{4} c_i A_{ij}. \tag{3}$$

where c_i and p_j denote respectively the relative importance of resilience criterion i and principle j, and A_{ij} denotes the relationship between resilience criterion i and principle j.

3.6 Correlation Between Resilience Criteria or Resilience Principles

For an integrated infrastructure SoS, engineering parameters are inter-correlated, and it is difficult to change one without affecting the others. For example, connectivity and independency cannot be enhanced simultaneously (e.g. increasing connectivity of nodes in a water supplies system always leads higher dependency), while diversity and adaptability can be enhanced at the same time (e.g. with diverse energy sources, the demand of power can be satisfied by adjusting supplies of different sources when some of them are lacking). This paper proposes two survey-based approaches to identify such correlations. The first approach is based on the direct score of the correlation by experts in a survey. The score has a scale of: −2 for strong negative correlation, −1 for negative correlation, 0 for no correlation, 1 for positive correlation, 2 for strong positive correlation. The second approach is based on the survey of resilience assessment in listed projects. The correlation between resilience criteria and principles can be analyzed with the SEM. To be used in QFD, the correlation should then be transformed to a scale of −2 –2.

3.7 Difficulty of Implementation of Resilience Criteria and Principles

Due to limited resources or technology, the implementation priority of resilience criteria or principles should be determined based on not only their relative importance but also their difficulty of implementation. For example, redundancy is usually preferred to achieve resilience but requires significant resources. Hence, it is significant to estimate the difficulty of implementation of resilience criteria and principles in practice. To this end, this paper proposed a survey-based approach. Experts are asked to provide a score of 1–5 (1-extreme easy and 5-extrem difficult) to estimate the implementation difficulty of each resilience criterion or principle based on their experience in the infrastructure domain. Possible factors that may impact the level of implementation difficulty include but are not limited to time, budget, and government policy. Moreover, this paper identifies several possible factors including time pressure, political pressure, stakeholder pressure and community based on literature review, which will be expanded by expert interview in future work. Experts are also asked to provide a score of 1–5 (1-weak and 5-strong) to estimate the effect of each factor on implementing resilience based on their experience in the infrastructure domain.

3.8 Improvement of Resilience Principles

The main purpose of this framework is to provide practical guidance of resilient infrastructure systems design. After resilience criteria are transformed into actionable resilience principles and the relative importance of resilience principles are assessed, the next step is to determine which resilience principles should be prioritized in infrastructure systems investment decision making, so as to maximize the resilience level of the infrastructure systems given the constraints of availability of resources. Based on the method of QFD, the gap (Δy) between the real and expected level of resilience criteria should be investigated first. Using the relationship (A) between resilience criteria and principles, the gap can be transformed into the improvement requirement (Δx) of resilience principles as shown in Eq. (4):

$$A\Delta x^T = \Delta y \tag{4}$$

Taking correlation between resilience principles into consideration, an optimized solution of improvement of resilience principles can be worked out to promote principles that have positive correlation and avoid those that have negative correlation. The correlations are shown as Eq. (5):

$$\mathrm{a}\Delta x_i \pm b\Delta x_j + c_{ij} = 0 \; i,j = 1 \sim n \tag{5}$$

where Δx_i and Δx_j denote the change of i-th and j-th resilience principles, respectively, c_{ij} denotes the correlation strength, n denotes the number of principles, and a, b denote constant parameters. Moreover, to achieve minimal implementation difficulty (d), with the constraints described in Eqs. (4) and (5), a more practical solution to the improvement of resilience principles can be worked out based on Eq. (6):

$$min\left(d\Delta x^T\right) \tag{6}$$

4 Outlook and Limitations

Based on the above explanation of implementation details of the proposed framework, the main strength of the framework can be summarized as follows:

- it could transform qualitative resilience criteria into engineering parameters (e.g. resilience principles) that can be addressed in practice;
- it could take into consideration all the stages (e.g. planning, design, operation, control) and involve different stakeholders (e.g. government employee, city planner, emergency personnel, public safety officer, architect, engineer, contractor, infrastructure operator, infrastructure investor) taking into consideration the complexity of resilient infrastructure systems design;
- it is applicable to a complex system since it could regard the system as a system of systems, by using the correlation of items in row and column;

- it could work out the specific improvement requirement of given items based on the gap between expected and real resilience criteria;
- it could optimize the solution of improvement of resilience principles by taking correlation between resilience principles and implementation difficulty into consideration.

There are also several limitations of the proposed framework that should be addressed in future research:

- it mainly depends on the literature review and survey and the scoring is subjective;
- the reliability of results may be hard to be ensured since different stakeholders have different understanding of the listed items;
- the respondents may be impatient with the lengthy questionnaire that includes a number of sections including relative importance, relationship, correlation, implementation difficulty.
- the implementation cost of the questionnaire could be higher compared to simulation since as it involves multiple stakeholders and a good number of experts.

5 Conclusions

This paper proposed a conceptual framework for designing resilient urban infrastructure system of systems based on QFD. It takes the first HoQ of QFD as an example to explain the development and implementation process of this framework. The first HoQ mainly focuses on the planning stage of urban infrastructure systems. The identification of resilience criteria and resilience principles based on literature review were explained firstly. Then the paper elaborated on a survey-based approach used to construct the main body of the HoQ. Different components of the HoQ represented the relative importance between resilience criteria, relationship between resilience criteria and principles, correlation between resilience criteria or principles, and implementation difficulty of resilience principles. Lastly, the main functions of QFD were introduced which could be used to optimize practical design schemes. Future research will be carried out by the authors to materialize the first HoQ with surveys and associated analysis, develop following HoQ that are related to later phases of the lifecycle of infrastructure systems, and integrate fuzzy decision-making and simulation as alternative approaches to the interpretation of survey results and construction of the HoQ.

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