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Measurement of Resilience Performance for Infrastructure Construction Project Delivery

Fei Han
Doctoral Student, Construction Management

Fei Han

Candidate

Civil, Construction and Environmental Engineering

Department

This dissertation is approved, and it is acceptable in quality and form for publication:

Approved by the Dissertation Committee:

Dr. Susan Bogus Halter, Chairperson

Dr. Kerry Howe

Dr. Su Zhang

Dr. Fan Zhang

MEASUREMENT OF RESILIENCE PERFORMANCE FOR INFRASTRUCTURE CONSTRUCTION PROJECT DELIVERY

by

FEI HAN

B.E., Building Environment and Facility Engineering, Beijing
University of Technology, 2003
M.S., Civil Engineering, University of New Mexico, 2013

DISSERTATION

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DEDICATION

I dedicate this dissertation to my wife Cher, families, and friends standing behind me on the journey to becoming a better myself.

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by

FEI HAN

B.E., BUILDING ENVIRONMENT AND FACILITY ENGINEERING, BEIJING UNIVERSITY OF TECHNOLOGY, 2003

M.S., CIVIL ENGINEERING, THE UNIVERSITY OF NEW MEXICO, 2013

PH.D., ENGINEERING, THE UNIVERSITY OF NEW MEXICO, 2021

ABSTRACT

In the past decade, infrastructure resilience in the U.S. has become critical due to increasing disruptions to the built environment and the resultant consequences on economic, social, and environmental goals. This attention to resilience research is drawn to investigating the ability of existing structures and facilities to resist and recover from natural and human-caused hazards. From a broader view, resilience also applies to processes, such as infrastructure project delivery processes. During these processes, a project often suffers inevitable threats and disruptions, which can significantly delay or derail the project if the process is not resilient.

This research aimed to conceptualize resilience for project delivery processes and develop a measurement approach that can be used to diagnose the resilience of infrastructure project delivery systematically. Several steps were taken to accomplish this research objective.

The author defined resilience as the ability of the project delivery system to withstand disruptions with the goal of mitigating the disruption-induced gap to intended project results. The proposed resilience definition highlights resistance, recovery, adaptation as the three stages for a project to respond to disruptions. The three resilience stages provide the fundamental dimensions from which seventeen resilience factors were identified to measure resilience in the context of road construction project delivery. The significance of the proposed resilience factors was verified by industry experts through a structured survey questionnaire. Based on the survey data, the author developed resilience criteria and the Project Delivery Resilience Index (PDRI) to evaluate the resilience of different project delivery methods: Design-Bid-Build (D-B-B), Design-Build (D-B), and Construction Manager/General Contractor (CM/GC). Furthermore, Tendency toward Inoperability (TI) was developed to quantitatively measure the project delivery resilience in the case that the project delivery process is considered a system consisting of different project phases linked to each other by interdependent input-output relationships. To compute the TI, the author proposed an inoperability-based model that holistically measures the variations of project phase-related TI before and after disruptive events. Thus, the gain in resilience for the project delivery system can be solved.

The findings of this research add to the body of knowledge by advancing the understanding of the resilience of project delivery and providing a comprehensive means to incorporate resilience assessment into infrastructure project delivery, and eventually improve the resiliency of completed infrastructure.

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CHAPTER I

INTRODUCTION

1.1 Background

Infrastructure resilience in the U.S. is critical due to increasing disruptions to the built environment and the enormous influence these disruptions have on economic, social, and environmental goals. Typically, disruptions to infrastructure systems (i.e., natural hazards and human-caused incidents) are unavoidable, unforeseeable, and consequential, making traditional risk-oriented approaches less effective, and resilience (i.e., inherent system capability) the key to withstanding disruptions. In this case, resilience is intended to supplement risk management by focusing on the performance of systems before, during, and after particular risk events.

Project delivery processes for infrastructure construction are subject to various disturbances which prevent projects from being completed as intended. Such project challenges are often addressed by traditional risk management, whose focus is on risk prevention from characterizing the uncertainty of risk events to evaluating the impact. Such risk-oriented protocols are considered inadequate, even if being widely recognized, due to the nature of certain risks – high inevitability and consequences to infrastructure construction (e.g., Covid-19 pandemic impacts on global supply chain). When it came to disruptions with a low likelihood of occurrence and substantial impact, public officials in the Architecture, Engineering, and Construction (AEC) industry began to pursue resilience – a system approach relevant to the risk-oriented protocol to enhance the capability of projects to withstand disruptions. For instance, the U.S. Department of Transportation (USDOT) recently required

incorporating resilience into transportation project development as a part of regular practice (USDOT FHWA, 2018).

Regardless of the context of resilience, the fundamental research questions to consider include why consider resilience, what to consider the resilience of, and how to achieve resilience. Existing research and applications about infrastructure resilience focuses on the examination of physical structures and facilities and their reaction to specific natural hazards in terms of their existing conditions of materials, structural integrity, lifeline functionality (e.g., transportation, communication, and utility supply), and the technologies to detect and evaluate the emerging issues and resultant impact.

Unlike the existing literature, this research focuses on the resilience of infrastructure project delivery – the processes to design, construct, and repair existing and new infrastructure, as an alternative solution to risk management to embrace disruptions. More importantly, resilient infrastructure project delivery will allow project owners and stakeholders to achieve intended project goals.

1.2 Problem Statement

While there has been increasing research regarding the resilience of existing infrastructure, examining resilience for prospective infrastructure and ongoing infrastructure projects in terms of the project delivery processes is lacking. The need for resilience applies to project delivery processes (PDP) because disruptions to PDP are unavoidable, and the impact of some disruptions (e.g., design defects) could persist, thus undermining the resiliency of the completed structures. In this case, meaningful questions to answer are: What does resilience

mean to PDP? Can this PDP resilience be measured? And how can it be measured? The questions mentioned above have not been discussed adequately in the existing literature on resilience. This research seeks to fill this gap by conceptualizing resilience for infrastructure PDP and developing qualitative and quantitative resilience measures associated with project delivery methods (PDMs) in road infrastructure construction. The anticipated results are intended to make resilience operational for public officials and project stakeholders to integrate resilience into each stage of the project lifecycle.

1.3 Research Objectives and Questions

The overall objective of this research is to operationalize the concept of project delivery (PD) resilience and measure the resilience of the project delivery process. To that end, the technical objectives of this research include:

1) Define resilience in the context of infrastructure project delivery, focusing on resilience attributes that are universally applied to different aspects of PDP.

2) Develop resilience criteria for infrastructure PD, which are applicable through different stages/aspects of infrastructure PDP and contribute to the resilience attributes.

3) Develop an applied resilience measurement construct to rate PD resilience, which can serve as a baseline for comparing resilience performance for different PDMs.

4) Propose a quantitative measurement method for resilience that is driven by the resulting performance of PD.

To achieve the objectives outlined above, this research aims to answer the following questions.

1) What does resilience mean for infrastructure project delivery? (Chapter II)

2) How can we conceptualize PD resilience in terms of resilience attributes associated with the performance of PDP? (Chapter II)

3) Based on the PD resilience attributes, what are the underlying indicators that can be used to measure the PD resilience? (Chapter III)

4) How can we measure the PD resilience based on the proposed resilience indicators? (Chapter IV)

5) For PDMs that are widely used for road infrastructure projects, which PDM is more resilient than others in response to disruptions to PDP? (Chapter IV)

6) What is a performance-based metric that can be used to quantitatively measure the PD resilience? (Chapter V)

1.4 Expected Significance of the Research

Upon the completion of the research, the contributions to the body of knowledge include but are not limited to the following:

This research can advance the understanding of resilience for infrastructure project delivery processes in terms of how resilience is relevant to existing theories dealing with the complexity of construction projects, such as risk assessment, lean construction, and sustainable

construction. Especially, resilience is considered an essential supplement to risk management when risks are significantly unpredictable and consequential (Linkov and Trump, 2019).

This research provides an assessment approach to rating PD resilience. The qualitative portion of the approach conceptualizes resilience by developing a resilience index consisting of the resilience indicators in the context of infrastructure PDP. The resilience index is intended to lay the foundation to standardize the resilience assessment for different PDMs and ultimately integrate the resilience mindset into infrastructure project development. The quantitative piece of the approach provides a performance-based resilience metric. The proposed metric can be used to simulate the variation of disruption-induced impact on intended project outcomes when PDP is viewed as a project phase-based system whose performance varies at different resilience stages.

The novelty of this research also lies in comparing PDMs and supports the selection and improvement of the PDMs from the resilience perspective. Unlike project cost- and time-related metrics usually unavailable until project completion, resilience metrics can be used to evaluate the PDMs and the corresponding project response before, during, and after disruptions.

1.5 Structure of the Dissertation

This dissertation is organized into six chapters, including this introductory chapter. Figure 1.1 illustrates the flow of the chapters. Chapter I provides the background of the research, the problem statement, research objectives, and questions. Following the introductory chapter, Chapter II provides the theoretical foundation of the resilience concept from two aspects: the multidisciplinary interpretation of resilience and relationships between resilience

and relevant theories (e.g., risk management and sustainability), which is based on an extensive literature review. Subsequently, the author developed a resilience definition for PDP and the conceptual framework where resilience attributes can be identified (Han and Bogus, 2017).

Chapter III develops resilience assessment criteria for PDP. As a result, an explanatory construct of resilience criteria was established based on a given list of resilience factors associated with best practices that have been used in road infrastructure project delivery (Han and Bogus, 2021). Chapter IV examines in detail the significance of the identified resilience criteria and subordinate factors using the Factor Analysis + Analytical Network Process (F'ANP) model. First, the author proposed a resilience measurement construct associated with three resilience stages – resistance, recovery, and adaptation. Second, the author aggregated the resilience criteria and factors into the Project Delivery Resilience Index (PDRI) and showcased how the proposed PDRI can be used to rate the resilience of three popular PDMs for road construction projects.

Chapter V proposes a quantitative resilience metric – Tendency toward Inoperability (TI), a performance-based measure reflecting how the disruption-induced impact on the project completion (i.e., percentage gap of the intended project progresses) can be measured in practice (Han and Bogus, 2020). Subsequently, the level of PD resilience is considered as the TI change across the interdependent project phases before and after disruptive events. The author measured the TI based on organizational and operational interdependencies among project phases using Inoperability Input-Output Model (IIM).

Lastly, Chapter VI presents the general discussion of the results, conclusions, limitations of the research, and recommendations for future research.

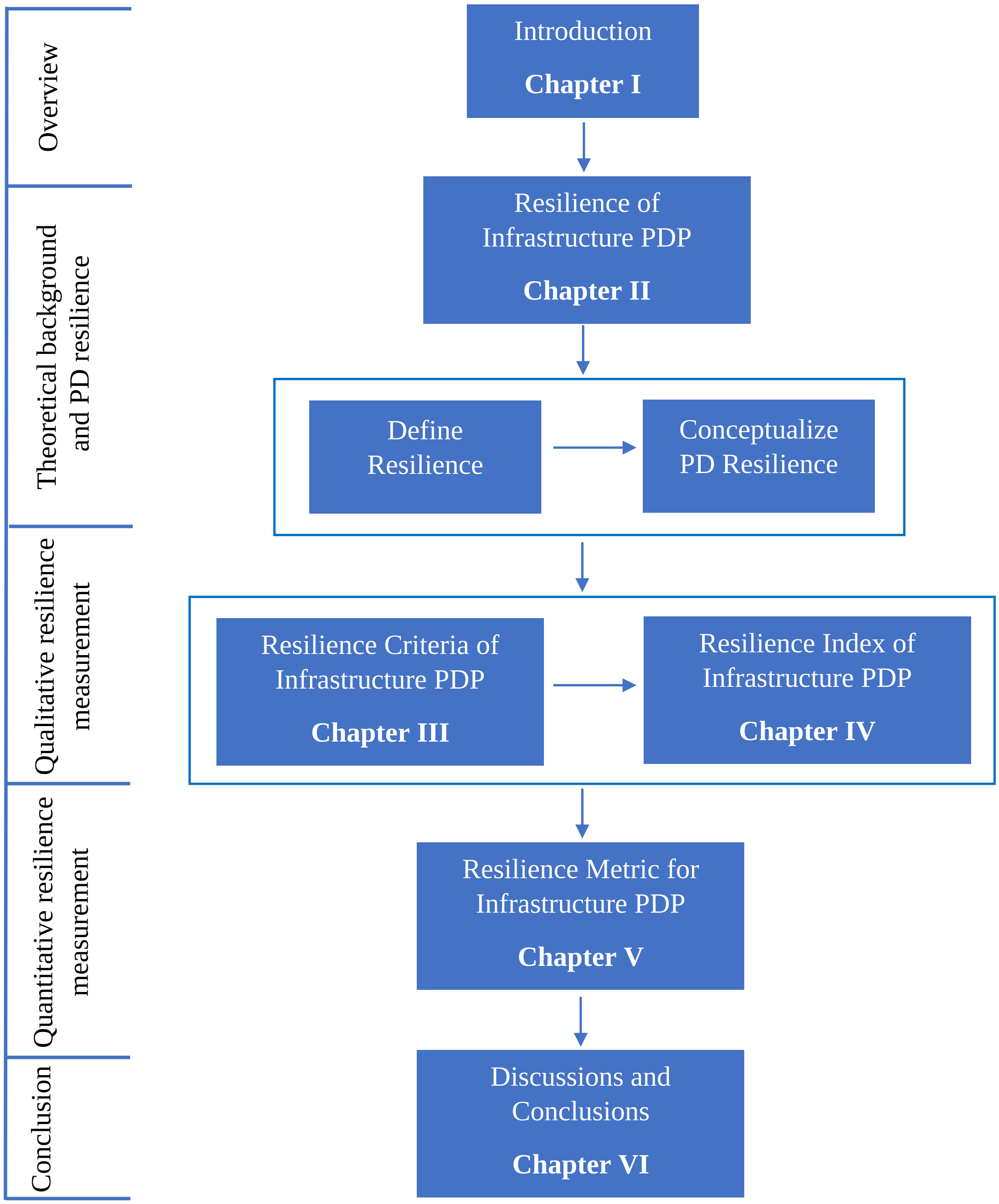

Fig. 1.1 Flow of the dissertation chapters

CHAPTER II

RESILIENCE OF INFRASTRUCTURE PROJECT DELIVERY

2.1 Introduction

Resilience has been studied in multi-disciplinary contexts, such as natural disaster relief, infrastructure, and human community security in responding to potential system failures, cyber threats, and terrorist threats. Infrastructure resilience demonstrates the ability of current structures to withstand natural and human-caused hazards. A broader view of resilience recognizes that resilience also applies to processes, such as project delivery processes (PDP) which are subject to inevitable threats and disruptions preventing a project from being completed as intended. Even if risk management is widely implemented in construction, a smooth project delivery remains challenging partly because certain risks are unpredictable. Given the inevitability of the risks, there is a need to integrate resilience as a part of PDP.

Compared to existing infrastructure, the resilience of its PDP is barely addressed in the literature. This chapter provides an essential literature review about resilience from two aspects: (1) the concept of resilience and its relationships with the relevant ideas, including risk, robustness, sustainability, and lean theories; and (2) methods to measure resilience. Then, the author defines the resilience for infrastructure PDP in terms of resilience attributes, dimensions, and operating modes. The result is presented in a conceptual resilience framework. The proposed framework can serve as a preliminary resilience matrix filled with analytical resilience measures that are applicable for an illustrative PDP.

2.2 Background

2.2.1 Definition of Resilience

Since first introduced to analyze the properties of ecological systems in the presence of disturbances (Holling, 1973), resilience has been defined and applied in diverse domains such as organization, supply chain, economics, social, engineering, material science, and psychology. A common driver for resilience stems from hazards, interruptions, changes, and risks, collectively named as “disruptions.” A system in need of resilience is subject to a certain degree of vulnerability, vulnerable to expected and unexpected disruptions. Despite remaining a familiar term in all walks of life, resilience carries different meanings across different contexts, as summarized in **Table 2.1** (Bhamra, 2011).

Table 2.1 Definition of resilience

Literature	Context	Definition
Bruneau et al. (2003)	Disaster management	The ability of social units to mitigate hazards, contain the effects of disasters when they occur and carry out recovery activities that minimize social disruption and mitigate the effects of future earthquakes
McDonald (2017)	Organizational	Resilience conveys the properties of being able to adapt to the requirements of the environment and being able to manage the environments variability
Hollnagel et al. (2006)	Engineering	The ability to sense, recognize, adapt and absorb variations, changes, disturbances, disruptions and surprises

Vugrin et al. (2010)	Infrastructure systems	Ability to reduce the degree and duration of the deviation from expected system performance levels following a particular disruption event.
Ponis and Koronis (2012)	Supply chain	Ability of supply chains to respond to disturbances and disruptions.
Walker et al. (2004)	Ecological systems	The capacity of a system to absorb a disturbance and reorganize while undergoing change while retaining the same function, structure, identity and feedback
Carpenter et al. (2001)	Socio–ecological systems	The magnitude of disturbance that a system can tolerate before it transitions into a different state that is controlled by a different set of processes
Rose (2007)	Economics	Ability of a system to continue its functionality, mitigate potential losses, and recover from a shock to a steady state.
Luthans et al. (2006)	Psychology	The developable capacity to rebound from adversity
Gere and Goodno (2013)	Physical systems	Ability of a material to absorb and release energy, within the elastic range

It is worth noting that resilience refers to an “ability” or a property that encompasses typical stages starting with resisting, then recovering from the disrupted to the normal state, and ultimately adapting to the disruptive event. During these stages, recovery is considered the most crucial for being resilient to disturbances (Hosseini et al., 2016). Until recently, the Architecture, Engineering, and Construction (AEC) industry acknowledged resilience as an

ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (Industry Statement on Resilience, 2016).

2.2.2 Multifaceted Outlook of Resilience

Resilience can be characterized by different conceptual elements as research contexts change. A significant amount of research focused on resilience for infrastructure systems under threat or in recovery from natural disasters and emergency events. The Multidisciplinary and National Center for Earthquake Engineering Research (MCEER) has developed a comprehensive resilience framework with "4R" dimensions of robustness, redundancy, resourcefulness, and rapidity to define seismic resilience of communities and performance measures of critical community functions, such as power, water, and hospital systems (Bruneau et al., 2003). In the building environment literature, resilience emerged as a part of building design principles. Per Hassler and Kohler (2014), simple oversizing of the building component, spaces, redundancy, and reparability can enhance the resilience of buildings for unknown uses and adaptions. Almufti and Willford (2014) proposed a rating system for the seismic design that not only ensures the "life-safety" but also allows more repairable damage by an earthquake to the building components to achieve "overdesign" seismic resilience.

The resilience of engineering systems focuses on the system's normal functioning and how much it could fail and regain in the presence of or after disruptions (Hollnagel et al., 2006). For instance, Dinh et al. (2012) identified six best practices to enhance the resilience of industrial processes, including minimization of failure, limitation of effects, administrative controls/procedures, flexibility, controllability, and early detection. Supply chain resilience emphasizes the normal operation and stability of a supply chain to the disturbance in three

phases: anticipation, resistance, and recovery and response (Barroso et al., 2011). Organizational resilience addresses the need for an organization to respond to rapid-changing business environments. Burnard and Bhamra (2011) simulated a generic process of organizational responses to disruptive events via major steps of detection, activation, response, adjustment, and organizational learning.

The resilience attributes that are most frequently cited across domains are resistance, recovery, adaptation, and redundancy, as shown in Table 2.2. Conceptualizing resilience attributes is intended to provide a better understanding of the contextually related measures which should be taken into account for resilience evaluation and enhancement.

Table 2.2 Resilience attributes

	Anticipation	Detection	Resistance (Robustness)	Adaptation	Redundancy (Absorption)	Recovery (Rapidity)	Learning
Bruneau et al. (2003)		x	x		x	x	
Madni (2009)				x	x		
McDonald (2017)				x	x	x	
Pettit et al. (2010)	x		x			x	
Burnard and Bhamra (2011)		x	x	x			x
Francis and Bekera (2014)				x	x	x	
Hollnagel (2014)	x	x				x	x
Wang (2015)			x			x	
Wood (2015)			x	x		x	

2.2.3 Resilience and Related Theories

The fragmentation of resilience knowledge introduces a barrier that prevents progress in resilience implementation in complex systems. This situation is partly because there is a conceptual overlapping between resilience and relevant theories, such as risk management and sustainability, that aim to retain and enhance system performance under adverse conditions. A brief comparison of resilience and several of such theories are listed below.

2.2.3.1 Resilience Management vs. Risk Management

The theories about resilience have been mingled with risk management as a system approach. According to the research by Linkov and his colleagues (Linkov et al., 2016, 2014, 2013), both risk and resilience theories set in similar thinking of reviewing systems for vulnerability, assessing the uncertainty of threats, and identifying resources and actions to resolve the vulnerability and mitigate the loss. Both theories share the similarities of anticipating, planning, and preparing for risk events and so to assess and mitigate the consequence of the threats. In essence, resilience is viewed as a complement of conventional risk management whose planning/analysis approaches are performed not only before but also during and after risk occurrence, in terms of specific risk versus the variety of disruptions, especially that are unforeseeable (Linkov et al., 2016, 2014, 2013; Park et al., 2013; Steen and Aven, 2011). The focus of resilience shifts from risks themselves (occurrences and potential impacts) to the variation of system performance due to the risk-induced impact. Moreover, resilience has a broader perspective of risks than that of risk management when risk is unmeasurable (Linkov and Trump, 2019).

2.2.3.2 Resilience vs. Robustness

The ability of a resilient system to withstand risks and disruptions introduces another term to describe this characteristic – robustness. The two concepts are often treated as synonymous, but they are conceptually distinct and not necessarily related to each other (Capano and Woo, 2017). Robustness means being “insensitive” to uncertainties and is often used to describe and assess actionable plans and strategies which can be applied to a system to maintain the same performance in the face of perturbation (Bankes, 2010). In contrast, resilience focuses on understanding the ability of systems, organizations to persist over time against perturbations, and in particular recover from the perturbations, as a kind of functionalistic (autonomous) processes (Bednar, 2016). Resilience is effective when robustness is inadequate to avoid shocks that affect systems for allowing the systems to rebound from shock, even if the systems lack the robustness necessary to withstand the shocks in the first place. In other words, robustness seems to inhibit resilience, whereas resilience becomes critical when robustness fails.

2.2.3.3 Resilience vs. Sustainability

Resilience and sustainability are closely related, mutual-inclusive, and interdependent, especially in the contexts of social and natural systems (Levin et al., 1998; Holling and Walker, 2003). Still, for social-ecological systems, resilience is considered a relevant concept of sustainability for sustaining the systems in the face of perturbations (Folke et al., 2003). For civil infrastructure, resilience and sustainability were suggested complementary attributes due to their shared or controversial definitions, dimensions, and targets, and thus, should be integrated to assess bridges’ service life (Bocchini et al., 2014). Other researchers claimed that resilience is one of the contributing factors for sustainability. For instance, the concept of

community resilience is regarded as a favorable feature of social and physical systems to lead to community sustainability against disaster (Klein et al., 2003; Cutter et al., 2008).

2.2.3.4 Resilience vs. Lean

Like resilience, lean is also a system approach by which the system performance is expected to improve as a result of lean practices. The theory about lean production addresses people and processes to eliminate waste by reducing variability (Shah and Ward, 2003). In contrast, when considering a production environment, resilience can be operational when its core functions emphasize proactive and reactive capabilities of production lines in handling unforeseen disruptions to sustain operations and adapt to changes (Birkie et al., 2014). Accordingly, Birkie (2016) presented synergies and trade-offs between operational resilience and lean paradigms upon disruptions. For the synergy argument, both can provide long-term cost savings without a significant performance loss. On the other hand, lean strategies reduce redundancy, while resilience theories advocate redundancy, such as over-design and preloading of resources for unexpected disturbances. The implication for redundancy also suggests the trade-off of resilience and efficiency.

2.2.4 Resilience Measurement

In addition to resilience definition, another focus of the literature is resilience assessment. Generally, resilience can be measured using either qualitative approaches or quantitative approaches.

2.2.4.1 Qualitative Resilience Measures

Qualitative methods to measure resilience either identify contextually related measures as resilience criteria or provide analytical approaches to model primary stages of resilience.

The conceptual framework is the most widely used method that not only promotes the understanding of resilience but also presents underlying resilience measures/indicators (e.g., strategies, principles, guidelines, and best practices). For disaster resilience, the well-known frameworks include the MCEER R4 resilience framework (Bruneau et al., 2003), the Disaster Resilience of Place (DROP) model (Cutter et al., 2008), the ResiliUS framework (Miles and Change, 2008), the Baseline Resilience Indicators for Communities (BRIC) (Cutter et al., 2010), the PEOPLE resilience framework (Renschler et al., 2010), and a multi-disciplinary framework for seismic resilience (Verrucci et al., 2012). The existing multi-criteria rating programs for resilience were developed to address natural hazards for the built environment at various scales (from buildings, lifeline infrastructure, and communities), such as the rating tools by the U.S. Resiliency Council, REDi by the Arup Group, and RELi by the U.S. Green Building Council.

As far as analytical assessment, resilience suggests a system dynamic in terms of how the system behaves before and during disruptions then adjusts the functioning to be better maintained for the future after the disruptive events. (Linkov et al., 2013). As seen in Figure 2.1, the "resilience triangle" is a widely used metric based on the size of degradation of the system functioning (Ayyub, 2015; Ayyub, 2014; Attoh-Okine et al., 2009; Bruneau and Reinhorn, 2007; Shinozuka et al., 2004). Thus, resilience can be measured using Equation 2.1.

$$Resilience = \frac{\int_{t_0}^{t_1} Q(t)dt}{100\,(t_1 - t_0)} \tag{2.1}$$

Where, Q is the system output, t_0 is the time of incident or disturbance occurrence, and t_1 is the time to full recovery. Thus, the metric of resilience is system performance (output)

per unit time, where system performance can be measured in percent, as shown in Figure 2.1. Likewise, the major stages of resilience, such as resistance and recovery, can be measured by Equations 2.2 and 2.3.

$$Resistance = B - C \tag{2.2}$$

$$Recovery = \frac{A-B}{t_1-t_0} \tag{2.3}$$

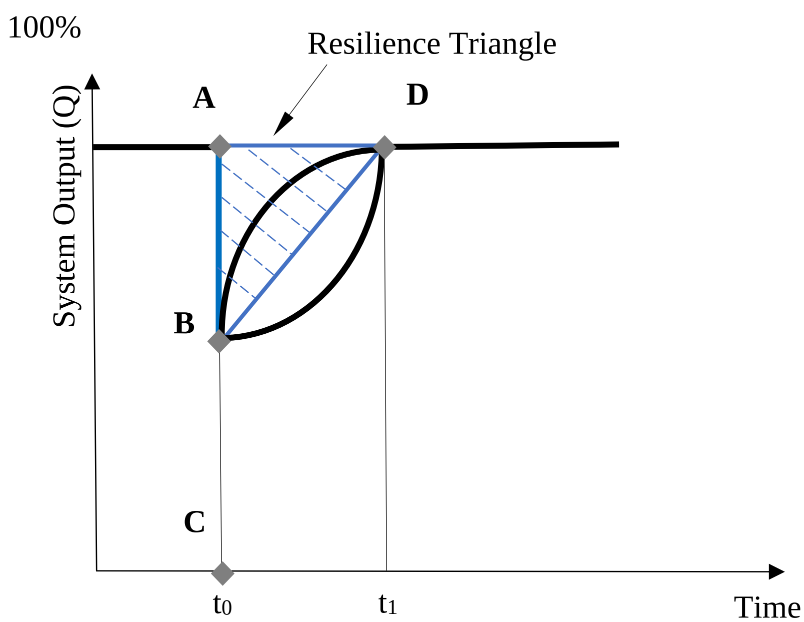

Fig. 2.1 Resilience triangle

2.2.4.2 Quantitative Resilience Measures

Quantitative resilience measures are often performance-based and focus on the continuity of critical system functions in response to disruptive events when the system or its components (e.g., roads, bridges, power, and communication) are assessed as the points of interest. One such resilience metric measures the gap before and after interruptions, such as a fraction of the actual level of power flow and the target flow for power transmission systems

(Quyang and Duenas-Osorio, 2012). Resilience for highway systems is often addressed at the network level regarding how the provision of service alters in pre- and post-disruptive events (Machado-León and Goodchild, 2017). Under the disruption of winter storms, Nogal et al. (2017) examined highway resilience as the network's capacity to absorb the adverse impacts by identifying different routes for the same pair of original-destination (O-D) points while minimizing travel costs. Adams et al. (2012) examined the restoration of highway corridors by tracking the truck speed and number of trucks on the move before and after adverse weather events. Another type of performance-driven metric involves the timing aspect when examining the performance variations, such as a time-dependent functionality ratio that considers recovery speed parameters in terms of slack time, time to initial recovery action, and full recovery (Francis and Bakera, 2014). Based on the cost and duration data for transport infrastructure reconstruction projects, Mojtahedi et al. (2017) modeled the relative recovery rates – calculated from probability distributions fitted by the frequency of the reconstruction duration data – for regional areas in Australia from bushfire, flood, and storm, using Cox's proportional hazards regression model. In practice, since the comprehensive performance of a system is hard to quantify, a key to identifying a quantitative resilience measure depends on the availability of quantifiable system performance indicators.

2.3 Conceptualizing Resilience of Infrastructure Project Delivery Processes

2.3.1 Infrastructure Project Delivery

As shown in Figure 2.2, infrastructure project delivery refers to a series of processes in chronological order, beginning with the conceptual phase by the owner and planner, through coordination of design and construction, to project completion. Per Oberlender (2014),

developing a project usually goes through the following phases regardless of the delivery methods, including project definition (to meet the owners' needs), project scoping (to meet the project definition), project budgeting (to meet the project definition and scope), project planning (to develop the strategy to accomplish the work), project scheduling (the product of scope, budgeting, and planning), project tracking (to ensure the project is progressing as planned), and project closeout (final completion to ensure owner satisfaction).

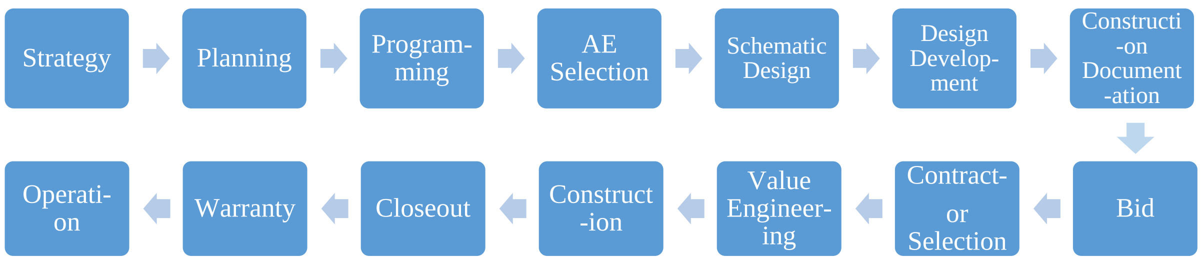

Fig. 2.2 Illustrative project delivery processes

2.3.2 Risk Management of Infrastructure Project Delivery

Infrastructure project delivery could be vulnerable as different project phases are subject to various risks and disruptions (i.e., once the risks occur), which affect the completion of the project objectives as intended. The causes of the disruptions are broad and specific to different project scenarios, which is not the concern of this research. Instead, this research classifies risks and the risk-induced disruptions to an infrastructure project in two general categories, including both shocks (e.g., a pandemic or natural hazard) and slow-moving risks (e.g., scope changes and design defects).

Existing literature about project delivery processes emphasize how to prepare for disruptions by better characterizing potential risks. For instance, Tran et al. (2014) proposed a list of risks specific to highway construction, such as hazardous materials, unforeseen utilities, railroad coordination, and third-party design approval. Also, in highway construction, Creedy et al. (2010) provided ten reasons for cost overruns, like design/scope change, deficient documentation, constructability, and price escalation. Forty-three factors that might cause time delays of road construction were identified in a matrix regarding the impact and the probability of occurrences and grouped into three zones according to the degree of factor severity (Mahamid, 2011).

For the decision of selecting suitable PDMs for infrastructure projects, the literature has evaluated traditional Design-Bid-Build (D-B-B) versus alternative PDM like Design-Build (D-B) and Construction Manager/General Contractor (CM/GC) by comparing common project performance measures (e.g., cost, schedule, and quality) for water, wastewater, and transportation projects (Abi Shdid et al., 2018; Bypaneni and Tran, 2018; Shrestha et al., 2018; Tran et al., 2017). For highway projects, the results showed that D-B and CM/GC outperform D-B-B partly because project risks can be better allocated and controlled by enhanced collaborations, such as integration of project teams and involving contractors during design processes (Antoine et al., 2018; Abi Shdid et al., 2018). Nevertheless, no single PDM is suitable for all projects; rather, the assessment of risks and characteristics of particular project scenarios is required (Tran et al., 2017). The emphasis of the risk assessment lies in estimating the probability of risk occurrences and the predictable consequences, based on historical data (e.g., past weather records for schedule risk accommodation) or knowledge-based judgments by industry experts (Kaplan and Garrick, 1981; Steen and Aven, 2011).

2.3.3 Why Resilience for Infrastructure Project Delivery

Despite the emphasis on risk management, poor performance for infrastructure project delivery such as budget and schedule overruns is pervasive. For instance, a recent case study reported that 60% of water infrastructure projects were completed over budget with a mean cost overrun of 20% (Love et al., 2018). The risk management process is considered insufficient since the likelihood of risk occurrence along with the corresponding consequences on intended project performance (e.g., fund cuts and unexpected utility encounters) are difficult to measure with estimable outcomes (Park et al., 2013, Linkov et al., 2014). When risks occur and subsequently impact project performance, there is a need for resilience management to get projects "back on track." Resilience management is considered an extension of conventional risk management (Steen and Aven, 2011; Linkov et al., 2014; Aven, 2017). One common resilience definition describes resilience as a combined system capability to resist, recover from, and adapt to disruptions in order to sustain intended system functionality (National Research Council, 2012; Hollnagel, 2014). It is noticeable that resilience management, unlike risk assessment, focuses more on recovering from the adverse consequences caused by various disruptive events than the likelihood of the occurrence of the disruptions (Steen and Aven, 2011).

The risk-based approach proves challenging to prepare for emerging threats (e.g., climate change) due to a wide range of possible impacts (e.g., extreme weather events vs. global warming). While the rhetoric to make infrastructure project development resilient is high, the theory and methods to do so remain in the early stage. There is a vital need to develop new knowledge of how resilience is defined, related to, and measured in the context of PDP. This chapter aims to define a resilience framework for project delivery by answering the

following questions: (1) How do we define resilience for infrastructure PDP? (2) What are the conceptual measures that can be used to assess resilient PDP?

2.3.4 Defining Project Delivery Resilience

Existing literature describes resilience as an intrinsic ability of a system to absorb threats, mitigate losses, and maintain system functionality and a global state of resiliency to achieve. In a general sense, the ability of resilience is considered as both process-oriented (i.e., the continuous process of developing resilience) and result-oriented (e.g., the degree and time of resistance and recovery).

Disruptions in construction are inevitable, unpredictable, and, more importantly, process oriented. Accordingly, resilience for the project delivery process is defined as an ability associated with each project stage to plan and allocate resources that can be used to constantly prepare for disruptions and reduce negative impact moving along the processes. Over the project delivery timespan, one disruption may appear only at a certain project stage while another can linger through multiple stages. Dealing with such disruptions requires continuous efforts throughout the affected project stages to anticipate, react to, and recover from the disturbances. Depending on whether or not disruptions occur, project delivery resilience can operate in two modes for the pre- and post-disruption environment. (1) Proactive/preventive resilience works through the project delivery process before any disruptions kick in. The goal is to either predict and prevent the possible disruptions or prepare for mitigating the impact of expected disruptions. (2) Reactive/restorative resilience takes over upon the occurrence of disturbances.

Figure 2.3 represents a visual explanation of project delivery resilience and how its two modes work based on the cost influence curve (solid lines), which is well-recognized in

construction management. In the graph, the x-axis illustrates major project stages for a typical project delivery process where disruptions could occur in any of these stages. The y-axis on the left side refers to the ability to influence the project against disruptions from 0 to 100%. The other y-axis represents the cost to fix the disruptions from low to high. The influence curve shows that the ability to influence the project decreases as the project develops. The cost curve is the reverse of the influence curve, which means the cost to fix disruptions increases as the project moves along the life cycle. The newly added curves stand for the trends under proactive/preventive (square-dot & long-dash-dot) and reactive/restorative (long-dash & dash) resilience. The transition point between the two resilience modes is assumed to be at the early stage of the construction phase.

As seen in Figure 2.3, resilience starts from the proactive/preventive mode. Compared to the original influence curve, the ability to influence projects (square-dot line) still trends down, but the downward trend flattens over the delivery process. This is because continuously detecting and preparing for possible disruptions enhances the ability of the project to influence the outcome, such as taking more responsive actions, developing contingency plans, and having a make-ready workforce in response to actual disturbances. Also, despite the upward trend for the cost curve, the cost to fix disruptions (long-dash-dot line) trends up more smoothly as the disruptions occur. The slowdown in the upward trend means that less cost is needed to fix the disruptions, as a result of the pre-detecting efforts stated above. For instance, a contractor relies on a vendor-managed inventory for the material supply, and the vendor partner regularly monitors the need for long-lead item orders. This contractor is more likely to have less-costly handling of unexpected long-lead items, compared to the situation with nothing prepared in advance.

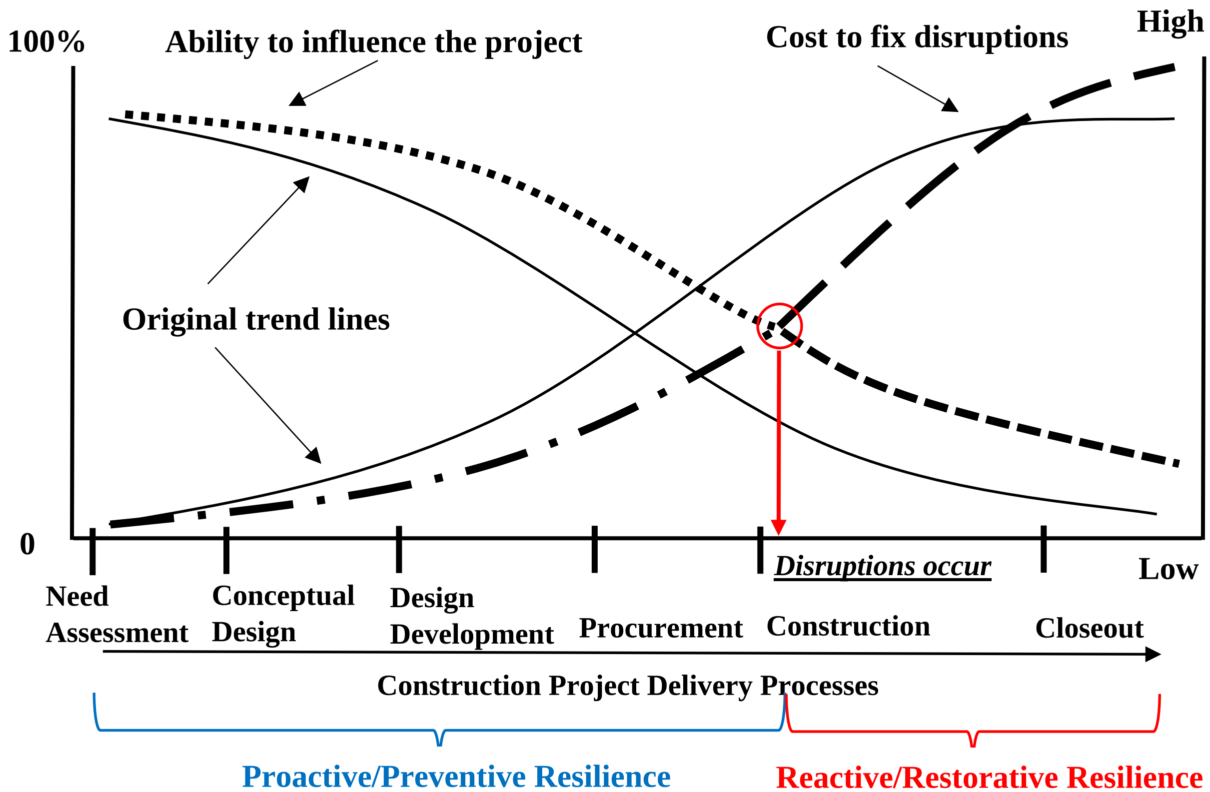

Fig. 2.3 Resilience operates in two modes for project delivery processes

The reactive/restorative resilience takes effect once a disruptive event happens. The remaining part of the influence curve (dash line) continues to hold a large ability to influence. In that case, any remedial actions (e.g., a rapid repair of the losses/damage caused by a power outage) actually make the project more "remediable" to go back to normal. Meanwhile, it is noticeable that the costs to implement changes (long-dash line) go up with a steeper slope than that of the original and end up with higher costs. In part because extra costs (e.g., contingency budget and workforce) are required to make up the losses and recover the affected portion of the project rapidly from the power blackout incident.

2.3.5 Resilience Framework for Project Delivery Processes

In this research, resilience is intended to enhance project performance throughout the disruption-prone project delivery processes. To that end, a conceptual framework (Figure 2.4) was developed in three parts: 1) project delivery processes; 2) dimensions of project performance; 3) two resilience modes along with three performance attributes. The message behind the framework is that the resilient performance of project delivery processes can be achieved in different dimensions by applying two resilience modes with respect to three resilience attributes.

When it comes to resilient performance, three resilience attributes commonly cited in the literature are selected: resistance, recovery, and adaptation. These resilience attributes are tweaked in the context of construction project delivery. The purpose is to make them generic criteria for assessing the resilience performance of individual stages of PDP.

- ***Resistance***: The ability of project delivery phases to withstand a given level of disruption without losing critical project performance.
- ***Recovery***: The ability of project delivery phases to bounce back from disruptions and recover the lost performance rapidly.
- ***Adaptation***: The ability of project delivery phases to extend lessons learned from disruptions and eventually adapt to the disruptions.

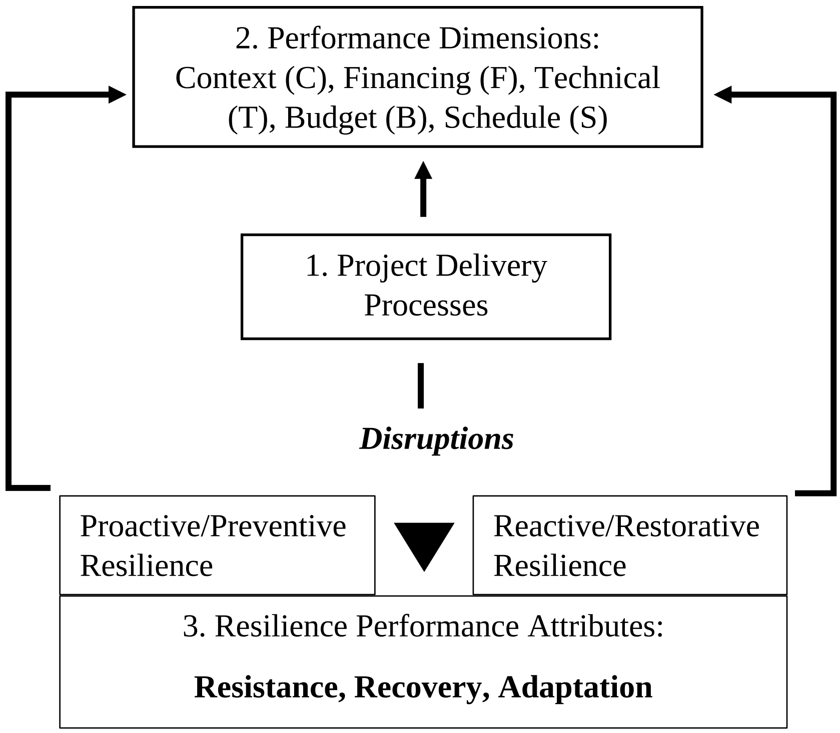

Fig. 2.4 Framework for resilient project delivery processes

The author conceptualizes project delivery resilience further in light of various project needs where the aforementioned resilience attributes can be related to. As shown in Table 2.3, the five interrelated dimensions (5-D) are used. These dimensions were identified in the context of highway project delivery but considered general to represent universal needs of construction project delivery, including context (C), financing (F), technical (T), budget (B), and schedule (S) aspects of a project (Shane et al., 2014).

Table 2.3 "5-D" of disruptions to project delivery (Shane et al., 2014)

Dimension	Description
Context (C)	Involves external influences that affect project development, such as environmental, social issues, resources availability, legal and regulatory requirements, safety/emergency incidents
Financing (F)	Relates to how the project is funded/paid for
Technical (T)	Includes contract, design/engineering requirements, and technology involved
Budget (B)	Involves quantifying the scope of work in dollar format
Schedule (S)	Involves timing aspects of the project

2.4 Conceptual Measurement of Project Delivery Resilience

2.4.1 Conceptual Resilience Assessment Matrix

The three resilience attributes and 5-D project dimensions constitute a structure for the resilience assessment matrix. Table 2.4 shows an illustrative resilience assessment matrix where each matrix element represents conceptual resilience measures for PDP.

Table 2.4 Illustrative resilience assessment matrix

	Resistance	**Recovery**	**Adaptation**
Context (C)	Avoidance of social/environmental code violation	Responsive actions to mitigate environmental/social consequences	Environmental/social justice as a part of project needs assessment and justification
Financing (F)	Reliable funding sources	Multi-phased financing/investment plans	Flexible/alternative financing mechanisms
Technical (T)	Early detection of unexpected technical issues	Collaborative design development	Risk-informed design
Budget (B)	Enhancement of budget accuracy	Budgetary contingency	Risk-informed budget processes
Schedule (S)	Enhancement of schedule accuracy	Schedule contingency	Short-interval scheduling processes

2.4.2 Case Study

It is worth noting that the conceptual resilience measures in Table 2.4 can be further refined to address the variety of project delivery methods and disruptive circumstances. This section only shows an illustrative application of the resilience assessment matrix to two common project delivery methods: Design-Bid-Build (D-B-B) and Design-Build (D-B).

D-B-B is the widely accepted PDM for public work that prioritizes the lowest bidders and owner-controlled planning and design. However, it is considered less resilient than D-B when being evaluated using the general measures in the conceptual resilience matrix. As far as resistance from the technical dimension, it is difficult for architects and engineers to pre-identify possible constructability issues due to inaccurate record drawings or unexpected site conditions. On the contrary, D-B shows its advantage over D-B-B for having early involvement of constructors who can provide critical inputs regarding the constructability issues to withstand the related disturbances during the construction stage of the project. Even though the constructability issue is realized, the D-B project is more recoverable than the D-B-B situation (i.e., recovery stage of resilience). On the one hand, collaborative (constructor-assisted) design, say during design development, allows the design-builder to respond to the equipment issue rapidly since it saves time to react when engineers and constructors work as one entity then the procedures of the reactions can be streamlined. On the other hand, the quality of recovery offered by the design-builder can be higher than that handled by the D-B-B project since the D-B project can have inclusive expertise/inputs from contractors and material vendors. For instance, an alternative equipment option generated from the collaborative value engineering process is a case in point. Similar arguments also apply to the resilience measures from the schedule and budget dimensions when D-B-B is considered less resilient than D-B especially for increasingly complex projects, in terms of enhancing budgetary and schedule accuracy due to lacking inputs from other project stakeholders.

For the context and financing dimensions, the proposed resilience measures are guidelines that cannot easily apply to D-B-B and D-B methods. Some measures (e.g., reliable funding sources and multi-phase project investments) are dependent on specific project

scenarios independent of PDMs. When considering D-B-B as the most common PDM for public work, it becomes apparent that the implementation of the resilience measure is difficult for such public-invested projects. For instance, some resilience measures, such as flexible financing mechanisms for adaptation to unstable funding sources in response to fund shortfalls, are often infeasible for D-B-B projects per the procurement law. Also, D-B-B is less likely to support rapid responses (recovery) particularly to address environmental- and social-related project challenges. Since D-B-B projects lack the clear and specific clarification of responsibility (e.g., matrix of work scope), it is time-consuming for fragmented project teams to respond to the change requests, let alone the speedy recovery actions. At the same time, the author wants to point out that rigid D-B-B does not automatically make its alternative PDMs, such as D-B, the best option. The constraint for D-B as a team approach is that the level of risk exposure could be high for collaborative project teams. During design coordination, for instance, the problem-solving goes back and forth between project parties involved is a case in point. In other words, it could take longer than necessary if some participants cannot perform as expected.

2.5 Discussions and Conclusions

This chapter conceptualizes resilience in the context of infrastructure construction project delivery. Given diverse disruptions to a project, the resilient PDP embraces such disruptions by acting in two modes – proactive/preventive and reactive/restorative in response to pre-, during, and post disruptive events. The resilience modes are characterized by the three attributes – resistance, recovery, and adaptation that describe a desirable status the project is expected to achieve in the presence of disruptions.

To present how the resilient project delivery works, we developed a conceptual framework in three parts. The resilience attributes are linked to the 5-D dimensions – context, financing, technical, budget, and schedule from which most projects can be evaluated. In between there comes the whole project delivery process. The resilience attributes along with the 5-D project dimensions form an assessment matrix that initiates a conceptual measurement for resilient project delivery. As a starting point, conceptual resilience measures were identified in the matrix. Also, a case study was presented showing how the assessment matrix can be applied to compare two common PDMs.

As emerging efforts exploring resilience in construction, most of the findings in this research are drawn from literature and analytical data analysis. The proposed resilience measures are forward-looking for developing standard resilience measures for infrastructure project delivery. More importantly, the matrix and framework together can guide a further look into the resilience assessment with quantitative methods to address specific project challenges.

CHAPTER III

RESILIENCE CRITERIA FOR PROJECT DELIVERY PROCESSES: AN EXPLORATORY ANALYSIS FOR HIGHWAY PROJECT DEVELOPMENT

3.1 Introduction

Integrating resilience into infrastructure project delivery is desirable due to the many risk-related impacts that can occur during project delivery, ranging from a pandemic-caused funding shortfall to periodic flooding due to sea-level rise along the coast. The impacts disrupt planning, design, and construction processes and end up affecting project completion as intended. Current research and policymaking related to resilience mainly focus on how physical structures and facilities behave to absorb impacts and maintain functionality in response to disastrous events (National Academy of Sciences, 2012).

When considering research in project delivery, the literature mainly addresses identifying, categorizing, or comparing risks for different PDMs. Unlike this risk management approach, the resilience approach emphasizes the ability of PDP to resist, recover, and adapt after a risk-related impact occurs, which is essential to critical infrastructure sectors. The U.S. Department of Transportation (USDOT) recently required incorporating resilience into transportation project development as a part of regular practice (USDOT FHWA, 2018). However, making the resilience mindset useful to support project development practices is still at the early stage, especially when it comes to what makes PDP resilient and clarifying the relationships (e.g., complement each other or replace one for another) of resilience and existing risk management.

To shorten this knowledge gap, this chapter of the dissertation explores the key resilience factors for road construction project delivery. The significance of the identified resilience factors was verified via a structured survey questionnaire taken by experts in civil infrastructure project development. The author developed an exploratory structure of resilience criteria and subordinate factors based on the survey data, using Principal Component Analysis (PCA). The findings of this research add to the body of knowledge by proposing a resilience assessment construct to incorporate resilience into highway project development and guide project stakeholders to achieve intended project outcomes, eventually promoting the resiliency of completed infrastructure.

3.2 Background

3.2.1 Risk and Resilience in Highway Project Delivery

Most research on resilience in highway project delivery is risk-centered and relies on subjective and empirical methods such as case studies and survey questionnaires to derive the patterns of risks and frequency of occurrences associated with different project delivery methods (PDMs). For instance, Bypaneni et al. (2018) identified delays in right-of-way (ROW) processes and unexpected utility encounters as the primary risks when selecting appropriate PDMs for highway construction, based on surveys, interviews, and case studies. With subjective data from surveys and interviews, scholars have also identified risk factors using the explanatory factor analysis to examine survey data as a multivariate problem (Bypaneni et al., 2018; Tran and Molenaar, 2014). A main purpose of using the factor analysis was to identify underlying factors from a given list of factor items based on the statistical significance derived from survey data.

Given the PDM-specific risks, the majority of literature about PDM evaluation focuses on the overall project outcome by investigating correlations between certain PDMs and enhanced performance of highway projects (e.g., time and cost saving) via statistical models (Tran and Molenaar, 2014; Tran and Molenaar, 2015; Tran et al., 2017; Antoine et al., 2019). Such risk-based approaches acknowledge a general acceptance that it is unrealistic to avoid all risks. Thus, a resilience approach, which places importance on how project delivery processes perform during and after the risk occurs, is required.

3.2.2 Resilience Management Approach

The resilience of project delivery processes extends conventional risk management from risk events themselves to recovery from the risk-related impact (Han and Bogus, 2020). As shown in Figure 3.1, traditional risk management focuses on potential disruptions in terms of specific risk events, the probability of occurrence, and the potential impact on a system (Kaplan and Garrick, 1981). Resilience management addresses how the system accommodates risk-induced impacts to achieve intended outputs. Researchers across domains have defined the different stages of resilience associated with corresponding system performance over time. The most widely-referred to resilience stages are resistance, recovery, and adaptation, which represent the typical behavior of a system after a disruption, from mitigating the performance drop to restoring the degraded performance, and finally, reaching an equilibrium point, as seen in Figure 3.1(Linkov et al., 2014; Francis and Bekera, 2014; Kamalahmadi and Parast, 2016; Vugrin et al., 2010; Bruneau et al., 2003).

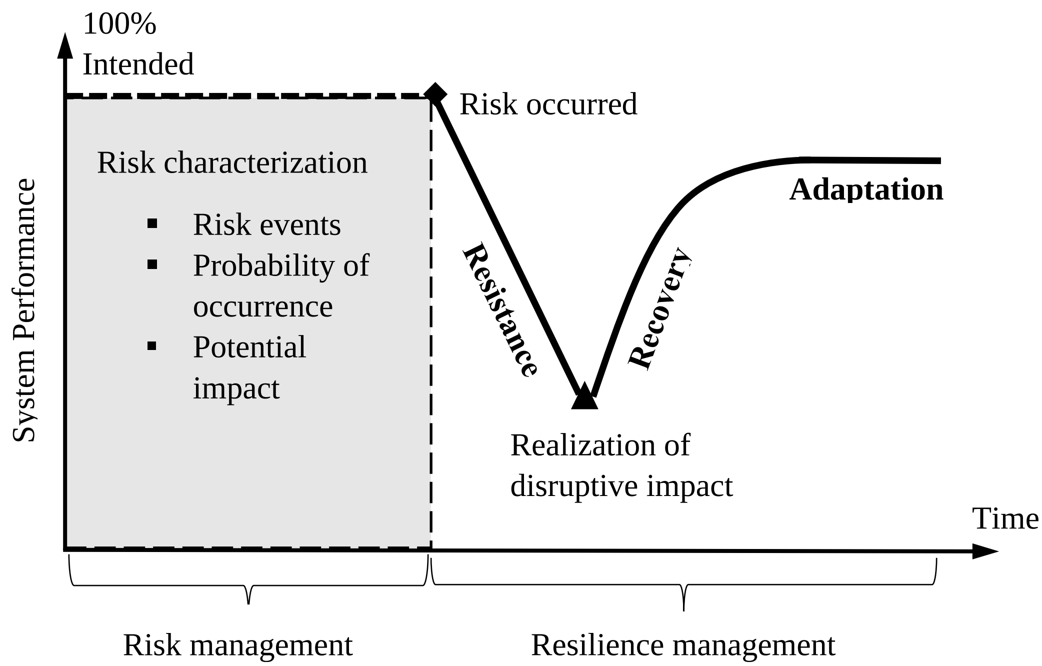

Fig. 3.1 Transition from risk to resilience management (Kaplan and Garrick, 1981; Linkov et al., 2014)

This view of resilience provides a framework where factors affecting resilience can be associated with the different stages of resilience, thus, creating a multi-criteria decision-making (MCDM) situation. There are several resilience assessment tools that have been developed for existing buildings, infrastructure, and communities in response to natural hazards (e.g., earthquake and hurricane disasters), such as the rating programs by the US Resiliency Council and the REDi rating system by the Arup Group. These resilience tools are intended to assess the structural robustness of buildings and facilities in nature. Compared to physical structures, assessing the resilience of the project delivery process requires a different approach. Some scholars promoted resilience-informed guidelines and practices for infrastructure planning and design to maximize utility against climate change and natural hazards (Rodehorst et al., 2018; DeAngelis et al., 2019). However, there is a lack of research into the specific factors that most

affect resilience of the project delivery process which could lead to future assessment tools. In a previous study, the author provided a foundation for assessing project delivery resilience by re-defining the three stages of resilience, including resistance, recovery, and adaptation, to respond to disruptive events over the course of entire project delivery processes (Han and Bogus, 2017). This provides a basis for expanding the work to include evaluation of factors affecting the resilience of the project delivery process.

3.3 Points of Departure

Risk management and risk-centered approaches are dominant in research about project delivery, with the focus on the risk-induced impacts on project performance in terms of time and cost metrics. The concept of integrating resilience into infrastructure project delivery is explored here to supplement the existing risk management approach so that further knowledge can be gathered into how the project delivery process can be modified to better react to risk-induced impacts. Another point of departure relates to the fact that current resilience assessment methods are mainly for infrastructure systems at the operating stage of the life cycle, and their purpose is to help retain functionality against hazard events. This research views the need for resilience assessment to begin at earlier stages of the infrastructure life cycle, such as planning and design as supported in DeAngelis et al. (2019). The anticipated resilience criteria should accommodate various disruptions to project delivery, encompassing shocks (e.g., broken supply chain due to a pandemic outbreak) and slow-moving stresses (e.g., threat of sea-level rise). To fill these knowledge gaps, this research develops a set of resilience criteria for project delivery processes that could eventually be used as part of an assessment

tool. The proposed resilience criteria are specific to highway project delivery processes, but could have broader application with future study.

3.4 Methodology

3.4.1 Project Delivery Resilience Assessment Framework

Figure 3.2 shows the assessment framework for the project delivery resilience. The resilience criteria consist of enabling factors, such as best guidelines, standards, and best practices used in project development, which could contribute to the pre-defined resilience stages (i.e., resistance, recovery, and adaptation). At this stage of research, the author does not pre-assume causal relationships between the identified factors and particular resilience stages. Instead, each identified factor is considered applicable to all three of the resilience stages, but distinct regarding the extent to which the individual factors could contribute to the different resilience stages. For instance, allowing innovative financing methods (e.g., engaging private funds for highway projects as a resilience factor) can resist a possible shortfall of public funds and enable a rapid "recovery" via alternative funding options once the fund shortfall is realized over the design period. In a broad context of project delivery, the successful experience or lessons learned of using innovative financing methods can make future project development more adaptive to similar financial challenges. Similar resilience factors could be other financing alternatives, such as loans and bonds, which can be used to alleviate fund shortfalls. Then such factors collectively represent a common theme (resilience criterion) of promoting alternative funding sources to withstand financial challenges for project development.

The resilience factors and criteria also suggest main aspects of a project, to which various disruptions could be related. For highway project delivery, it often involves five key dimensions (5-D), including context (C), financing (F), technical (T), budget (B), and schedule (S) aspects of a project, aforementioned in Table 2.3 from Chapter 2 (Shane et al., 2014). These five project aspects encompass the origins of both shocks and slowing-moving disruptions to project delivery processes. An example of a disruptive event associated with the context dimension can be public objections to a proposed highway segment in proximity to residential areas. This disruption reflects social justice concerns for highway development and can prompt a resilience measure by engaging the public in general for the project planning justification to tackle and eventually resist the objections.

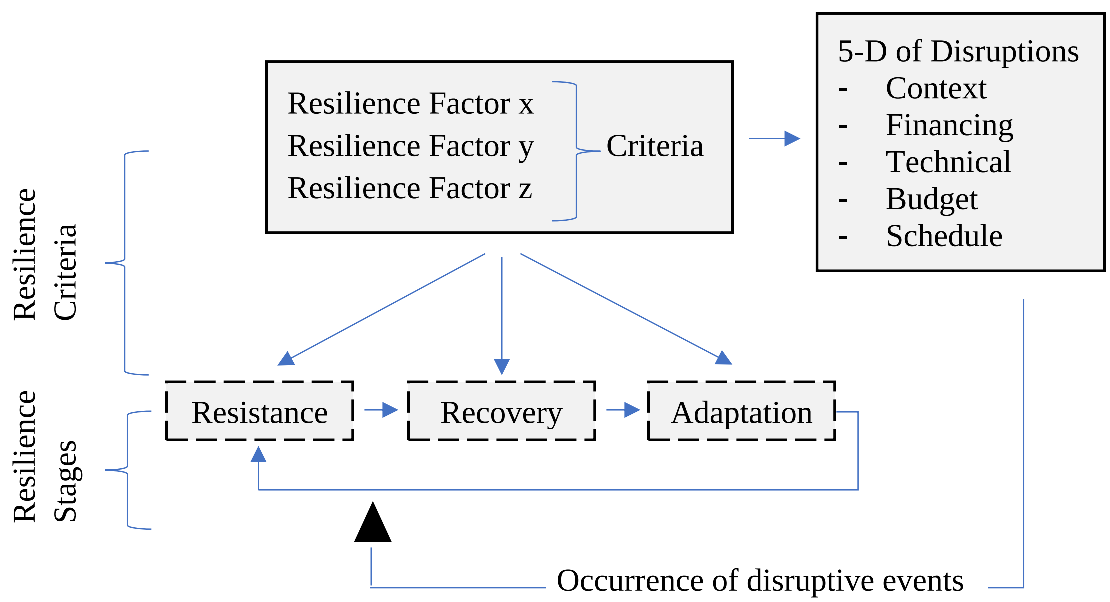

Fig. 3.2 Assessment framework for project delivery resilience

3.4.2 Identification and Validation of Resilience Factors

The author conducted an extensive review of literature regarding construction project delivery, project risk assessment, and infrastructure resilience to identify a list of resilience factors. The main approach used in the development of the resilience factors is the content analysis with the use of coding existing research findings. The coding process was used to transform raw data into a standardized form (e.g., key words with respect to resilience) for processing and analysis. Based on the content analysis, the resilience factors were generalized from the thematic contents of the existing practices, guideline principles, and technologies that can be used to manage various disruptions to the planning, design, and construction stages of a project. Alternatively, some factors are defined as the countermeasure of risks involved in different PDMs. For instance, a clearly defined project scope is considered a resilience factor against project scope risk, one of the most significant risks for D-B projects (Tran and Molenaar, 2014).

To validate the resilience factors' significance, a structured survey questionnaire was designed for experts from industry and academia to provide their opinions about the importance of the given set of resilience factors to the three specified resilience stages. The content of the survey questionnaire can be found in Appendix I. The content validity of the questionnaire was performed by several experts from local planning and transportation agencies to ensure the clarity and rationality of the resilience stages and factors presented in the questionnaire. The selected survey respondents have expertise in dealing with the intricacies of project delivery processes, including staff from the New Mexico DOT, Mid-Region Council of Governments, Associated General Contractors of America (AGC), American Planning Association (APA), and private architect, engineering, and construction

firms. The author also reached out to specific agencies (e.g., DOTs of Colorado, Louisiana, and Florida) who either incorporated resilience into their project managerial programs or were concerned about disaster resiliency for infrastructure development. The survey was conducted online via Qualtrics, which asked the respondents to judge the level of importance (a five-point Likert scale from 1 as "not important" to 5 as "very important") for the list of the identified resilience factors for the different resilience stages. An example question for the "resistance" stage is depicted as "*How important do you think the factor 1 – "public involvement using focus groups" is in contributing to the ability of the transportation project delivery process to withstand a given level of disruption without the loss of critical project performance?*" By the end of the survey, the respondents were asked to suggest any additional resilience factors or comments on the given factors, which will be reported as a part of the survey data analysis.

3.4.3 Resilience Factor Analysis via PCA

The survey data were examined to derive resilience criteria for project delivery by evaluating the underlying dimensions of the resilience factors that cannot be observed directly from the survey data. Given the survey results in the form of discrete and ordinal Likert-point data do not meet the multivariate normality assumption for regular explanatory factor analysis, Principal Component Analysis (PCA) is used (Fabrigar et al., 1999). PCA, a non-parametric and multivariate statistic approach, is widely used for survey data analysis due to its explanatory power of modeling an underlying and simplified construct – principal components (PCs) from a larger set of variables (Field, 2009; Jolliffe, 2011). The underlying constructs (i.e., PCs) existing in subsets of interrelated variables suggest that those variables can be measuring aspects of the same underlying dimensions (Field, 2009). For instance, Zhang (2005, 2006) utilized the PCA approach to reveal underlying indicators for gaining the best

value objectives and concessionaire's financial capability in Public-Private Partnership (P3) project development. Underlying dimensions from subsets of variables can be considered as linear combinations of PCs whose variances (loadings) are as large as possible and have higher explanatory power for their dependent variables (i.e., resilience stages). The objective function of PCA is shown in Equation 3.1, which can be used to identify PCs by calculating eigenvalues (loadings) and eigenvectors associated with the correlation matrix of observed variables. Detailed descriptions of the PCA calculation can be found in the research by Jolliffe (2011) and Hair et al. (2013).

$$RV_j = V_j \lambda_j \tag{3.1}$$

R is the correlation matrix of the observed variables

λ_j is scalar matrix containing eigenvalues

V_j is j-th eigenvector of correlation matrix

Equation 3.2 shows the correlation matrix for a sample of n observations of the variables.

$$R = \frac{1}{n-1} X_s X_s' \tag{3.2}$$

X_s is the matrix of sample correlation coefficients for observed variables

X_s' is the transpose of X_s

In this research, the identified PCs represent a two-tier structure of resilience criteria for project delivery processes. Individual PCs are considered the tier-one resilience criteria and indicate common themes of the given resilience factors regrouped based on the patterns of correlations loaded on the PCs. The subordinate resilience factors act as the tier-two criteria associated with the PCs they belong to. The factor loading represents the variance that can be explained by each PC, and the impact of the given resilience factors could vary when the same list of the factors is evaluated under the three resilience stages. For each attribute, the two-tier resilience criteria refer to the combinations of PCs and their subordinator resilience factors whose level of importance is ranked by the amount of the PC/factor loadings. To that end, IBM SPSS statistics was used to conduct PCA in the following steps.

Extraction – PCs are determined by the eigenvalues of the correlation matrix that represent the relationships between the resilience factors in the context of the three resilience stages. The eigenvalue associated with each PC indicates the amount of variance that PC can explain, and it is logical to retain the PCs with large eigenvalues (i.e., substantive importance) (Field, 2009). For the given set of resilience factors, the dimension reduction is achieved by extracting a relatively small number of components (PCs) with large eigenvalues accounting for most of the variance. And determining the significant eigenvalues often involves a degree of subjectivity and rules-of-thumb, depending on the practical needs of research (Costello and Osborne, 2005).

Rotation – Factor rotation is used to distinguish the extracted PCs by examining to what degree the factors load onto these PCs. In this case, the PCs can be considered a linear combination of given resilience factors that sufficiently account for correlations within the

given factors and indicate how the particular factors contribute to the PCs via factor loadings (Jolliffe, 2011). The factor loadings pattern could be unclear since all the given resilience factors are more or less loaded on each PC. Considering the PCs are classification axes along which factors can be plotted, the rotation technique rotates these PC axes until some factors are loaded maximally to only a single PC while less loaded to the remaining PCs, so a clear pattern of the PC structure is shown. In this research, the orthogonal rotation was performed in SPSS using the Varimax method for the three resilience stages.

Naming Principal Components – Once the PC structure is obtained, the author will assign meaning to each PC. The resilience factors with higher loadings have greater influence on the common themes/names selected to represent the PCs the factors belong to (Hair et al., 2013). For a PC loaded with multiple resilience factors, the subordinating factors with the highest loadings provide a strong clue to name the PC. The criticality of the PCs is determined by the percent of variance explained by each PC.

Lastly, reliability analysis was conducted using SPSS to test the internal consistency of the PC constructs, which means that subordinating factors within a PC subscale should measure the same PC subscale and thus be highly intercorrelated (Hair et al., 2013). Cronbach’s alpha, the common measure of scale reliability, is used. If the value of the Cronbach’s alpha is greater than 0.6 (an empirical threshold), it suggests the tested resilience factors under particular PC scales correlate well with the scales (Field, 2009).

3.5 Results

3.5.1 Resilience Factors for Highway Project Delivery

Table 3.1 lists a total of 17 resilience factors that are identified from the literature review. As holistic resilience measures, the identified factors consist of the best practices involved in major project phases (i.e., planning, financing, design, and construction) and different PDMs for highway projects. The utility of the resilience factors is also generalized by contextualizing each factor in the “5-D” sources of disruptions to project delivery. For instance, public involvement using focus groups to foster consensus (F1) can be used to handle objections during public engagement, which belongs to the context (“C”) dimension of disruptions.

3.5.2 Survey Results

A total of 480 online questionnaires were distributed to the target survey participants. The author collected 107 valid responses, which yields a response rate of 22%. The survey respondents include 38 planners and program managers (36%), 30 engineers (29%), 26 construction professionals such as project managers and field superintendents (25%), and 11 researchers/professors in the related field (10%), with relevant experience of no less than five years in their respective expertise domains.

Table 3.1 Resilience factors for highway project delivery

#	Resilience Factors (Remarks)	5-D of Disruptions					Selection of Literature
		C	F	T	B	S	
F1	Public involvement using focus groups to foster consensus	x					Corral and Monagas (2017); Valdes-Vasquez and Klotz (2012)
F2	Regional (multi-state) scenario planning to address future disruptions (e.g., population growth and climate change)	x			x		Volpe (2011); Humphrey (2008)
F3	Smooth land acquisition (e.g., Right-Of-Way (ROW) acquisition for highway infrastructure)	x	x		x	x	Mostaan and Ashuri (2016)
F4	Land use restrictions in hazardous (inundation) areas (e.g., zoning overlays that restrict permitted land use & density)	x			x		Berke et al. (2015); Olsen (2015)
F5	Innovative financing methods (e.g., toll revenues, fuel taxes, engaging private funds, loan of future funds)		x		x		Liu et al. (2107); Mostaan and Ashuri 2016;
F6	Clearly defined project scope (scoping with timelines for deliverables and accountable team members to avoid project creep)	x			x	x	Tran and Molenaar (2014)
F7	Design factoring in natural hazards & emergency incidents (e.g., roadway elevation, heat-resistant pavement mix)	x			x		Phillips et al. (2017); Rodehorst et al. (2018)
F8	Early detection of regulatory & technical constraints (e.g., permitting, jurisdictional overlap, unexpected utility encounters)	x		x	x	x	Tran and Molenaar (2014)
F9	Performance-based design (e.g., value engineering)	x		x	x	x	Humphrey (2008)
F10	Sensing technology applications for disruption (damage) detection/monitoring	x		x	x	x	Guo et al. (2016)

F11	Virtual design and construction (e.g., GIS and BIM applications)	x		x	x	x	Zou et al. (2016)
F12	Modular design and construction	x		x	x	x	Humphrey (2008); Zhang (2006)
F13	Consistent and accountable decision-making from public agencies	x	x	x	x	x	Mostaan and Ashuri (2016)
F14	Early involvement of contractors/O&M professionals	x		x	x	x	Wondimu et al. (2106)
F15	Project progress audits on budget, schedule, and scope (e.g., forecasting & issue resolution)	x		x	x	x	Grau et al. (2017)
F16	Appropriate contingencies for budget and schedule	x	x	x	x	x	Baccarini and Love (2014)
F17	Well-established claim and emergency response plans and measures (e.g., post-event analysis)	x		x	x	x	Mostaan and Ashuri (2016)

As a rule of thumb, the preferred sample size is to have at least five times as many observations as the number of variables (resilience factors) to be analyzed (Hair et al., 2013). In this research, the survey sample size has an item ratio of 6:1 for the observations vs. variables, which meets the threshold mentioned above. The necessary size of the survey data was further tested using Kaiser-Meyer-Olkin (KMO) and Bartlett's tests, as shown in Table 3.2. The KMO statistic values for all three resilience stages are greater than the threshold value of 0.5 and considered sufficient to generate the compact patterns of correlation coefficients (Kaiser, 1974) to yield distinct principal components (PCs) from the given set of resilience factors. Therefore, the sample size is appropriate for the PCA to proceed. Also, the Bartlett statistic tells if there exist correlations between variables (resilience factors) reflected from the survey data to ensure the survey results can generate clusters of the variables in a subsequent PCA. The Bartlett statistic is considered significant ($p < 0.001$), suggesting that clusters will be found in the PCA.

Table 3.2 KMO and Bartlett's test

		Resistance	**Recovery**	**Adaptation**
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.753	0.698	0.770
Bartlett's Test of Sphericity	Approx. Chi-Square	485.99	472.38	552.81
	df	136	136	136
	Sig.	0.000	0.000	0.000

Within individual resilience stages, the examination of the correlation matrices (Appendix II) shows that no correlation coefficients between the resilience factors exceed 0.9, thus indicating no problems with multicollinearity (i.e., factors that correlate too highly) (Field, 2009). The survey data are further examined to establish the construct of the attribute-related resilience criteria via PCA by decomposing the resilience factors into a smaller number of underlying dimensions (PCs) based on the relative impact of the given variables.

3.5.3 PCA Results

Factor Extraction – As shown in Table 3.3, there were 17 generated components that are associated with the same number of the given resilience factors. To select the number of components to be retained, this research uses a sensible cutoff eigenvalue point – 70% of the cumulative variance, recommended by Jolliffe (2011). Accordingly, seven PCs are retained for all three resilience stages, which cut out at the cumulative percent of the eigenvalues as 70.381%, 70.78%, and 71.246%, respectively. The implications for the extracted PCs are twofold. Each PC correlates substantially with a group of the resilience factors only, but not the factors outside of that group. More importantly, all seven PCs are ranked in descending order of their explanatory power (% of variance explained), as shown in Table 3.3. The higher the eigenvalue of a PC, the more significant that PC is in contributing to the corresponding resilience stages. The next step of the PCA process is to interpret the extracted PCs by identifying the subordinate groups of resilience factors and their practical meanings, and thus, the explanatory constructs of the given factors are established for each resilience stage.

Factor Rotation – Tables 3.4 – 3.6 show the outcomes in the rotated component matrices that indicate which factors make up which PCs, based on the significance of the factor

loadings. To aid the PC interpretation, the author set a loading threshold of 0.4 to determine the significant loadings, as recommended by existing PCA literature (Stevens, 2002; Hair et al., 2013). The factor loadings with an absolute value greater than 0.4 are displayed, whereas loadings smaller than 0.4 are suppressed (blank spaces in Tables 3.4 – 3.6). Thus, clear and distinct patterns of the factor loadings can be observed for different resilience stages. Under the resistance stage, for instance, four resilience factors (F12, F13, F14, and F15) load strongly on PC #1 with loading coefficients of 0.617, 0.741, 0.627, and 0.617. The factor loadings indicate to what extent the factors correlate with the individual PCs. Similarly, the resilience factors that belong to PC #2 are F9, F10, and F11 due to the relatively high loadings of 0.621, 0.709, and 0.675.

It is worth noting that significant factors loadings only serve as the indicators for indicating the PC structures. Knowing the factors and the PCs they belong to is useful to interpret the practical meanings of the PCs by capturing common themes that the subordinate resilience factors suggest. Another implication for the identified PC structures is that the PCs have varying weights in achieving the particular resilience stages. Since the resulting PC structure is explanatory in nature, the weighting scheme is nominal in terms of the eigenvalues and factor loadings associated with the PCs and subordinating resilience factors. Given the extracted PCs (#1 – #7) are displayed in a descending order per the eigenvalues (Table 3.3), PC #1 is considered more significant than PC #2 because the eigenvalue (% of variance) for PC #1 is greater than that of PC #2. At the factor level, the same resilience factors could weigh differently when being loaded onto different PC themes under different resilience stages.

Table 3.3 Total variance explained

Comp-onent	***Resistance***			***Recovery***			***Adaptation***		
	Eigenvalue	% of Variance	Cumulative %	Eigenvalue	% of Variance	Cumulative %	Eigenvalue	% of Variance	Cumulative %
1	4.520	26.588	26.588	3.904	22.967	22.967	4.897	28.808	28.808
2	1.809	10.641	37.229	2.297	13.515	36.482	1.774	10.436	39.243
3	1.598	9.400	46.629	1.643	9.666	46.148	1.471	8.652	47.896
4	1.208	7.104	53.734	1.286	7.565	53.713	1.202	7.072	54.967
5	1.059	6.231	59.965	1.125	6.616	60.329	1.037	6.101	61.068
6	0.905	5.325	65.290	0.924	5.435	65.764	0.887	5.216	66.284
7	0.866	5.091	**70.381**	0.853	5.016	**70.780**	0.844	4.962	**71.246**
8	0.763	4.491	74.872	0.726	4.268	75.048	0.798	4.692	75.938
9	0.736	4.328	79.200	0.702	4.130	79.178	0.792	4.661	80.600
10	0.627	3.687	82.888	0.677	3.985	83.163	0.613	3.606	84.206
11	0.594	3.495	86.382	0.592	3.484	86.647	0.591	3.475	87.680
12	0.495	2.910	89.292	0.550	3.234	89.881	0.473	2.784	90.464
13	0.478	2.810	92.103	0.445	2.615	92.496	0.425	2.500	92.964
14	0.431	2.535	94.638	0.398	2.340	94.835	0.382	2.246	95.210
15	0.355	2.087	96.725	0.328	1.931	96.766	0.322	1.896	97.107

16	0.312	1.834	98.559	0.286	1.680	98.446	0.303	1.783	98.889
17	0.245	1.441	100.000	0.264	1.554	100.000	0.189	1.111	100.000

Table 3.4 Rotated component matrix – resistance

Resilience Factor	Principal Component						
	1	2	3	4	5	6	7
F1							0.876
F2					0.863		
F3						0.664	
F4				0.813			
F5						0.839	
F6				0.702			
F7			0.533				
F8				0.466			
F9		0.621					
F10		0.709					
F11		0.675					
F12	0.617						
F13	0.741						
F14	0.627						
F15	0.617		0.514				
F16			0.754				
F17			0.630				

Table 3.5 Rotated component matrix – recovery

Resilience Factor	Principal Component						
	1	2	3	4	5	6	7
F1				0.850			
F2				0.659			
F3						0.847	
F4						0.818	

F5				0.624			
F6							0.853
F7	0.679						
F8		0.795					
F9		0.694					
F10		0.665					
F11			0.762				
F12			0.853				
F13							0.546
F14					0.686		
F15					0.765		
F16	0.727						
F17	0.875						

Table 3.6 Rotated component matrix – adaptation

Resilience Factor	**Principal Component**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
F1							0.825
F2			0.625				
F3					0.860		
F4					0.704		
F5			0.793				
F6				0.762			
F7				0.497			
F8				0.647			
F9	0.795						
F10	0.720						
F11	0.868						
F12	0.591						

F13					0.825	
F14						0.518
F15	0.795					
F16	0.578					
F17	0.691					

Naming Principal Components – To aid the interpretation of the PCs, the resilience factors are re-grouped into the resilience stage-specific PCs, as shown in Tables 3.7 – 3.9. Under each resilience stage, resilience criteria consist of PCs (tier-one criteria), subordinating resilience factors (tier-two criteria), and the 5-D of disruptions which suggest the contexts the corresponding criteria could apply to. As a part of the results for this research, the resilience criteria will be discussed in the following sections to provide the explanatory meanings of the PCs, including both statistical and empirical implications obtained from the survey results and literature.

Reliability of PCA Construct – The results in Table 3.10 show that alpha values for all the PC scales with more than one subordinate resilience factor are greater than 0.6, an empirical threshold, indicating the acceptable and good internal consistency reliability (Field, 2009).

Table 3.7 Resilience criteria – resistance

PC	Resilience Criteria (% of variance)	Resilience Factors (loading)	5-D of Disruptions				
			C	**F**	**T**	**B**	**S**
#1	*Continuity of Project Alignment* (26.588)	F13 - Consistent and accountable decision-making from public agencies (0.741)	x	x	x	x	x
		F14 - Early involvement of contractors/O&M professionals (0.627)	x		x	x	x
		F15 - Project progress audits on budget, schedule, and scope (0.617)	x		x	x	x
		F12 - Modular design and construction (0.617)	x		x	x	x
#2	*Adaptive Design and Automatic Issue Identification* (10.641)	F10 - Sensing technology applications for disruption detection/monitoring (0.709)	x		x	x	x
		F11 - Virtual design and construction (0.675)	x		x	x	x
		F9 - Performance-based design (0.621)	x		x	x	x
		F7 - Design factoring in natural hazards & emergency incidents (0.511)	x			x	
#3	*Contingency Measures* (9.4)	F16 - Appropriate contingencies for budget and schedule (0.754)	x	x	x	x	x
		F17 - Well-established claim and emergency response plans and measures (0.63)	x		x	x	x
#4	*Constraint & Scope Management* (7.104)	F4 - Land use restrictions in hazardous areas (0.813)	x			x	
		F6 - Clearly-defined project scope (0.702)	x			x	x
		F8 - Early detection of regulatory & technical constraints (0.466)	x		x	x	x
#5	*Scenario Planning (6.231)*	F2 - Regional scenario planning to address future disruptions (0.863)	x			x	

#6	*Early Land Acquisition and Innovative Financing* (5.325)	F5 - Innovative financing methods (0.839)		x		x	
		F3 - Early completion of land acquisition (0.664)	x	x		x	x
#7	*Consensus-Driven Project Justification* (5.091)	F1 - Public involvement using focus groups to foster consensus (0.876)	x				

Table 3.8 Resilience criteria – recovery

PC	**Resilience Criteria (% of variance)**	**Resilience Factors (loading)**	**5-D of Disruptions**				
			C	**F**	**T**	**B**	**S**
#1	*Contingency-Oriented Planning and Design* (22.967)	F17 - Well-established claim and emergency response plans and measures (0.875)	x		x	x	x
		F16 - Appropriate contingencies for budget and schedule (0.727)	x	x	x	x	x
		F7 - Design factoring in natural hazards & emergency incidents (0.679)	x			x	
#2	*Issue Detection and Adaptive Design* (13.515)	F8 - Early detection of regulatory & technical constraints (0.795)	x		x	x	x
		F9 - Performance-based design (0.694)	x		x	x	x
		F10 - Sensing technology applications for disruption detection/monitoring (0.665)	x		x	x	x
#3	*Industrialized Project Delivery* (9.666)	F12 - Modular design and construction (0.853)	x		x	x	x
		F11 - Virtual design and construction (0.762)	x		x	x	x
#4		F1 - Public involvement using focus groups to foster consensus (0.85)	x				

	Project Justification and Innovative Financing (7.565)	F2 - Regional (multi-state) scenario planning to address future disruptions (0.659)	x			x	
		F5 - Innovative financing methods (0.624)		x		x	
#5	*Project Tracking and Team Collaboration* (6.616)	F15 - Project progress audits on budget, schedule, and scope (0.765)	x		x	x	x
		F14 - Early involvement of contractors/O&M professionals (0.686)	x		x	x	x
#6	*Early Land Acquisition and Land-Use Restriction* (5.435)	F3 - Early completion of land acquisition (0.847)	x	x		x	x
		F4 - Land use restrictions in hazardous areas (0.818)	x			x	
#7	*Clear Project Scoping and Owners' Accountability* (5.016)	F6 - Clearly-defined project scope (0.853)	x			x	x
		F13 - Consistent and accountable decision-making from public agencies (0.546)	x	x	x	x	x

Table 3.9 Resilience criteria – adaptation

PC	**Resilience Criteria (% of variance)**	**Resilience Factors (loading)**	**5-D of Disruptions**				
			C	**F**	**T**	**B**	**S**
#1	*Performance-Informed and Industrialized Project Delivery* (28.808)	F11 - Virtual design and construction (0.868)	x		x	x	x
		F9 - Performance-based design (0.795)	x		x	x	x
		F10 - Sensing technology applications for disruption detection/monitoring (0.72)	x		x	x	x

		F12 - Modular design and construction (0.591)	x		x	x	x
#2	*Project Tracking and Contingency Management* (10.436)	F15 - Project progress audits on budget, schedule, and scope (0.795)	x		x	x	x
		F17 - Well-established claim and emergency response plans and measures (0.691)	x		x	x	x
		F16 - Appropriate contingencies for budget and schedule (0.578)	x	x	x	x	x
#3	*Scenario Planning and Innovative Financing* (8.652)	F5 - Innovative financing methods (0.793)		x		x	
		F2 - Regional scenario planning to address future disruptions (0.625)	x			x	
#4	*Adaptive Planning/Design and Clear Project Scoping* (7.072)	F6 - Clearly-defined project scope (0.762)	x			x	x
		F8 - Early detection of regulatory & technical constraints (0.647)	x		x	x	x
		F7 - Design factoring in natural hazards & emergency incidents (0.497)	x			x	
#5	*Early Land Acquisition and Land-Use Restriction* (6.101)	F3 - Early completion of land acquisition (0.86)	x	x		x	x
		F4 - Land use restrictions in hazardous areas (0.704)	x			x	
#6	*Owners' Accountability* (5.216)	F13 - Consistent and accountable decision-making from public agencies (0.825)	x	x	x	x	x
#7	*Early and Harmonious Involvement of Project Stakeholders* (4.962)	F1 - Public involvement using focus groups to foster consensus (0.825)	x				
		F14 - Early involvement of contractors/O&M professionals (0.518)	x		x	x	x

Table 3.10 Reliability analysis

Resistance		Recovery		Adaptation	
PC #	**Cronbach's alpha**	**PC #**	**Cronbach's alpha**	**PC #**	**Cronbach's alpha**
1	0.710	1	0.710	1	0.808
2	0.744	2	0.790	2	0.717
3	0.607	3	0.705	3	0.696
4	0.667	4	0.670	4	0.624
--	--	5	0.684	5	0.685
6	0.641	6	0.712	--	--
--	--	7	0.666	7	0.605

3.5.4 Project Delivery Resilience Criteria

3.5.4.1 Resistance Stage

The most critical PC for the resistance stage is *Continuity of Project Alignment* (PC #1), which accounts for 26.6% of the variance. This component involves four resilience factors (factors loadings), including F13 - consistent and accountable decision-making from public agencies (0.741), F14 - early involvement of contractors/O&M professionals (0.627), F15 - project progress audits on budget, schedule, and scope (0.617), F12 - modular design and construction (0.617). Resisting disruptions to project delivery requires project alignment at organizational and technical levels. Alternative PDMs (e.g., Integrated Project Delivery) are characterized as practicing project alignment, including gaining considerable buy-in from project owners (Mostaan and Ashuri, 2016) and having all project parties "play in the same ballpark" from day one to better anticipate and prepare for the known and unknown risks (Villachica et al., 2004). Such project team collaboration, per the survey comments from several project managers, takes not only early involvement but also continuous

communication/coordination (e.g., regular project audits) between all stakeholders through the duration of disruptions. Also, modular design/construction applications provide project alignment at the technical level as the variation of project parameters can be greatly reduced.

Adaptive Design and Automatic Issue Identification (PC #2) is considered essential to withstand chronic stressors (e.g., climate change) and shocks during the design and construction stages of projects. Per a recent FHWA guideline, integrating climate and disaster vulnerability into the preliminary design before environmental studies becomes necessary to promote disaster-informed design practices in highway project sectors (Rodehorst et al., 2018). During project execution, latent signs of disruptive events can be better captured by modeling and sensing processes and technologies (e.g., using motion sensors to detect and respond to safety near misses on job sites) for data-driven decision-making across project parties. PC #3 – *Contingency Measures for Known and Unknown Risks*, PC #4 – *Constraint & Scope Management*, and PC #5 – *Regional Scenario Planning* collectively emphasize the importance of early detection of potential risks, via appropriate contingencies, well-defined scoping, and strategic-level scenario planning, to mitigate the worst-case impact once the anticipated risks are realized. Then, the remaining PC #6 – *Early Land Acquisition and Innovative Financing* and PC #7 – *Consensus-Driven Project Justification* allow projects at the planning stage to prepare and resist challenges from land acquisition, financing, and public involvement.

3.5.4.2 Recovery Stage

Contingency-Oriented Planning and Design (PC #1) is the most significant (22.967% of variance) based on three subordinating resilience factors, including F17 - well-established claim and emergency response plans and measures (0.875), F16 - appropriate contingencies

for budget and schedule (0.727), and F7 - design factoring in natural hazards & emergency incidents (0.679). Contingency measures featured in PC #1 provide the most direct aid to impacted projects for recovery from disturbances, which is dependent on the resource readiness (e.g., a reserve of funds above budget to restore projects from budget shortfall) and organizational plans and processes (e.g., emergency planning) required to respond to disruptive events (Marcelo et al., 2018). In addition to budget- and timing-related buffers, contingencies should be factored as a part of project teams qualifications during the procurement phase as the contractor, vendor, and design firm selection should favor firms with some excess capacity, as mentioned by several survey respondents from DOTs. For the threats with low likelihood yet disastrous consequences, contingency-informed design (e.g., roadway elevation in flood-prone areas) eases the recovery of road functionality in the aftermath of the disasters for maintaining road infrastructure in a sustainable manner, even if such design exceeds the regular code requirements and causes budget growth.

Issue Detection and Adaptive Design (PC #2) and *Industrialized Project Delivery* (PC #3) are ranked as the second and third significant measures for recovery. Detecting regulatory and technical constraints via advanced technologies allows fast response to latent risks through different project phases. Performance-based design (value engineering alternatives) becomes standard practice for complex highway projects which need to absorb budget overruns or create budget reserves for missed and changed items, while the intended design functionality can be retained. Industrialized project delivery that is characterized by virtual/modular design and construction eases the restoration of degraded projects due to consistent and integrated response to disruptions (e.g., clashes detected during design development and change orders performed in the industrialized work environment). *Project Justification and Innovative*

Financing (PC #4) and *Early Land Acquisition and Land-Use Restriction* (PC #6) contribute to the recovery attribute for expediting projects' preparation and action on related disruptions (e.g., community objection to project justification and unknown utility encounters during ROW acquisition) which, if delayed, could substantially slow the pace of the projects. *Project Tracking and Team Collaboration* (PC #5) and *Clear Project Scoping and Owners' Accountability* (PC #7) belong to organizational practices that are useful through project delivery processes to restore the degraded project outcome to its intended level, which results from a fast response to problems and synchronized resource allocation for issue resolution.

3.5.4.3 Adaptation Stage

Performance-Informed and Industrialized Project Delivery (PC #1) is the most significant criterion (28.808% of variance) to achieve adaptive project delivery to disruptions. This theme captures the four high-loading resilience factors, including F11 - virtual design and construction (0.868), F9 - performance-based design (0.795), F10 - sensing technology applications for disruption detection/monitoring (0.72), F12 - modular design and construction (0.591). In addition to reviewing present and historical records of threats, adaptable approaches like disaster-informed planning/design accommodate future conditions, which can be supported by advanced sensing and modeling technologies for a data-driven description of project scenarios. At the execution level, modular design/construction promotes adaptable project delivery as it reduces the inherent uncertainty of projects by adopting standard project parameters and allows customization to suit alternating project needs. Assessing the evolving nature of projects requires constant *Project Tracking and Contingency Management* (PC #2) against risks that are anticipated but difficult to measure. Adaptive responses to such risks result if the contingencies can be developed by tracking the historical distribution rather than

pure empirical estimates (Baccarini and Love, 2014). For the after-disruption remedy, the adaptive project capacity can be fulfilled from emergency measures (e.g., shifting partial work resources to remote platforms reacting to the COVID-19 pandemic) for keeping the project moving in adversity.

Scenario Planning and Innovative Financing (PC #3) represents adaptation strategies well-recognized by transportation agencies for long term project planning and financing. Given risk mitigation to infrastructure projects could occur in isolation from local planners and project practitioners (DeAngelis et al., 2019), scenario planning that anticipates and copes with changes at regional levels not only accommodates risks for individual infrastructure assets but also acknowledges how surrounding infrastructure may also be at risk to the same stressors (Rodehorst et al., 2018). Even though adapting highway infrastructure through the means of elevation, hardening, and relocation can add to upfront costs, it is also likely to pay dividends from alternative funding mechanisms (e.g., revenue-based and private funds). P3 highway projects often adopt such alternative financing methods that make the projects adaptable to funding shortfalls via shared financial risks among investors (Liu et al., 2017). *Early Land Acquisition and Land-Use Restriction* (PC #5) and *Owners' Accountability* (PC #6) are particularly vital for highway projects to handle time- and budget-consuming ROW permit, utility coordination, and relevant perturbations via private sectors' expertise as well as owners' commitment to project success (Mostaan and Ashuri, 2016). PC #4 – *Adaptive Planning/Design and Clear Project Scoping* and PC #7 – *Early and Harmonious Involvement of Project Stakeholders* contributes to adaptive project delivery by coherent anticipate, recognize, and adjust to stressors and shocks by reconfiguration of existing resources, such as redesign or plans to minimize consequences of perturbations (Park et al., 2013).

3.6 Discussion

The performance of project delivery processes is often addressed through technical (design) and regulatory (contractual) codes and principles without explicit consideration of resilience in response to disruptions. This research fills this knowledge gap by identifying key resilience criteria that can be used to inform what can be done to allow different phases of a highway project to resist, recover from, and adapt to disruptive events over the course of the project delivery. Resilience assessment for project delivery is still in the early stages of development, and generalizable resilience measures are lacking. This research provides insight into how resilience can be measured, where the proposed resilience criteria are explanatory in nature based on the survey and PCA results. Some sense-making and meaningful patterns can be observed from the PCA results. For instance, the resilience factors, including *well-established claim and emergency response plans and measures* (F17), *appropriate contingencies for budget and schedule* (F16), are the most important measures from the recovery perspective. Moreover, several resilience factors, such as *virtual design and construction* (F11) and *sensing technology applications for disruption detection/monitoring* (F10), are considered critical across all three stages of resilience.

The findings from this research provide infrastructure owners and practitioners with new knowledge that can be used to integrate resilience into project development, and eventually, to be able to assess the resilience of different PDMs. Specifically, the resilience criteria framework provides insight into how resilience management can be related to and measured in parallel with conventional risk assessment, a common obstacle to incorporating

resilience into public agencies' (e.g., DOTs) existing programs (Flannery et al., 2018). The proposed resilience measures focus on retaining project performance over risk characterization in terms of how affected project phases bounce back and adapt to the risk scenarios. Moreover, the proposed resilience criteria provide a baseline that can be developed for standard resilience practices. For instance, *Contingency-Oriented Planning and Design* (the most critical criterion for recovery) can trigger specific measures above and beyond allocating time/cost buffers, by establishing procedures to evaluate the speed and degree of the recovery brought by the contingency measures.

3.7 Conclusions

Based on existing resources and practices applicable for highway projects, the author identified seventeen resilience factors that could lead to the designated resilience stages of resistance, recovery, and adaptation, then had the factors verified by project delivery experts via a structured survey. Seven resilience criteria were then identified for using the PCA approach for each of the three stages of resilience. The most critical resilience criteria (and the associated stage) are *continuity of project alignment* (resistance), *contingency-oriented planning and design* (recovery), and *performance-informed and industrialized project delivery* (adaptation). The findings from this research provide the foundation for resilience assessment during infrastructure project delivery. The proposed resilience criteria provide a tool for practitioners to communicate resilience during decision-making and ultimately enhance a project's ability to accommodate risk-related impacts, and continue producing intended project results.

Owing to the explanatory nature of the proposed resilience criteria, the author realized several limitations of this study, which introduce relevant directions for future research. The PCA results can be sensitive to changes in survey sample size, survey respondents, and their level of expertise. More extensive surveys are needed to establish knowledge about resilience in project development beyond highway projects. Also, the identified resilience factors are general and could be refined and expanded when the project contexts (e.g., type and size) change or the need is to address specific PDMs and disruptions. To make resilience assessment applicable for practitioners, there exists a need to determine the performance metrics associated with different resilience factors as well as developing quantitative weights for the resilience criteria via confirmative factor analysis.

CHAPTER IV

CONSTRUCTING A COMPOSITE RESILIENCE INDEX FOR HIGHWAY PROJECT DELIVERY

4.1 Introduction

Based on the constructs of seventeen resilience factors in the previous chapter, this chapter of the dissertation develops the Project Delivery Resilience Index (PDRI) in the context of road construction projects. The PDRI represents a relative scale that focuses on projects' response to disruptions (i.e., realized risks) instead of risk characterization advocated by traditional risk analysis. The author developed the PDRI by restructuring the given set of resilience factors separately for three resilience stages of project delivery processes, including resistance, recovery, and adaptation. For each resilience stage, the weights of the resilience factors were determined using the Factor Analysis + Analytical Network Process (F'ANP) approach. Lastly, an illustrative application of the PDRI was presented to compare Design-Bid-Build (D-B-B), Design-Build (D-B), and Construction Manager/General Contractor (CM/GC) that are commonly used for road construction project delivery.

The findings of this chapter add to the body of knowledge by proposing an assessment tool for project delivery resilience. The abstract theories of resilience can be conceptualized by the resilience factors in terms of best practices practitioners have utilized or pursued in their projects. Moreover, the PDRI provides a quantitative resilience metric to integrate various resilience criteria and simplify the resilience determination, facilitating project stakeholders to incorporate resilience measures into road infrastructure project development.

4.2 Background

4.2.1 Resilience of Highway Project Delivery

When considering the literature about highway project delivery, scholars focused on identifying risks associated with different PDMs for enhanced project outcomes in time and money metrics (Tran et al., 2017; Antoine et al., 2019). Such risk-centered approaches acknowledge a general acceptance that it is virtually unrealistic to avoid all the risks, thus causing gaps between intended and actual project outcomes. Integrating resilience into Infrastructure projects has been addressed from the early stages of the project development, such as resilience-informed planning and design principles against the long-term risks (e.g., climate change and natural hazards) to maximize the utility (Rodehorst et al., 2018; DeAngelis et al., 2019).

For entire project delivery processes, the author defined resilience as the ability of the project phase-based system to respond to disruptions to retain intended project results (Han and Bogus, 2017). As illustrated in Figure 3.1 in Chapter 3, this system ability is commonly conceptualized as three resilience stages, including resistance, recovery, and adaptation, from mitigating the performance drop to restoring the degraded performance toward the intended state until reaching an equilibrium point. These resilience stages indicate a process that features risk-induced variations of the system functionality. Analytical measures based on these resilience stages (e.g., resistance and recovery) became widely accepted metrics for disaster resilience assessment in the context of civil infrastructure systems (Ayyub, 2015; Ayyub, 2014).

4.2.2 Multi-Criteria Decision for Resilience Assessment

Resilience assessment can be considered as a multi-criteria decision-making (MCDM) problem where the different resilience stages and contextually related measures of system performance are taken into account. A practical concern of utilizing resilience measures is to determine the priority of those measures in contributing to particular resilience attributes. In the context of disaster resilience assessment, for instance, stakeholders expedite the decision about which resilience measures are more urgent than the other for recovery (e.g., temporary shelter availability vs. property insurance coverage). The common MCDM approaches are Analytic Hierarchical Process (AHP) and Analytical Network Process (ANP) which use the pairwise comparisons among decision criteria to derive relative importance scales of the decision criteria with respect to the goal (Saaty, 1996). A decision problem can be designed in a unidirectional hierarchical form (AHP) between decision criteria or a network form (ANP) when there exist interrelationships among the criteria at different decision levels. With the interrelationships, decision criteria at one level influence or are influenced by criteria at another level (Saaty, 2004; Saaty and Vargas, 2013). AHP and ANP are widely used to assign weighting for multi-criteria decision problems, such as identifying critical flood mitigation practices for wastewater treatment plants (Karamouz et al., 2019), evaluating critical defective conditions of subway stations and tunnels (Gkountis and Zayed, 2015), and impacting factors for bridge resilience (Patel et al., 2020).

The resilience assessment is still in the early stage of development in the AEC industry. Several rating programs were developed for existing buildings, infrastructure, and communities in response to natural hazards (e.g., earthquake and hurricane) (US Resiliency Council, 2015; Almufti and Willford, 2014; Cutter et al., 2010). These tools mainly address

the building and facilities' structural robustness and serve as a checklist that practitioners can refer to when examining an existing built environment against potential seismic hazards. Since the resilience criteria stem from contextually related measures of the system performance, qualitative research is the main means to identify resilience decision criteria from literature and practice. Subsequently, verifying the significance of the criteria requires empirical inputs from practitioners and experts via surveys and case studies. The results can be further explored to obtain priorities for the resilience criteria, using explanatory factor analysis methods like Principal Component Analysis (PCA). Osei-Kyei et al. (2017) developed fifteen critical success criteria for Public-Private Partnership (PPP) projects in Ghana, such as profitability, adherence to time/budget, long-term partnership, and effective technology transfer and innovation. As the extended application, the success criteria were used to construct project success index using the Fuzzy Synthetic Evaluation (FSE) technique (Osei-Kyei and Chan, 2017). Cimellaro et al. (2018) developed resilience indicators derived from the given eight variables for healthcare facilities using PCA. The weights associated with the three indicators and subordinate variables were derived from the factor scores from PCA. The resilience rating for each variable was rated as either 0 or 1, representing either inapplicable or applicable.

4.2.3 Indexing for Multi-Criteria Decision-Making

Indexing is a useful and simple approach to aggregate decision criteria that are qualitative or a mix of qualitative and quantitative variables. Pyke et al. (2012) developed a climate sensitivity index to rate new building construction with weighted scores of the predefined LEED credit items rated on an equal-interval scale. Jang et al. (2018) developed the sustainable performance index (SPI) for assessing and selecting green technologies used in urban infrastructure. Fuzzy AHP was used to determine the weights of the indicators based on

the survey outcome. The key to such indexing methods is about how the weighing is determined for the decision variables. The common weighing methods can be specific to different research contexts from empirical judgments to more data-driven methods such as correlation coefficients (Nasir et al., 2016), z-score (El Asmar et al., 2016), and Fuzzy Synthetic Evaluation (FSE) technique (Ameyaw et al., 2015).

4.2.4 Resilience Index

Making resilience useful for decision-making is driven by the desire to standardize criteria and generate measurable results. The resilience index is a trendy approach to operationalize resilience in practice, originally driven by the desire to compartmentalize different steps of risk management processes (Orencio and Fujii, 2013). This indexing method is especially suitable for complex systems such as civil infrastructure and community systems whose performance measures are multidimensional and less quantifiable. The disaster resilience index, such as Baseline Resilience Indicators for Communities, was created based on resilience criteria associated with extensive performance aspects (Cutter et al., 2010; Cutter, 2016; Orencio and Fujii, 2013). Summation and multiplication are two commonly applied methods to aggregate the criteria at different scales of measurement (Bepetista, 2014). The major steps of index construction and validation encompass (1) Developing a theoretical framework for indicator development. (2) Identifying indicators. (3) Data reduction and factors retention (latent dimensions). (4) Weighting and aggregation. (5) Index validation (Cutter et al., 2014; Mayunga, 2009; Verrucci et al., 2012; Zebardast, 2013).

The core of constructing a composite index is the individual indicator's weighting. There are two types of methods to weigh and aggregate decision indicators in the process of composite index development (Cutter et al., 2014; Tate, 2013).

- Equal weighting is applied when researchers do not have sufficient knowledge about the interactions among the different indicators.
- Unequal or differential weighting is utilized when there is considerable understanding about the relative importance of the indicators.

For differential weighing, the weighting assignment can be performed using data-driven and normative methods (Decancq and Lugo, 2013). Data-driven approaches apply statistical methods for multivariable data analysis. Normative methods involve subjective decisions from experts' judgment via surveys and interviews. The qualitative output data can be processed by the MCDM approaches, such as AHP and ANP. The individual resilience indicators can be both quantitative and qualitative. For the qualitative indicators, such as best practices and guidelines, a common means to inspect the effect of the best practices and guidelines is using qualitative descriptions, such as a linguistic scale of effectiveness (i.e., excellent, good, fair, and poor) (Gkountis and Zayed, 2015), or the degree of to what extent each criterion has been achieved (Osei-Kyei and Chan, 2017).

4.3 Points of Departure

Given the multifaceted outlook of resilience, a list of resilience criteria and subordinate factors alone does not easily support the adoption of those criteria for resilience assessment. In essence, the resilience criteria are qualitative based on theoretical and empirical justification

from past literature and practices. The applications of the qualitative criteria are often limited to guidelines that can bring positive effects on resilience or a checklist with which users can go through and see if the criteria are met for a specific project. Even if qualitative approaches are widely accepted, a drawback of the qualitative approaches is the difficulty of providing straightforward and comparable results for the different criteria. There is a need to determine a quantitative demonstration of the resilience criteria. Thus, comparable ratings can be obtained when comparing different projects and PDM scenarios using the same criteria.

The objective of this research is to develop a composite resilience index based on the resilience criteria in the context of highway project delivery processes. Constructing Composite Indices is considered an effective way to assess resilience because "the indices aggregate multiple indicators to provide a synthetic measure of complex, multidimensional, and meaningful phenomena" (Bepetista, 2014). The composite index is considered a powerful approach to depict the results of an analytical construct for multidimensional systems (i.e., the phase-based system of project delivery processes). A well-designed index can also provide summary statistics that communicate the system status and trends to a variety of relevant users (Balica et al., 2012; Zhou and Ang, 2009). Another consideration for using the composite index is its understandability when results are presented as scores that project stakeholders can easily comprehend. The author also wanted to point out that the composite index should be adjusted and refined to accommodate new variables and data specific to different project and PDM scenarios.

4.4 Methodology

4.4.1 Resilience Criteria Structuring

A hybrid approach that combines the normative factor analysis (FA) and data-driven ANP (F'ANP) is used to develop the resilience index for highway project delivery. The F'ANP approach was introduced by Zebardast (2013) to measure the social vulnerability of urban systems to earthquake hazards. The F'ANP approach involves two major steps. First, the structure of the resilience index is established in terms of decision criteria for project delivery resilience in two levels: the given set of resilience factors and the underlying dimensions of the resilience factors (criteria). Subsequently, the resilience index structure is applied to an ANP model to derive the relative importance of the resilience criteria and sub-criteria. In this research, the resilience factors (sub-criteria) are interrelated with respect to the control resilience criteria. The interdependencies among the resilience factors suggest that one resilience factor is influenced by other resilience factors within the same clusters of resilience criteria.

When identifying the relative importance of the resilience criteria/sub-criteria, ANP is chosen to construct the resilience index because the ANP model allows interdependent relationships between the decision elements and constitutes a network of the criteria and sub-criteria. Specifically, the resilience constructs extracted from the PCA were entered into the ANP to constitute network frameworks for resistance, recovery, and adaptation, as shown in Figures 4.1, 4.2, and 4.3. Each ANP framework involves three tiers of decision-making elements. The first element represents the control criteria in three resilience stages (i.e., resistance, recovery, and adaptation). The second element refers to the level-one cluster of

seven resilience criteria. The third element is for the level-two clusters composed of the interdependent resilience factors associated with each resilience criterion. The interdependencies are shown in the network framework via the arcs (between PC and factors) and loops (inner dependencies of the factors under the same PC). For instance, as far as the control criterion of resistance (in Figure 4.1), Continuity of Project Alignment is the first of the seven resilience criteria, and it involves four subordinate resilience factors (i.e., F13, F14, F15, and F12).

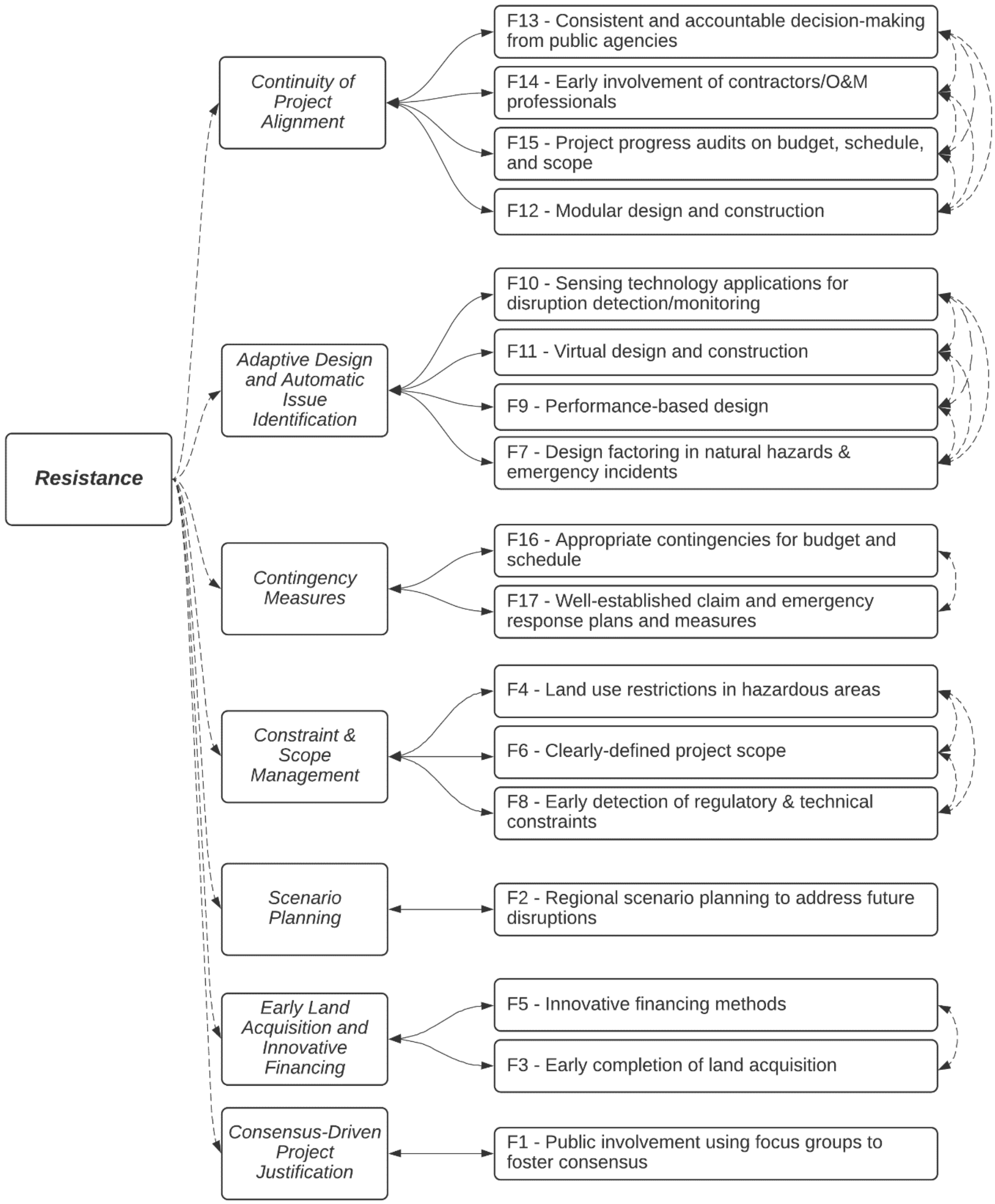

Fig. 4.1 ANP model to construct resilience index for project delivery – resistance

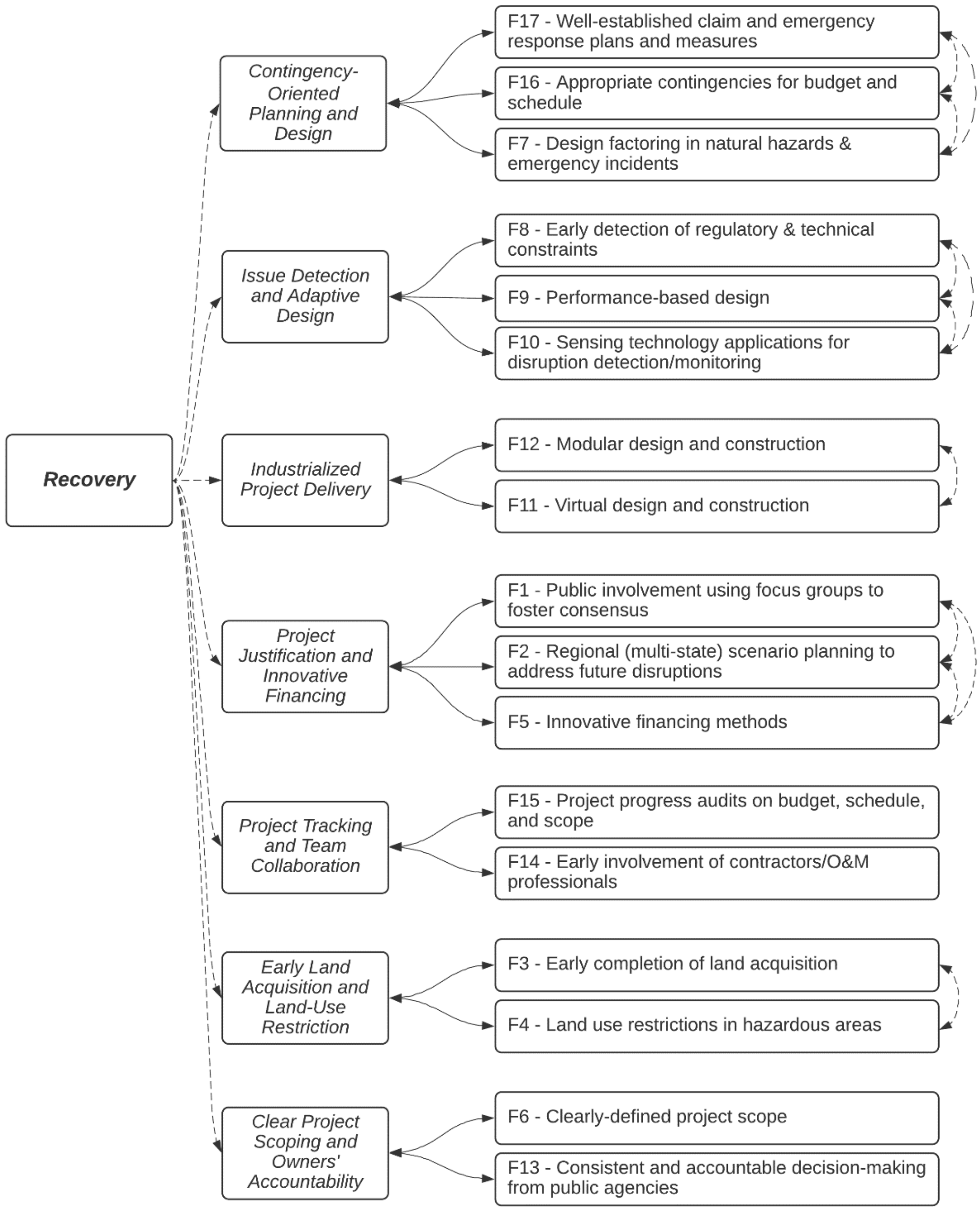

Fig. 4.2 ANP model to construct resilience index for project delivery – recovery

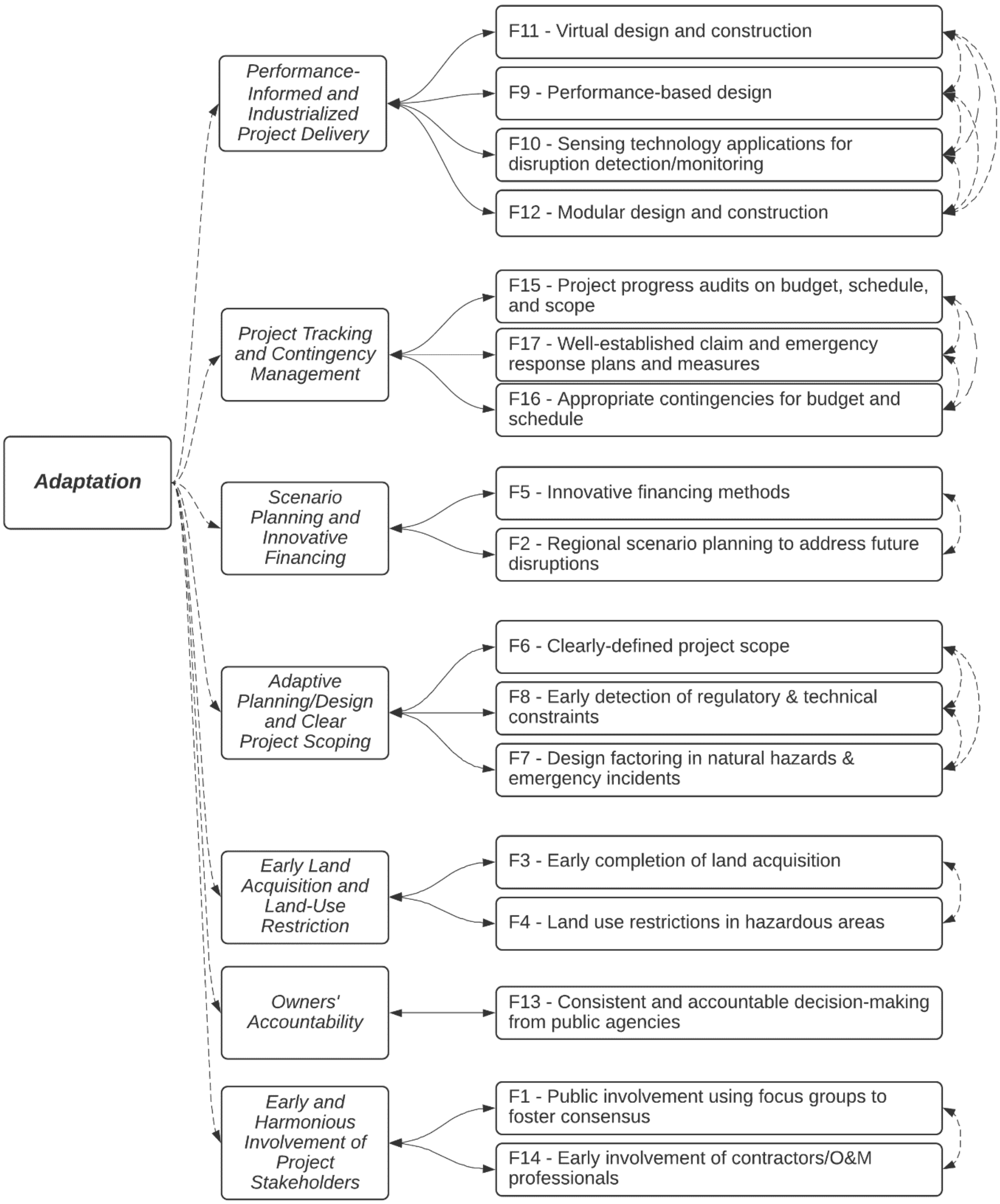

Fig. 4.3 ANP model to construct resilience index for project delivery – adaptation

4.4.2 Formation of Supermatrix to Obtain Weights for Resilience Criteria

The next step of F'ANP is the pairwise comparison between the decision-making elements at different levels (L) of hierarchy in the network framework to form the supermatrix, as shown in Table 4.1. The elements in the supermatrix refer to the relationships between decision elements in the network framework (Saaty, 2004). The decision elements at different levels (e.g., seven resilience PC) are compared pairwise by asking how important each element is with respect to their importance towards their control criteria (e.g., resistance). The results of the pairwise comparisons are priority vectors used to constitute the initial supermatrix (Yazgan and Üstün, 2011; Li et al., 2013). In this research, the priority vector $[W_{L2L1}]_{7\times3}$ indicates the impact of the seven principal resilience criteria in contributing to the three resilience stages. $[W_{L3L2}]_{17\times7}$ is the priority vector obtained from the pairwise comparison of the given 17 resilience factors with respect to their significance to the seven control principal resilience criteria. Lastly, $[W_{L3L3}]_{17\times17}$ is the priority vector that shows the interdependencies of the 17 resilience factors evaluated for their explanatory power with respect to the corresponding resilience stages.

Table 4.1 Schematic supermatrix of the ANP network

	Resilience Stages (L1)	**Principal Resilience Criteria (L2)**	**Resilience Factors (L3)**
Resilience Stages (L1)	0	0	0
Principal Resilience Criteria (L2)	$[W_{L2L1}]_{7\times3}$	0	0

Resilience Factors (L3)	0	$[W_{L3L2}]_{17\times7}$	$[W_{L3L3}]_{17\times17}$

The pairwise comparison was made based on the amount of variance decision-making elements can explain (e.g., factor loadings obtained from the PCA), as suggested by Zebardast (2013). All the pairwise comparisons were calculated for the different levels of decision elements using SuperDecisions, a decision-making software that is often used to construct AHP and ANP models.

4.4.2.1 Relationships Between Principal Resilience Criteria and Resilience Stages

Based on the variance explained by the PC, the pairwise comparisons for the seven resilience criteria are made to generate the pairwise comparison matrix. Once the pairwise comparison matrix is obtained, the priority vector $[W_{L2L1}]_{7\times1}$ can be computed. For instance, Table 4.2 shows the comparison matrix for the resistance stage. The element PC_{12} (the relative importance of PC1 over PC2) is calculated by dividing the variance of PC1 (26.588) to that of PC2 (10.641) and equal to 2.5. The PC_{21} is the inverse of PC_{12} , thus equal to 0.4. Also, the importance coefficients of the principal resilience criteria in the L1 priority vector $[W_{L2L1}]_{7\times1}$ can be estimated by normalizing the total variance explained. Specifically, the priority of PC1 is calculated by having its value row-wise (e.g., 1) divided by the corresponding column sum (e.g., 1 + 0.4 + 0.35 + 0.27 + 0.23 + 0.2 + 0.19 = 2.647), and equal to 0.378. The same normalization procedure was used when calculating the L2 and L3 priority vectors. The priority vectors $[W_{L2L1}]_{7\times1}$ for the recovery and adaptation stages were calculated in the same manner, as shown in Tables 4.3 and 4.4.

Table 4.2 Resistance – Pairwise comparison for priority vector $\mathbf{W_{L2L1}}$

Percent of Variance (%)		PC1	PC2	PC3	PC4	PC5	PC6	PC7	W_{L2L1}
26.588	**PC1**	1	2.50	2.83	3.74	4.27	4.99	5.22	***0.378***
10.641	**PC2**	0.40	1	1.13	1.50	1.71	2.00	2.09	***0.151***
9.4	**PC3**	0.35	0.88	1	1.32	1.51	1.77	1.85	***0.134***
7.104	**PC4**	0.27	0.67	0.76	1	1.14	1.33	1.40	***0.101***
6.231	**PC5**	0.23	0.59	0.66	0.88	1	1.17	1.22	***0.089***
5.325	**PC6**	0.20	0.5	0.57	0.75	0.85	1	1.05	***0.076***
5.091	**PC7**	0.19	0.48	0.54	0.72	0.82	0.96	1	***0.072***

Table 4.3 Recovery – Pairwise comparison for priority vector $\mathbf{W_{L2L1}}$

Percent of Variance (%)		PC1	PC2	PC3	PC4	PC5	PC6	PC7	W_{L2L1}
22.967	**PC1**	1	1.70	2.38	3.04	3.47	4.23	4.58	***0.324***
13.515	**PC2**	0.59	1	1.40	1.79	2.04	2.49	2.69	***0.191***
9.666	**PC3**	0.42	0.72	1	1.28	1.46	1.78	1.93	***0.137***
7.565	**PC4**	0.33	0.56	0.78	1	1.14	1.39	1.51	***0.107***
6.616	**PC5**	0.29	0.49	0.68	0.87	1	1.22	1.32	***0.093***
5.435	**PC6**	0.24	0.4	0.56	0.72	0.82	1	1.08	***0.077***
5.016	**PC7**	0.22	0.37	0.52	0.66	0.76	0.92	1	***0.071***

Table 4.4 Adaptation – Pairwise comparison for priority vector $\mathbf{W_{L2L1}}$

Percent of Variance (%)		PC1	PC2	PC3	PC4	PC5	PC6	PC7	W_{L2L1}
28.808	**PC1**	1	2.76	3.33	4.07	4.72	5.52	5.81	***0.404***
10.436	**PC2**	0.36	1	1.21	1.48	1.71	2.00	2.1	***0.146***

8.652	**PC3**	0.30	0.83	1	1.22	1.42	1.66	1.74	***0.121***
7.072	**PC4**	0.25	0.68	0.82	1	1.16	1.36	1.43	***0.099***
6.101	**PC5**	0.21	0.58	0.71	0.86	1	1.17	1.23	***0.086***
5.216	**PC6**	0.18	0.5	0.6	0.74	0.85	1	1.05	***0.073***
4.962	**PC7**	0.17	0.48	0.57	0.7	0.81	0.95	1	***0.070***

4.4.2.2 Relationships Between Principal Resilience Criteria and Resilience Factors

The pairwise comparison matrix for the subordinate resilience factors of each PC is constructed based on the corresponding factor loadings obtained from the PCA. The factor loadings are equivalent to correlations between resilience PC and factors and represent how much each factor explains the parent PC. Then, the factor-specific importance coefficients in the L2 priority vector $[W_{L3L2}]_{17\times7}$ can be calculated through the normalization of the factor loadings associated with the corresponding PC. Tables 4.5, 4.6, and 4.7 show the clusters of the pairwise comparison matrices and priority vectors for the seven PC under the resistance, recovery, and adaptation scenarios, respectively.

Table 4.5 Resistance – Pairwise comparison for priority vector $\mathbf{W_{L3L2}}$

Factor Loadings	**PC1**	F13	F14	F15	F12	W_{L3L2}
0.741	**F13**	1	1.18	1.2	1.2	***0.285***
0.627	**F14**	0.85	1	1.02	1.02	***0.241***
0.617	**F15**	0.83	0.98	1	1	***0.237***
0.617	**F12**	0.83	0.98	1	1	***0.237***
	PC2	F10	F11	F9	F7	
0.709	**F10**	1	1.05	1.14	1.39	***0.282***

0.675	**F11**	0.95	1	1.09	1.32	***0.268***
0.621	**F9**	0.88	0.92	1	1.22	***0.247***
0.511	**F7**	0.72	0.76	1	1	***0.203***

	PC3	F16	F17	
0.754	**F16**	1	1.20	***0.545***
0.63	**F17**	0.84	1	***0.455***

	PC4	F4	F6	F8	
0.813	**F4**	1	1.16	1.74	***0.410***
0.702	**F6**	0.86	1	1.51	***0.354***
0.466	**F8**	0.57	0.66	1	***0.235***

	PC5	F2	
0.863	**F2**	1	***1.000***

	PC6	F5	F3	
0.839	**F5**	1	1.26	***0.558***
0.664	**F3**	0.79	1	***0.442***

	PC7	F1	
0.876	**F1**	1	***1.000***

Table 4.6 Recovery – Pairwise comparison for priority vector $\mathbf{W_{L3L2}}$

Factor Loadings	**PC1**	F17	F16	F7	W_{L3L2}
0.875	**F17**	1	1.2	1.29	***0.384***
0.727	**F16**	0.83	1	1.07	***0.319***
0.679	**F7**	0.78	0.93	1	***0.298***

	PC2	F8	F9	F10	
0.795	**F8**	1	1.15	1.2	***0.369***
0.694	**F9**	0.87	1	1.04	***0.322***
0.665	**F10**	0.84	0.96	1	***0.309***

	PC3	F12	F11		
0.853	**F12**	1	1.12		***0.528***
0.762	**F11**	0.89	1		***0.472***

	PC4	F1	F2	F5	
0.85	**F1**	1	1.29	1.36	***0.398***
0.659	**F2**	0.78	1	1.06	***0.309***
0.624	**F5**	0.73	0.95	1	***0.293***

	PC5	F15	F14		
0.765	**F15**	1	1.12		***0.527***
0.686	**F14**	0.9	1		***0.473***

	PC6	F3	F4		
0.847	**F3**	1	1.04		***0.509***
0.818	**F4**	0.97	1		***0.491***

	PC7	F6	F13		
0.853	**F6**	1	1.56		***0.610***
0.546	**F13**	0.64	1		***0.390***

Table 4.7 Adaptation – Pairwise comparison for priority vector $\mathbf{W_{L3L2}}$

Factor Loadings	PC1	F11	F9	F10	F12	W_{L3L2}
0.868	**F11**	1	1.09	1.21	1.47	***0.292***

0.795	**F9**	0.92	1	1.1	1.35	***0.267***
0.72	**F10**	0.83	0.91	1	1.22	***0.242***
0.591	**F12**	0.68	0.74	0.82	1	***0.199***
	PC2	F15	F17	F16		
0.795	**F15**	1	1.15	1.38		***0.385***
0.691	**F17**	0.87	1	1.2		***0.335***
0.578	**F16**	0.73	0.84	1		***0.280***
	PC3	F5	F2			
0.793	**F5**	1	1.27			***0.559***
0.625	**F2**	0.79	1			***0.441***
	PC4	F6	F8	F7		
0.762	**F6**	1	1.18	1.53		***0.400***
0.647	**F8**	0.85	1	1.3		***0.339***
0.497	**F7**	0.65	0.77	1		***0.261***
	PC5	F3	F4			
0.86	**F3**	1	1.22			***0.550***
0.704	**F4**	0.82	1			***0.450***
	PC6	F13				
0.825	**F13**	1				***1.000***
	PC7	F1	F14			
0.825	**F1**	1	1.59			***0.614***
0.518	**F14**	0.63	1			***0.386***

4.4.2.3 Relationships Between Resilience Factors

The elements of the L3 pairwise comparison matrix indicate the interdependencies of the resilience factors under each PC. The resilience factors are significantly interrelated in terms of their contribution to different stages of resilience. Based on the survey results (Chapter III), the Pearson correlation matrices for the three resilience stages can be found in Appendix II. The absolute values of the correlation coefficients for these interdependent factors were used to construct the pairwise comparison matrices, as suggested by (Zebardast, 2013). The pairwise comparison was conducted respectively based on each of the resilience factors under the same parent PC. Thus, the L3 priority vector $[W_{L3L3}]_{17\times17}$ contains the importance coefficients of the resilience factors, which can be calculated through the normalization of the correlation coefficients column-wise for each pairwise comparison matrix. Accordingly, Tables 4.8, 4.9, and 4.10 display the clusters of the priority vectors at this level of the pairwise comparison between the resilience factors for the resistance, recovery, and adaptation stages.

Table 4.8 Resistance – Importance coefficients for priority vector $\mathbf{W_{L3L3}}$

PC1		**F13**	**F14**	**F15**	**F12**
	F13	0.4440	0.2050	0.2146	0.1689
	F14	0.1910	0.4764	0.1561	0.1573
	F15	0.2103	0.1641	0.4529	0.1889
	F12	0.1547	0.1545	0.1764	0.4849

PC2		**F10**	**F11**	**F9**	**F7**
	F10	0.4029	0.2156	0.2475	0.2082
	F11	0.1805	0.4814	0.162	0.1136
	F9	0.2405	0.1882	0.4145	0.2021

	F7	0.1762	0.1148	0.1759	0.4761

PC3		**F16**	**F17**
	F16	0.7399	0.2601
	F17	0.2601	0.7399

PC4		**F4**	**F6**	**F8**
	F4	0.6083	0.2214	0.178
	F6	0.2224	0.6056	0.1827
	F8	0.1693	0.173	0.6394

PC5		**F2**
	F2	1

PC6		**F5**	**F3**
	F5	0.7785	0.2215
	F3	0.2215	0.7785

PC7		**F1**
	F1	1

Table 4.9 Recovery – Importance coefficients for priority vector $\mathbf{W_{L3L3}}$

PC1		**F17**	**F16**	**F7**
	F17	0.4870	0.2904	0.2769
	F16	0.2650	0.5337	0.1792
	F7	0.2479	0.1759	0.5439

PC2		**F8**	**F9**	**F10**

	F8	0.5625	0.1781	0.2322
	F9	0.1826	0.5486	0.2553
	F10	0.2549	0.2733	0.5125

PC3		**F12**	**F11**
	F12	0.6506	0.3494
	F11	0.3494	0.6506

PC4		**F1**	**F2**	**F5**
	F1	0.5599	0.2163	0.2177
	F2	0.2192	0.5526	0.2306
	F5	0.2209	0.2311	0.5517

PC5		**F15**	**F14**
	F15	0.7495	0.2505
	F14	0.2505	0.7495

PC6		**F3**	**F4**
	F3	0.6459	0.3541
	F4	0.3541	0.6459

PC7		**F6**	**F13**
	F6	0.7920	0.2080
	F13	0.2080	0.7920

Table 4.10 Adaptation – Importance coefficients for priority vector $\mathbf{W}_{\mathbf{L3L3}}$

PC1		**F11**	**F9**	**F10**	**F12**
	F11	0.3672	0.2446	0.2309	0.2159

	F9	0.2273	0.3953	0.1975	0.1705
	F10	0.2167	0.1995	0.3912	0.1938
	F12	0.1888	0.1605	0.1805	0.4199

PC2		**F15**	**F17**	**F16**
	F15	0.5502	0.2281	0.1868
	F17	0.2531	0.4959	0.2907
	F16	0.1967	0.2760	0.5225

PC3		**F5**	**F2**
	F5	0.7502	0.2498
	F2	0.2498	0.7502

PC4		**F6**	**F8**	**F7**
	F6	0.5973	0.2248	0.1613
	F8	0.2421	0.5546	0.2387
	F7	0.1605	0.2206	0.6000

PC5		**F3**	**F4**
	F3	0.7072	0.2928
	F4	0.2928	0.7072

PC6		**F13**
	F13	1

PC7		**F1**	**F14**
	F1	0.9715	0.0285
	F14	0.0285	0.9715

4.4.2.4 Relative Weights of Resilience Criteria

The priority vectors solved from the pairwise comparison matrices at different levels were entered as the segments of the columns in the weighted supermatrix. The supermatrix is a partitioned matrix where each cluster matrix represents the influence priority of an element on the left of the matrix on an element at the top of the matrix with respect to a particular control criterion in the ANP network (Saaty, 2004). The steady priorities (weights) will be derived from a limit supermatrix and used as their final relative weights of the resilience PC and factors. The limit is obtained by raising the supermatrix to the power of an arbitrary large number until the limit converges when the column is stochastic (i.e., the sum of each column is equal to one). In the resultant limit supermatrix, the final weights will be in the "goal" column. The rest of the filled columns in terms of the resilience PC and factors that belong to the same PC will have the same element values.

4.4.3 Resilience Index Aggregation

The resilience index for highway project delivery is computed as a weighted sum of the resilience criteria, as shown in Equation 4.1. The weighted summation is a simple and widely used MCDM technique that linearly aggregates criteria items with the relative importance values into a composite index (Tzeng and Huang, 2011; Cutter et al., 2010). In this method, the criteria items (i.e., resilience factors) with higher weights will significantly influence on the outcome of composite indicators (Munda and Nardo, 2005).

$$\text{PDRI} = \sum_{i=n} c_{RC_i} \times W_{RC_i} \times RS_i \tag{4.1}$$

Where, PDRI represents the project delivery resilience index. c_{RC_i} represents a binary value (either “1” or “0”) for the feasibility of resilience criteria. “1” means a resilience factor is applicable for a project, while “0” means not applicable.

W_{RC_i} is the weight of the resilience criterion *i*. In this research, W_{RC_i} shows the relative weights for the 17 resilience factors, obtained from the ANP results. The weights for their resilience criteria will be calculated as the sum of the weights with respect to the subordinate resilience factors.

RS_i refers to the standardized score of the resilience criterion *i* based on the assessment of the 17 resilience factors. It is assumed that the resilience factors are intended to pose positive effects on resilience when they are implemented during project delivery processes. To measure this effectiveness, the author used consistent scalability for the resilience factors as the level of implementation, such as intensity and scope for the resilience factors to be carried out during the project delivery processes. Accordingly, the subjective assessment can be provided by evaluators to assess the magnitude of implementation for individual resilience factors in a three-point Likert scale of “low,” “medium,” and “high,” which will be converted to corresponding numerical ratings of 0.33, 0.67, and 1, as suggested by Pyke et al. (2012). Subsequently, the ratings for the resilience factors will be applied to resilience index equations (Equation 4.1) to compute scores for resistance, recovery, and adaptation stages, respectively.

4.5 Results

4.5.1 Relative Weights of Resilience Factors

Tables 4.11 – 4.13 show the limit supermatrices of the resilience criteria in which the weights of the 17 resilience factors can be found in the "goal" columns, associated with the three resilience stages. For the resistance stage (Table 4.11), the weights of the resilience factor cluster F13, F14, F15, and F12 under the PC 1 are 0.099, 0.092, 0.097, and 0.09. F13 – *Consistent and accountable decision-making from public agencies* carries the highest weight (0.099) for a project to achieve resistance to disruptions to the project delivery processes. On the contrary, F8 – *Early detection of regulatory & technical constraints* is considered least important (0.032) in enhancing projects' resistance to disruptions. These numerical weights indicate the combined importance of this factor, reflecting its priority over not only other interrelated resilience factors but also the importance of its "parent" PC it belongs to, through the ANP network. As the project advances to the recovery stage (Table 4.12), F17 – *Established claim and emergency response plans and measures* takes the highest weight (0.115). This finding reflects that preplanned emergency measures are considered effective means to restore the project from realized disruptions rapidly. To achieve adaptation to the disruptions (Table 4.13), F11 – *Virtual design and construction* is considered the most significant factor with the weight of 0.108. The widely applied virtual design and construction promotes "standardized" projects by reducing and accommodating project-specific issues, thus making the projects adapt to disruptions. For instance, modeling various scenarios about how a proposed highway segment (e.g., via BIM and GIS applications) could function against extreme weather conditions helps generate the scenario-specific design for weather-resilience-informed project deliverables.

Suppose the high factor weights suggest the strong explanatory power of resilience if the corresponding factors are successfully implemented. For the given list of the resilience factors, Figure 4.4 demonstrates how the utility of the same factors varies across the different stages of resilience. Most resilience factors display different weights when they are applied to the different resilience stages. For instance, F11 – *Virtual design and construction* is considered relatively significant for projects' adaptation to disruptions but moderately significant for recovery and least significant for resistance. This pattern also applies to F9 – *Performance-based design* and F10 – *Sensing technology applications for disruption detection/monitoring*. Some resilience factors are "insensitive" to the change of the resilience stages. In other words, the variations of the wights for the same resilience factors are relatively small when they are evaluated under resistance, recovery, and adaptation scenarios. The examples of such resilience factors include F3 – *Early completion of land acquisition*, F4 – *Land use restrictions in hazardous areas*, and F6 – *Clearly-defined project scope*, which are considered similarly important across three resilience stages.

Table 4.11 Resistance – Limit supermatrix

Resistance	**Goal**	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**F13**	**F14**	**F15**	**F12**	**F10**	**F11**
PC1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F13	0.099	0.261	0	0	0	0	0	0	0.261	0.261	0.261	0.261	0	0
F14	0.092	0.243	0	0	0	0	0	0	0.243	0.243	0.243	0.243	0	0
F15	0.097	0.256	0	0	0	0	0	0	0.256	0.256	0.256	0.256	0	0
F12	0.090	0.239	0	0	0	0	0	0	0.239	0.239	0.239	0.239	0	0
F10	0.041	0	0.274	0	0	0	0	0	0	0	0	0	0.274	0.274
F11	0.035	0	0.229	0	0	0	0	0	0	0	0	0	0.229	0.229
F9	0.040	0	0.266	0	0	0	0	0	0	0	0	0	0.266	0.266
F7	0.035	0	0.231	0	0	0	0	0	0	0	0	0	0.231	0.231
F16	0.067	0	0	0.500	0	0	0	0	0	0	0	0	0	0
F17	0.067	0	0	0.500	0	0	0	0	0	0	0	0	0	0
F4	0.034	0	0	0	0.338	0	0	0	0	0	0	0	0	0
F6	0.034	0	0	0	0.340	0	0	0	0	0	0	0	0	0
F8	0.032	0	0	0	0.322	0	0	0	0	0	0	0	0	0
F2	0.089	0	0	0	0	1.000	0	0	0	0	0	0	0	0
F5	0.038	0	0	0	0	0	0.500	0	0	0	0	0	0	0
F3	0.038	0	0	0	0	0	0.500	0	0	0	0	0	0	0
F1	0.072	0	0	0	0	0	0	1.000	0	0	0	0	0	0

F9	F7	F16	F17	F4	F6	F8	F2	F5	F3	F1
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0.274	0.274	0	0	0	0	0	0	0	0	0
0.229	0.229	0	0	0	0	0	0	0	0	0
0.266	0.266	0	0	0	0	0	0	0	0	0
0.231	0.231	0	0	0	0	0	0	0	0	0
0	0	0.500	0.500	0	0	0	0	0	0	0
0	0	0.500	0.500	0	0	0	0	0	0	0
0	0	0	0	0.338	0.338	0.338	0	0	0	0
0	0	0	0	0.340	0.340	0.340	0	0	0	0
0	0	0	0	0.322	0.322	0.322	0	0	0	0
0	0	0	0	0	0	0	1.000	0	0	0
0	0	0	0	0	0	0	0	0.500	0.500	0
0	0	0	0	0	0	0	0	0.500	0.500	0
0	0	0	0	0	0	0	0	0	0	1.000

Table 4.12 Recovery – Limit supermatrix

Recovery	**Goal**	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**F17**	**F16**	**F7**	**F8**	**F9**	**F10**
PC1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F17	0.115	0.356	0	0	0	0	0	0	0.356	0.356	0.356	0	0	0
F16	0.105	0.325	0	0	0	0	0	0	0.325	0.325	0.325	0	0	0
F7	0.103	0.319	0	0	0	0	0	0	0.319	0.319	0.319	0	0	0
F8	0.061	0	0.320	0	0	0	0	0	0	0	0	0.320	0.320	0.320
F9	0.063	0	0.328	0	0	0	0	0	0	0	0	0.328	0.328	0.328
F10	0.067	0	0.351	0	0	0	0	0	0	0	0	0.351	0.351	0.351
F12	0.069	0	0	0.500	0	0	0	0	0	0	0	0	0	0
F11	0.069	0	0	0.500	0	0	0	0	0	0	0	0	0	0
F1	0.035	0	0	0	0.330	0	0	0	0	0	0	0	0	0
F2	0.036	0	0	0	0.335	0	0	0	0	0	0	0	0	0
F5	0.036	0	0	0	0.335	0	0	0	0	0	0	0	0	0
F15	0.047	0	0	0	0	0.500	0	0	0	0	0	0	0	0
F14	0.047	0	0	0	0	0.500	0	0	0	0	0	0	0	0
F3	0.039	0	0	0	0	0	0.500	0	0	0	0	0	0	0
F4	0.039	0	0	0	0	0	0.500	0	0	0	0	0	0	0
F6	0.036	0	0	0	0	0	0	0.500	0	0	0	0	0	0
F13	0.036	0	0	0	0	0	0	0.500	0	0	0	0	0	0

F12	F11	F1	F2	F5	F15	F14	F3	F4	F6	F13
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0.500	0.500	0	0	0	0	0	0	0	0	0
0.500	0.500	0	0	0	0	0	0	0	0	0
0	0	0.330	0.330	0.330	0	0	0	0	0	0
0	0	0.335	0.335	0.335	0	0	0	0	0	0
0	0	0.335	0.335	0.335	0	0	0	0	0	0
0	0	0	0	0	0.500	0.500	0	0	0	0
0	0	0	0	0	0.500	0.500	0	0	0	0
0	0	0	0	0	0	0	0.500	0.500	0	0
0	0	0	0	0	0	0	0.500	0.500	0	0
0	0	0	0	0	0	0	0	0	0.500	0.500
0	0	0	0	0	0	0	0	0	0.500	0.500

Table 4.13 Adaptation – Limit supermatrix

Adaptation	Goal	PC1	PC2	PC3	PC4	PC5	PC6	PC7	F11	F9	F10	F12	F15	F17
PC1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F11	0.108	0.267	0	0	0	0	0	0	0.267	0.267	0.267	0.267	0	0
F9	0.100	0.248	0	0	0	0	0	0	0.248	0.248	0.248	0.248	0	0
F10	0.101	0.251	0	0	0	0	0	0	0.251	0.251	0.251	0.251	0	0
F12	0.095	0.234	0	0	0	0	0	0	0.234	0.234	0.234	0.234	0	0
F15	0.046	0	0.316	0	0	0	0	0	0	0	0	0	0.316	0.316
F17	0.051	0	0.351	0	0	0	0	0	0	0	0	0	0.351	0.351
F16	0.049	0	0.333	0	0	0	0	0	0	0	0	0	0.333	0.333
F5	0.061	0	0	0.500	0	0	0	0	0	0	0	0	0	0
F2	0.061	0	0	0.500	0	0	0	0	0	0	0	0	0	0
F6	0.032	0	0	0	0.325	0	0	0	0	0	0	0	0	0
F8	0.035	0	0	0	0.351	0	0	0	0	0	0	0	0	0
F7	0.032	0	0	0	0.324	0	0	0	0	0	0	0	0	0
F3	0.043	0	0	0	0	0.500	0	0	0	0	0	0	0	0
F4	0.043	0	0	0	0	0.500	0	0	0	0	0	0	0	0
F13	0.073	0	0	0	0	0	1.000	0	0	0	0	0	0	0
F1	0.035	0	0	0	0	0	0	0.500	0	0	0	0	0	0
F14	0.035	0	0	0	0	0	0	0.500	0	0	0	0	0	0

F16	**F5**	**F2**	**F6**	**F8**	**F7**	**F3**	**F4**	**F13**	**F1**	**F14**
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0.316	0	0	0	0	0	0	0	0	0	0
0.351	0	0	0	0	0	0	0	0	0	0
0.333	0	0	0	0	0	0	0	0	0	0
0	0.500	0.500	0	0	0	0	0	0	0	0
0	0.500	0.500	0	0	0	0	0	0	0	0
0	0	0	0.325	0.325	0.325	0	0	0	0	0
0	0	0	0.351	0.351	0.351	0	0	0	0	0
0	0	0	0.324	0.324	0.324	0	0	0	0	0
0	0	0	0	0	0	0.500	0.500	0	0	0
0	0	0	0	0	0	0.500	0.500	0	0	0
0	0	0	0	0	0	0	0	1.000	0	0
0	0	0	0	0	0	0	0	0	0.500	0.500
0	0	0	0	0	0	0	0	0	0.500	0.500

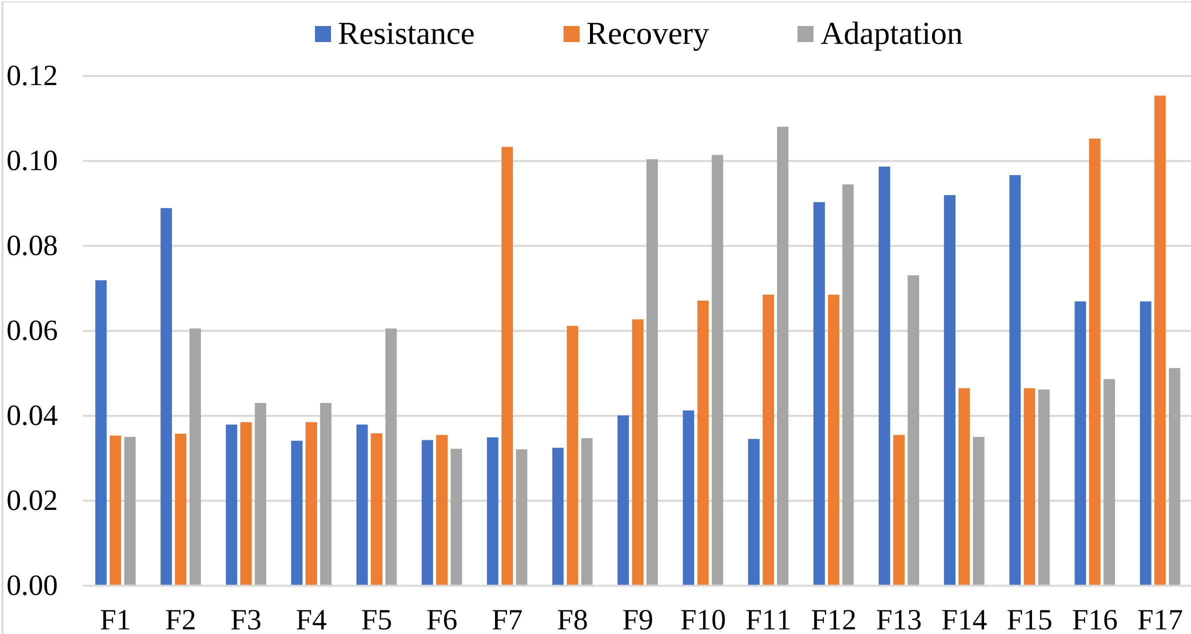

Fig. 4.4 Resilience factor weights across three resilience stages

4.5.2 Project Delivery Resilience Index

Per Equation 4.1, the proposed PDRI represents a weighted sum of the resilience factors for each of the three resilience stages. In addition to the factors' weights, obtaining PDRI involves determining the level of implementation as the scores for the given list of the resilience factors. To present a user-friendly format of the PDRI assessment, the author constructed a PDRI scorecard involving the resilience factors, weights, and scores, as shown in Table 4.14.

Table 4.14 Resilience score card for infrastructure project delivery processes

Resilience Stage	Principal Criteria (PC)	Resilience Factor (F)		Weights (W)	Criteria Feasibility ("0" or "1")	Resilience Score (RS)	PDRI
RESISTANCE	#1		**Continuity of Project Alignment**				
		F13	Consistent and accountable decision-making from public agencies	0.099			
		F14	Early involvement of contractors/O&M professionals	0.092			
		F15	Project progress audits on budget, schedule, and scope	0.097			
		F12	Modular design and construction	0.090			
	#2		**Adaptive Design and Automatic Issue Identification**				
		F10	Sensing technology applications for disruption detection/monitoring	0.041			
		F11	Virtual design and construction	0.035			
		F9	Performance-based design	0.040			
		F7	Design factoring in natural hazards & emergency incidents	0.035			
	#3		**Contingency Measures**				
		F16	Appropriate contingencies for budget and schedule	0.067			

		F17	Well-established claim and emergency response plans and measures	0.067			
	#4		**Constraint & Scope Management**				
		F4	Land use restrictions in hazardous areas	0.034			
		F6	Clearly-defined project scope	0.034			
		F8	Early detection of regulatory & technical constraints	0.032			
	#5		**Scenario Planning**				
		F2	Regional scenario planning to address future disruptions	0.089			
	#6		**Early Land Acquisition and Innovative Financing**				
		F5	Innovative financing methods	0.038			
		F3	Early completion of land acquisition	0.038			
	#7		**Consensus-Driven Project Justification**				
		F1	Public involvement using focus groups to foster consensus	0.072			
				Subtotal of PDRI			
RECOVERY	#1		**Contingency-Oriented Planning and Design**				
		F17	Well-established claim and emergency response plans and measures	0.115			
		F16	Appropriate contingencies for budget and schedule	0.105			
		F7	Design factoring in natural hazards & emergency incidents	0.103			
	#2		**Issue Detection and Adaptive Design**				

		F8	Early detection of regulatory & technical constraints	0.061			
		F9	Performance-based design	0.063			
		F10	Sensing technology applications for disruption detection/monitoring	0.067			
	#3		**Industrialized Project Delivery**				
		F12	Modular design and construction	0.069			
		F11	Virtual design and construction	0.069			
	#4		**Project Justification and Innovative Financing**				
		F1	Public involvement using focus groups to foster consensus	0.035			
		F2	Regional (multi-state) scenario planning to address future disruptions	0.036			
		F5	Innovative financing methods	0.036			
	#5		**Project Tracking and Team Collaboration**				
		F15	Project progress audits on budget, schedule, and scope	0.047			
		F14	Early involvement of contractors/O&M professionals	0.047			
	#6		**Early Land Acquisition and Land-Use Restriction**				
		F3	Early completion of land acquisition	0.039			
		F4	Land use restrictions in hazardous areas	0.039			
	#7		**Clear Project Scoping and Owners' Accountability**				
		F6	Clearly-defined project scope	0.036			

		F13	Consistent and accountable decision-making from public agencies	0.036			
				Subtotal of PDRI			
ADAPTATION	#1		**Performance-Informed and Industrialized Project Delivery**				
		F11	Virtual design and construction	0.108			
		F9	Performance-based design	0.100			
		F10	Sensing technology applications for disruption detection/monitoring	0.101			
		F12	Modular design and construction	0.095			
	#2		**Project Tracking and Contingency Management**				
		F15	Project progress audits on budget, schedule, and scope	0.046			
		F17	Well-established claim and emergency response plans and measures	0.051			
		F16	Appropriate contingencies for budget and schedule	0.049			
	#3		**Scenario Planning and Innovative Financing**				
		F5	Innovative financing methods	0.061			
		F2	Regional scenario planning to address future disruptions	0.061			
	#4		**Adaptive Planning/Design and Clear Project Scoping**				
		F6	Clearly-defined project scope	0.032			

		F8	Early detection of regulatory & technical constraints	0.035			
		F7	Design factoring in natural hazards & emergency incidents	0.032			
	#5		**Early Land Acquisition and Land-Use Restriction**				
		F3	Early completion of land acquisition	0.043			
		F4	Land use restrictions in hazardous areas	0.043			
	#6		**Owners' Accountability**				
		F13	Consistent and accountable decision-making from public agencies	0.073			
	#7		**Early and Harmonious Involvement of Project Stakeholders**				
		F1	Public involvement using focus groups to foster consensus	0.035			
		F14	Early involvement of contractors/O&M professionals	0.035			
				Subtotal of PDRI			
				Total of PDRI			

4.5.3 Illustrative Example

This section showcases an illustrative example of how the proposed resilience index works to evaluate different PDMs, including D-B-B, D-B, and CM/GC. These three PDMs were chosen because they are all used for delivering road construction projects – the context from which the resilience factors were identified.

4.5.3.1 PDRI Rating Processes

Several interviews were conducted with selected industry professionals who participated in the previous survey for PCA. The selection of the interview participants is a purposive sampling which means the ones being interviewed were selected based on the author's judgment about which participants will be representative (Bingham, 2010). The selected evaluators provided their ratings for the resilience of different PDMs by judging the level of implementation of the given list of resilience factors in the context of a particular PDM.

Given the uniqueness of individual construction projects, the implementation level cannot be project-specific but refers to the patterns of how resilience factors are applicable for different PDMs. Specifically, the evaluators were asked to consider a road project they were involved with, as a reference during their rating processes. They were instructed to make their ratings on the resilience factors, which best typify the specified PDMs. The rating values would be recorded as low (poor implementation), moderate, and high (full implementation). If a resilience factor is not applicable for the PDM, no rating would be given for that factor but recorded as "N/A," which will be assigned with a value of 0. During the interviews, the evaluators were shown a PDRI scorecard without showing the weights for each resilience factor so that there would be no bias in the evaluation of each factor. In case that a resilience

factor is applicable to a PDM, but the evaluators are not familiar with it, the evaluators were suggested to judge the factor based on their general knowledge and experience in a project of related factor characteristics.

4.5.3.2 PDRI Ratings

Table 4.15 shows the PDRI ratings across D-B-B, D-B, and CM/CG PDMs. Since the rating focused on the general characteristics of the PDMs, all the resilience factors are considered applicable for the three PDMs (i.e., the factor feasibility c_{RC_i} = 1 per Equation 4.1). These qualitative results (i.e., "L" for low, "M" for moderate, and "H" for high) show that D-B-B obtains relatively low ratings for most of the resilience factors except for two moderate ratings for F11 - *Virtual design and construction* and F15 - *Project progress audits on budget, schedule, and scope*. In contrast, the PDRI ratings for D-B and CM/GC are obviously higher than the traditional D-B-B. For D-B, seven resilience factors are rated as "high," including F3 - *Early completion of land acquisition*, F8 - *Early detection of regulatory & technical constraints*, F9 - *Performance-based design*, F10 - *Sensing technology applications for disruption detection/monitoring*, F11 - *Virtual design and construction*, F14 - *Early involvement of contractors/O&M professionals*, F16 - *Appropriate contingencies for budget and schedule*. These results reflect the advantages of D-B in terms of allowing innovation in design and construction methods, risk allocation to design-builders, and enhanced partnership (El Asmar, 2018; Borowiec et al., 2016).

Table 4.15 PDRI ratings for different PDMs

#	Resilience Factors (Remarks)	D-B-B			CM/GC			D-B		
		L	M	H	L	M	H	L	M	H
F1	Public involvement using focus groups to foster consensus									
F2	Regional (multi-state) scenario planning to address future disruptions (e.g., population/climate change)									
F3	Smooth land acquisition (e.g., Right-Of-Way (ROW) acquisition for highway infrastructure)									
F4	Land use restrictions in hazardous (inundation) areas (e.g., zoning overlays)									
F5	Innovative financing methods (e.g., toll revenues, engaging private funds, loan of future funds)									
F6	Clearly defined project scope (scoping with timelines for deliverables to avoid project creep)									
F7	Design factoring in natural hazards & emergency incidents (e.g., heat-resistant pavement mix)									
F8	Early detection of regulatory/technical constraints (e.g., jurisdictional overlap, utility encounters)									

F9	Performance-based design (e.g., value engineering)									
F10	Sensing technology applications for disruption (damage) detection/monitoring									
F11	Virtual design and construction (e.g., GIS and BIM applications)									
F12	Modular design and construction									
F13	Consistent and accountable decision-making from public agencies									
F14	Early involvement of contractors/O&M professionals									
F15	Project progress audits on budget, schedule, and scope (e.g., forecasting & issue resolution)									
F16	Appropriate contingencies for budget and schedule									
F17	Well-established claim and emergency response plans and measures (e.g., post-event analysis)									

Similar to D-B, CM/GC emphasizes the team approach via a construction manager who works in close liaison with involved project parties as early as the planning stage of a project and maintains the collaboration through the entire project delivery (Borowiec et al., 2016). In the context of CM/GC, the high ratings are observed particularly for F6 - *Clearly-defined project scope*, F13 - *Consistent and accountable decision-making from public agencies*, F15 - *Project progress audits on budget, schedule, and scope*.

To indicate the effectiveness of the resilience factors to achieve the resilience of project delivery, the factor ratings were plugged in the PDRI scorecards to calculate the weighted PDRI scores (Appendix III) associated with different resilience stages and overall resilience. The results are summarized in Table 4.16. D-B has the highest PDRI score of 2.3 while the PDRI score of 1.1 for D-B-B is the lowest. The PDRI score for CM/GC is slightly lower than D-B with the rating of 2.2.

Moreover, several patterns for the PDRI ratings can be observed with respect to different resilience stages and PDMs. The three PDMs show a consistent trend of PDRI scores that adaptation ratings are slightly greater than resistance and recovery ratings. In the context of D-B-B, for instance, the PDRI for adaptation is 0.3824 which is greater than the PDRI for resistance (0.3749) and recovery (0.3704). This trend indicates that the proposed resilience factors which drive adaptation are rated relatively high across the three PDMs. Another consistent trend is that the PDRI scores for overall resilience and each resilience stage are ranked from high to low as D-B, CM/GC, and D-B-B. The PDR for D-B (2.3) is noticeably greater than that of D-B-B (1.1), while the PDRI gap between D-B (2.3) and CM/GC (2.2) is relatively small.

Table 4.16 PDRI scores for different PDMs

	D-B-B	CM/GC	D-B
Resistance	0.3749	0.7098	0.7288
Recovery	0.3704	0.7191	0.7613
Adaptation	0.3824	0.7354	0.7731
Overall (Rounding to the nearest tenths)	1.1	2.2	2.3

4.5.4 Validation of Illustrative PDRI Ratings

To validate the proposed PDRI, the author supposes resilient project delivery processes can aid the project completion as intended, thus leading to enhanced project performance. In other words, the higher a PDM is rated, the better record (e.g., on budget and schedule) is expected for projects using this PDM. The index validation is performed by either theoretical justification or empirical validation (Bakkensen et al., 2017). Theoretical is from a meta-analysis of the literature, which is important but may not meaningfully relate to specific outcomes of interest. Empirical is using real-world observations so the ability of the index to explain the situation it represents can be estimated.

This research uses empirical validation by comparing the illustrative PDRI ratings to recent research regarding the performance comparison of D-B-B, CM/GC, and D-B (Franz et al., 2020). Table 4.17 shows the PDM comparison in terms of the PDRI ratings plus cost growth and project delivery speed. On average, DB projects are expected to experience 2.4% less cost growth than a similarly scoped project using CM/GC and 3.8% less cost growth than a comparable D-B-B project. Also, projects using D-B are delivered 61% faster from design

through completion when compared to projects using CM/GC and 102% faster than D-B-B projects. D-B outperforms CM/GC and D-B-B accordingly for having less cost growth and faster delivery speed. Per the PDRI ratings, projects using D-B are considered more resilient than CM/GC and then D-B-B projects. The pattern of the PDRI ratings is generally consistent with findings by Franz et al. (2020).

Table 4.17 Validation of illustrative PDRI ratings (Franz et al., 2020)

Performance Measure	D-B vs. CM/GC	CM/GC vs. D-B-B	D-B vs. D-B-B
PDRI overall	0.1 higher	1.1 higher	1.2 higher
Cost growth (%)	2.4 less	1.4 less	3.8 less
Delivery speed (%)	61 faster	25 faster	102 faster

4.6 Discussions

4.6.1 Implications for Illustrative PDRI Ratings

The illustrative PDRI ratings reflect the characteristics of the PDMs in response to project risks. The prevalent way of comparing one PDM to another is how project risks are shared among project entities (e.g., owners and constructors) (Gransberg and Shane, 2010). How different PDMs handle risks (i.e., from withstanding potential risks to getting recovered from and embracing the realized risks) makes the PDM performance relevant to resilience.

Despite being well acknowledged by procurement laws, the traditional D-B-B is considered less resilient for a project to respond to disruptions. First, the means of risk handling

for D-B-B projects is risk-shifting. From an owner's perspective, choosing D-B-B allows them to transfer cost and delay risks to contractors. D-B-B is also known for adversarial relationships between project parties because, under separate contracts, each party prioritizes their own interests over common project goals in the case of risk occurrence. D-B-B projects tend to be barely resistant to risks such as cost growth associated with design defects due to the lack of contractors' inputs at the design stage. Moreover, the inherent rigidity of D-B-B processes makes the innovation (e.g., alternative financing methods and new technologies) stifled or difficult to implement, let alone adapting to evolving risks (Borowiec et al., 2016; Walewski et al., 2001).

D-B and CM/GC, as alternative PDMs to traditional D-B-B, obtain relatively high PDRI ratings because of their strength in risk-handling. Both PDMs emphasize the team approach through the project delivery, thus leading to better risk allocation. For instance, early detection of design defects can be achieved by allowing the early involvement of contractors and independent construction managers. Less cost growth is anticipated when construction managers are incentivized because they can share the cost-saving (Borowiec et al., 2016; El Asmar, 2018). In addition, the collaborative culture featured by D-B and CM/GC aids a project's recovery from realized risks for resources available to a project team. For instance, D-B is considered especially effective in dealing with issues regarding right-of-way acquisitions and utility relocation coordination as these responsibilities fall within the private consortia's (i.e., through design-builder) scope of work rather than public agencies (Borowiec et al., 2016). It is worth noting that D-B and CM/GC can promote the adaption of projects to the disruptive project environment simply because they allow the flexibility for innovation in financing, design, materials, and construction methods (Walewski et al., 2001).

4.6.2 PDRI Applications

The PDRI ratings for the illustrative example only reflect the typical characteristics of D-B-B, D-B, and CM/GC. In reality, PDRI for different PDMs should be assessed with careful considerations to specific PDM scenarios. For instance, there exist variations of D-B-B when alternative procurement methods become available, such as Cost-Plus-Time bidding, which allows both time and cost to be considered in the low bid determination. CM/GC and D-B also have their evolving forms (e.g., Design-Build-Operate). For instance, the Federal Highway Administration (FHWA) approved alternative technical concepts (ATCs) in project procurement and execution that especially apply to CM/GC and D-B to promote integrating the collective expertise and creativity of various stakeholders (El Asmar, 2018).

The PDRI can be viewed as a benchmark for the resilience of project delivery processes when all the resilience factors are rated as the highest of "1". For a case-specific PDRI, it shows the integrated resilience rating since the PDRI itself refers to a structure of the resilience factors (i.e., factor weights). The resilience factors consisting of the PDRI are intended to provide practitioners with a checklist to examine the performance of project delivery processes qualitatively with respect to particular resilience stages.

4.7 Concluding Remarks

This research proposed the PDRI that can be used to evaluate the resilience of project delivery processes in response to inevitable disruptions to the project. The key results of the PDRI constructs show the priorities of the given set of resilience factors when they are viewed in the context of different resilience stages. The most significant (i.e., highest weight) resilience factors for resistance, recovery, and adaptation are F13 – *Consistent and accountable decision-*

making from public agencies; F17 – *Established claim and emergency response plans and measures*; F11 – *Virtual design and construction*. To showcase how the proposed PDRI works, an illustrative application was presented to compare the D-B-B, D-B, and CM/GC – three PDMs used for road project delivery. The results show that the rank of the PDRI ratings (including overall and each resilience stage) in the descending order is D-B, CM/GC, and D-B-B. Hence, PDMs based on the integrated approach (i.e., D-B and CM/GC) are considered more resilient than traditional D-B-B to achieve intended project goals.

In practice, the proposed PDRI is expected to inform multicriteria decisions when determining the project delivery resilience with a quantitative and comparable result. The focus shift from risk to resilience in project performance assessment can help project stakeholders identify priorities, establish and refine practices and guidelines for current PDMs, and ultimately enhance the resiliency of road infrastructure project delivery. Meanwhile, the author realized the limitations of this research. Since the weights built in the PDRI are derived from experts' opinions, so the weights' significance is sensitive to the change of the opinions, which makes the verification of the research results (e.g., via comparison to actual project records) necessary. The resilience factors are subject to updates specific to the variations of projects and PDMs. Therefore, the proposed should be treated as an initial result for the assessment of project delivery resilience.

CHAPTER V

DEVELOPMENT OF RESILIENCE MEASURES FOR ASSESSING THE PERFORMANCE OF CIVIL INFRASTRUCTURE PROJECT DELIVERY

5.1 Introduction

Widespread risks in the AEC industry make resilience management an essential means to enhance performance over the life cycle of a project (Industry Statement on Resilience, 2016). While resilience is often discussed in the context of physical infrastructure, there is also a need to consider the resilience of project delivery processes that cover different project phases, such as planning, design, and construction. Chapters 3 and 4 of the dissertation develop the resilience criteria and index that are based on the attributes (stages) of resilience (i.e., resistance, recovery, and adaptation). In essence, the resilience criteria and indices are qualitative and require multi-criteria decisions.

Unlike the previous chapters, this chapter develops a single point of metric to measure the resilience of infrastructure PDP. A quantitative approach based on the proposed new metric is developed and then illustrated through an example project.

5.2 Background

The successful development of civil infrastructure projects is difficult due to diverse disruptions such as the uncertainty of public financing, scope change, and manpower shortages. The tendency for disruption throughout the project delivery process means that individual project phases seldom proceed as planned, leading to cost and schedule overruns. Traditional

project management approaches like the Critical Path Method (CPM) for scheduling cannot predict or eliminate discrepancies between planned and actual project outcomes. Risk management is often adopted as a systematic approach to identify, assess, and control for those project risks which can lead to disruptions. However, risk management is insufficient when the risks are unknown or when there are shock events with a low likelihood of occurrence (Park et al., 2013). Another management approach – resilience management – can be considered a complement to risk management as the resilience approach shifts focus away from the risks (what they are and how likely is it that they will occur) and towards the consequences (the tendency for loss of performance and degree of performance loss) (Steen and Aven, 2011). The goal of resilience management is to increase the ability of a project to resist and recover from the negative consequences of risks.

Resilience is usually evaluated systematically in both qualitative and quantitative metrics. Figure 5.1 shows an analytical representation of resilience showing how a system's functionality (output) initially decreases when a disruption occurs and then increases to some extent after the disruption (Hollnagel, 2014; Linkov et al., 2014).

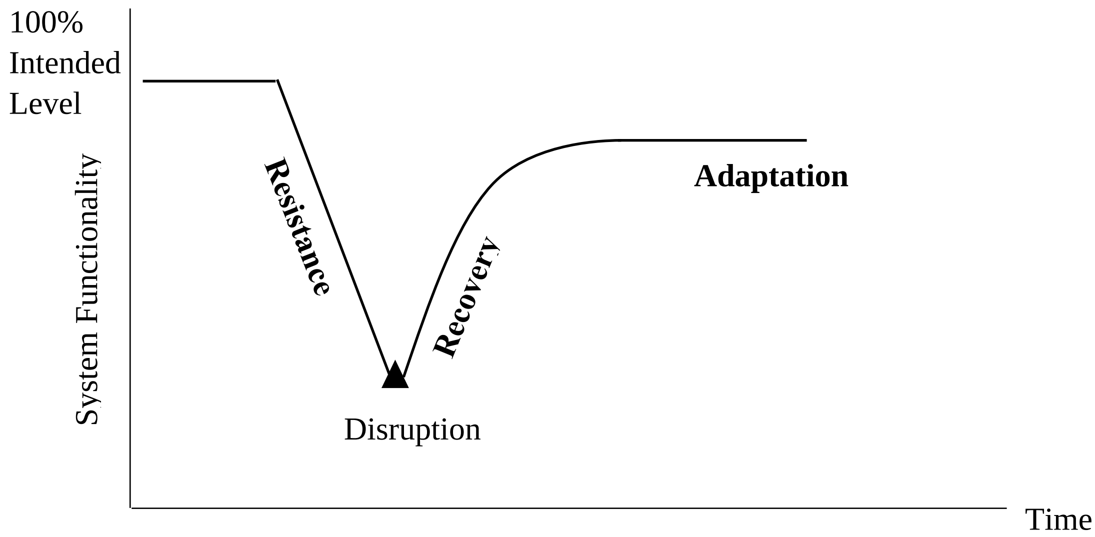

Fig. 5.1 System resilience

As shown in Figure 5.1, qualitative resilience metrics consist of “resistance” to negative impact of disruptions (e.g., degraded system functionality); “recovery” of the degraded functionality; and “adaptation” to the disruptions with an adjusted level of functionality often less than the originally intended level (Bruneau et al., 2003; Sheffi, 2005; Linkov et al., 2013; Linkov et al., 2014). Likewise, quantitative metrics for resilience also highlight the varying consequences of disruptive events on intended system outputs by measuring a dimensionless ratio of the disrupted system state (with quantifiable outputs) before and after the disruptive events (Hosseini et al., 2016; Adjetey-Bahun et al., 2016). For complicated system scenarios (e.g., interrelated infrastructure sectors), the interrelationships among the system components are considered to evaluate how disruptive impact spreads to the functionality that is indirectly affected by disruptions. The corresponding resilience measures include the inoperability (e.g., loss of performance) based on economic input-output interdependencies, or physical

interconnections (e.g., topological attributes for transportation networks) among the system components (Haimes et al., 2005; Ip and Wang, 2011; Pant et al., 2014).

5.3 Points of Departure

Resilience for infrastructure project delivery is critical to achieving the completed project to some extent because certain disruptive issues (e.g., inadequate stormwater drainage capacity due to poor design oversight), if neglected, could reduce the resilience of the completed project to respond to hazards (e.g., intense precipitation). Due to the inherent complexity of infrastructure projects, it is impossible to identify all potentially disruptive events. Even for those that are likely to occur (e.g., labor and material shortages) during project delivery, estimating the likelihood of the disruptions could be ill-conceived due to a common trend of “optimism bias” for human estimation during project planning and management (Meyer, 2014). Meanwhile, the fact that projects can be completed in a disruptive environment implies that there exists certain natural resilience for project delivery processes. Being able to quantify and manage such resilience helps guide project stakeholders to identify project delivery methods that are more likely to allow them to reach the intended project performance.

The author defined project delivery resilience as a phase-based capability of withstanding disruptions and restoring unfulfilled project deliverables, so the continuity of projects is allowed. This chapter extends the previous work (i.e., qualitative resilience measures) to the development of quantitative resilience measures for project delivery. The intended resilience metric should reflect typical resilience attributes (e.g., “resistance” and “recovery”) in terms of performance fluctuations of project phases in response to disruptive

events. Based on this metric, resilience can be measured with numerical outcomes that accommodate various performance measures from different project aspects. Accordingly, two research questions are formulated including: 1) What is a performance-driven metric that measures the resilience for project delivery in a holistic manner? 2) How can we quantitatively evaluate the resilience for project delivery using the proposed metric?

5.4 Performance-Driven Resilience for Infrastructure Project Delivery

5.4.1 Resilience for Project Delivery System Performance

The processes for infrastructure project delivery can be viewed as a complex system or "system-of-systems" due to the interactional relationships among elements within the system (Naderpajouh and Hastak, 2014). This study defines the system boundary for project delivery processes as different phases of a project with the corresponding phase deliverables. According to Haimes (2009), system resilience is a demonstration of the states of the systems in response to disruptive events. The states of project delivery systems alter over time when disruptive events occur in different project phases and result in the loss of performance. The outcomes for individual project phases refer to the completion of the intended scope of work which can be quantifiable physical work put-in-place (e.g., installation quantity for construction phases) and less-quantifiable tasks (e.g., project scoping and programming for planning phases). As shown in Figure 5.2, the completion of the design and construction phases means that the intended outcomes are 100% complete. In the case of disruptive events, the phase state change and the phase may end up with a portion of the intended outcomes completed at less than 100% (this is considered as the gain) along with some unfulfilled portion of the intended outcomes

(this is considered as the loss). A system that is considered to be resilient has a larger gain and smaller loss which results from the system absorbing the negative impact (e.g., resisting the disruption) and restoring many of the outcomes (e.g., recovering from the disruption).

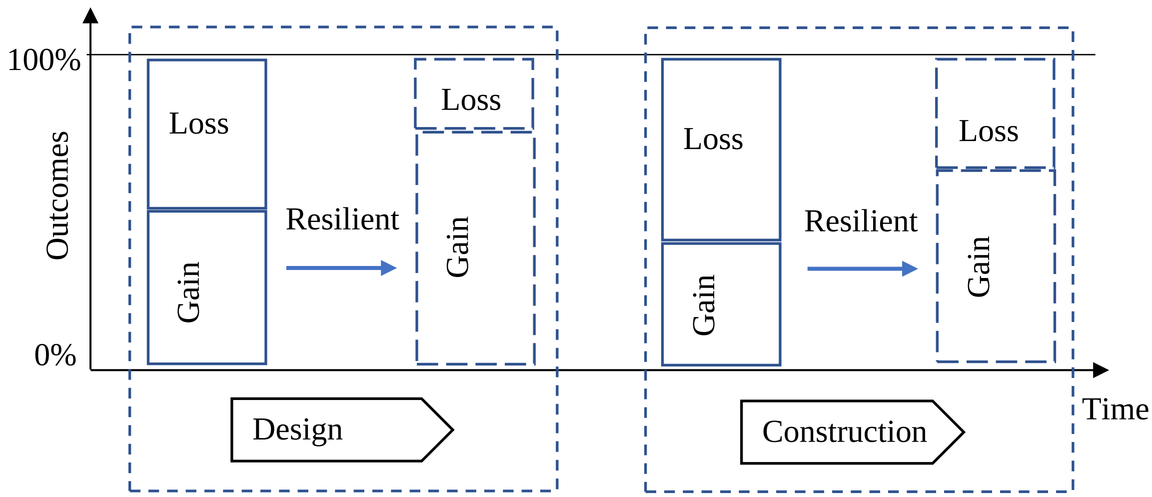

Fig. 5.2 Resilience for project delivery processes (design & construction phases)

A common performance measure for project delivery that combines different project objectives is the difference between the baseline and actual outcomes, such as cost and schedule growth rates (El Asmar et al., 2013). Such performance discrepancies occur in disrupted project phases and prevent them from being delivered as planned. The resulting performance gap can be quantified based on the estimation of actual project progress (observed work % completion) related to cost and or time metrics compared to the baseline (intended) outcomes. Supposing the baseline phase outcomes are constant, then the performance gap can be measured as an absolute magnitude of the difference between the actual and the planned outcomes. For example, a performance gap of 20% for the construction phase, based on cost as the reference metric, can suggest the following scenarios: 80% of intended work is

completed within 100% of the baseline budget; or an extra 20% of the baseline budget is needed to complete 100% of the intended work, which is treated as a 20% cost overrun compared to the baseline budget.

5.4.2 Inoperability-Based Project Delivery Resilience

The performance gap for different project phases represents the degree that phase outcomes are not delivered as planned. The loss of performance or lack of completion of different phase outcomes can be treated collectively as the *inoperability* of project phases, a performance-driven concept that is used to depict the magnitude to which a system does not perform to its intended level of functionality (Lian and Haimes, 2006; Haimes and Jiang, 2001). Also, the performance gap between what is delivered compared to what was originally planned for individual project phases is related to inoperability as both ideas can be measured as a level of incompleteness of system outcomes. Thus, the inoperability for project delivery is defined as the inability of the project phases to achieve the planned deliverables and is evaluated as a continuous variable between "0" (intended system state) and "1" (completely inoperable system state) (Haimes and Jiang, 2001). Moreover, the level of inoperability of project phases directly correlates to the vulnerability of the project delivery process, and thus, identifies when there is a need for increased resilience (Bruneau et al., 2003). To mitigate for loss of function (e.g., inoperability), two aspects of resilience should be considered. The first is increased resistance where disruptions are anticipated and prepared for in every project phase. Increasing resistance mitigates the worst-case consequences but often results in partially unfulfilled outcomes when the disruptions occur (Rogers et al., 2012). The second is improved recovery where the resulting inoperable state triggers a recovery which restores some or all of the unfulfilled outcomes (Woods, 2015).

5.5 Inoperability-Based Metric for Project Delivery Resilience

5.5.1 Tendency toward Inoperability for Project Delivery Processes

This research proposes an inoperability-based metric for measuring the resilience of project delivery processes. The objective of the metric is to provide decision makers with the information necessary to reduce the inoperability associated with project disruptions, and thus, increase the resilience of the project delivery process. Basing the metric on the level of inoperability captures project outcomes via a dimensionless unit (percentage), independent of project size, type, and complexity. In addition, stressing inoperability (e.g., a loss in function) will likely lead to more action on the part of decision makers, since behavioral economics (Bolton and Ockenfels, 2012) states that people tend to over-react to losses and under-react to gains.

For the phase-based system of project delivery, the inoperability-based resilience metric refers to the tendency towards inoperability which provides an insight into how a loss of function in one phase (e.g., inoperability) can cause a change in functionality for other phases due to interdependencies that exist between project phases. Given the difficulties or delays in collecting actual project data for deterministic impact analysis, assessing the tendency toward inoperability allows for the proactive detection and response to potential interoperability based on a known inoperable state caused by disruptive events. In other words, the tendency towards inoperability indicates a joint effect of the likelihood of the inoperable state and the possible degree of inoperability in terms of unfulfilled system outcomes, as suggested by Haimes and Jiang (2001). For resilience evaluation, this research focuses on solving the tendency toward inoperability for project delivery, based on the interdependent

relationships between project phases and the realized impact on the related outcomes of the phases.

Consider the example (see Figure 5.3) where a disruptive scenario for a water treatment plant expansion project halts the design at 40% complete due to a disruptive event such as unexpected utility encounter. In this situation, the design phase becomes 60% inoperable since 60% of the design deliverables have not been completed as planned. The completed portion (40% of the design deliverables) indicates the effect of resistance which can result from preventative measures like investigating existing site conditions that allow for the completion of the partial design deliverables. If the design phase continues with no recovery measures to address the unexpected utility encounter, the design phase will still likely end up with an inoperable state in terms of a defective design (because incorrect utility assumptions were used) and corresponding cost overruns (to address the defective designs). In this case, there would be a high tendency toward inoperability for this phase, since the measure of inoperability is negatively correlated with the amount of work that has been adequately completed. If "recovery" measures are performed in the design phase (e.g., the engineers work with the utility companies and adjust the project scope to accommodate the existing conditions), the design work would then resume correctly and could possibly fulfill much of the missing design. If, for example, the recovery measures allow an additional 45% of the originally unfulfilled design deliverables to be completed, then the tendency toward inoperability would decrease due to these recovery measures. In this situation, the project may still move forward to the construction phase with the design phase still having 15% of the intended design deliverables unfulfilled due to scope changes or budgetary constraints.

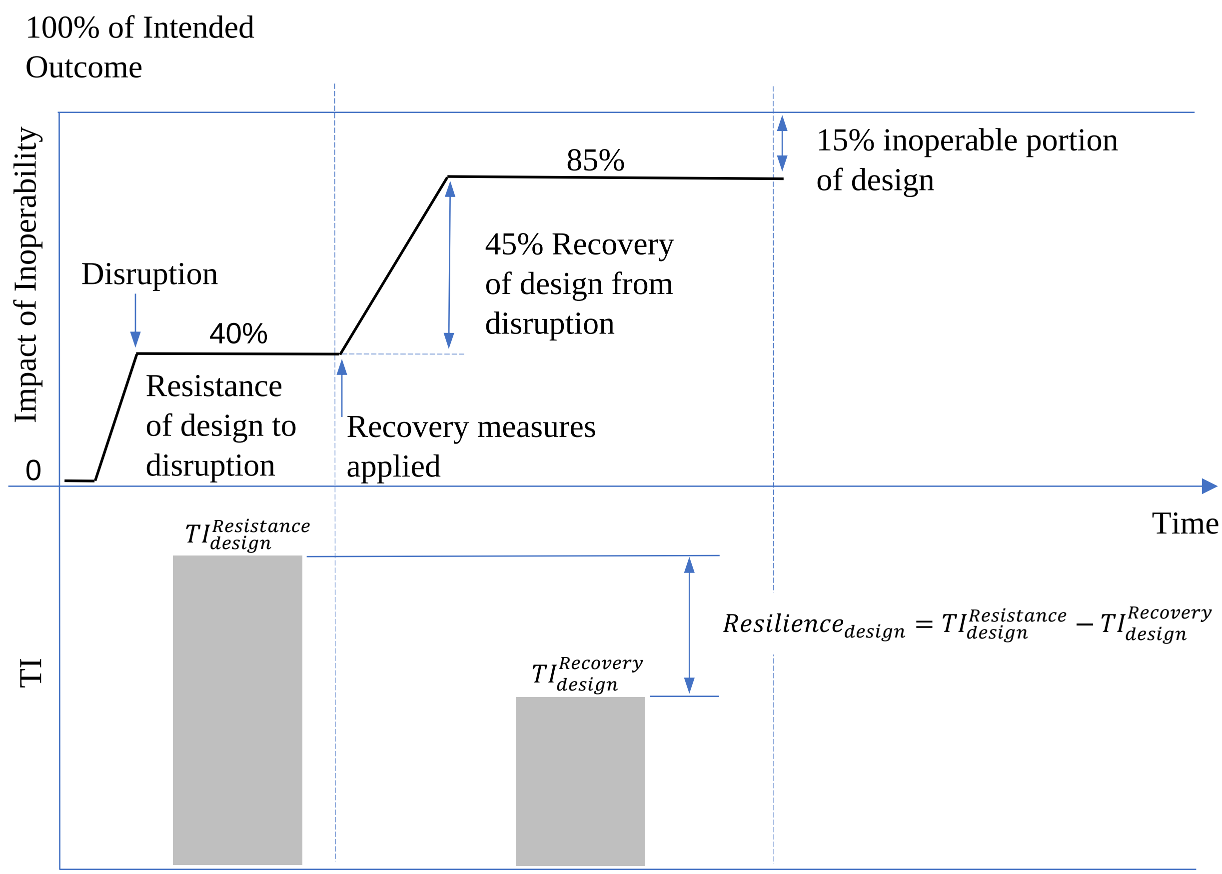

Fig. 5.3 Tendency toward inoperability (TI) for project delivery resilience (design phase)

Note that in this research inoperability could consist of either unfulfilled deliverables or costs in excess of the intended budget. The degraded outcomes from the design phase could potentially affect the outcomes of the construction phase due to the interdependency between the two phases. For instance, the construction phase is more likely to generate inoperable outcomes if the drawings and specifications from the precedent design phase are defective. Accordingly, the tendency toward inoperability would propagate from the design to construction phases reflecting the effect of the any resistance and recovery measures applied in the design phase.

5.5.2 Tendency toward Inoperability as A Resilience Metric

In this research, the phase-specific resilience for project delivery is measured by the new metric Tendency toward Inoperability (TI). Unlike existing methods that measure resilience as a ratio of actual and intended system outputs, resilience is considered to be the difference between the TI metric at the resistance stage and the recovery stage, as shown in Equation 5.1. The consideration for having the TI difference instead of a fractional value is that initial TI values can be zero (i.e., there are no disruptions to a project), therefore cannot be the denominator in the fractional format. Based on actual phase performance gaps, the TI difference captures the degree of the recovery, which reflects an impact-driven resilience approach adopted by existing resilience measures in the context of economic systems and transportation system operations (the variety of system performance drop before and after restoration) (Rose, 2007, Cox et al., 2011; Hosseini et al., 2016).

$$Resilience_{phase} = TI_{phase}^{Resistance} - TI_{phase}^{Recovery} \tag{5.1}$$

Where,

$Resilience_{phase}$ refers to the resilience status for a project phase.

$TI_{phase}^{Resistance}$ is the tendency toward inoperability that results following disruptive events despite resistance measures engaged upfront.

$TI_{phase}^{Recovery}$ is the tendency toward inoperability that still exists despite recovery measures.

An assumption behind Equation 5.1 is that resilience measures reduce but cannot eliminate the inoperability caused by disruptive events. The resilience, in this case, suggests a

decrease in the TI metric as the joint effect of both the tendency and degree of the restoration of the intended phase outputs. The gain in resilience also reveals an equilibrium status for the disrupted phase that is achieved by the end of recovery and enables the project to move forward.

5.5.3 Inoperability Input-Output Models

To calculate the TI metric, the author proposed a quantitative method based on the existing Inoperability Input-Output Model (IIM) and its extension, Dynamic Inoperability Input-Output Model (DIIM) developed by Haimes and his fellows (Haimes and Jiang, 2001; Santos, 2006; Haimes et al., 2005). IIM and DIIM were developed for analyzing the impact propagation of natural or man-made perturbations on interrelated infrastructure system sectors with the metric of inoperability, which refers to the level of a system's dysfunction, as a percentage of the system's intended functionality (Haimes and Jiang, 2001). The inoperability propagation is driven by the interdependencies of the system components, the core of IIM, which can be derived from input-output relationships in terms of economic and logical interdependencies (Haimes and Jiang, 2001; Haimes et al, 2005; Santos 2006; Lian and Haimes, 2006). The original assumptions for IIM focus on the system interdependencies from the economic perspective by assuming the input-output relationships among the system components are deterministic, linear and can reach an equilibrium state (Haimes et al, 2005; Santos 2006). The standard formulations of IIM and DIIM are shown in Equations 5.2 and 5.3 as follows.

$$q = (I - A)^{-1} c^{*} \tag{5.2}$$

$$q(t) = e^{-K(I-A)t} q(0) \tag{5.3}$$

Where,

- q refers to the inoperability vector (matrix), $q \in [0, 1]$, representing the degraded outputs as opposed to the intended outputs for disrupted system components.
- A is the interdependence matrix indicating how much inoperability of the column sectors contributes to that of the row sectors.
- c^* is the perturbation vector, in a percentage value indicating the output loss as opposed to the intended output of system components.
- I represents the identity matrix.
- $q(t)$ refers to the dynamic inoperability vector (matrix) $\in [0, 1]$ and is time dependent.
- K is the coefficient matrix solely with diagonal elements $Ki \in [0, 1]$ and $i \in 1, 2, 3 \ldots n$, the greater Ki value comes with the faster speed of recovery.
- The vector, $q\ (0)$ is a "transitional" inoperability at the moment of $(t) = 0$, the equilibrium of the inoperable state before any recovery actions begin.

In the case of disruptions, IIM via Equation 5.2 presents a linear balance via the inoperability (q) between the supply and demand sides of the interrelated system components and solves the static inoperability that results from perturbations (c^*), despite the inherent resistance capabilities of the interrelated system components. DIIM in Equation 5.3 captures a dynamic equilibrium that is achieved by the end of the recovery process following disruptive events. This equilibrium shows the effect of recovery actions that end up with a reduced degree of inoperability. Detailed justifications regarding the linearization assumption and the

derivation of the equations above can be found in the literature (Haimes and Jiang, 2001; Lian and Haimes, 2006).

5.6 Interdependencies Among Project Delivery Processes

5.6.1 Construct of Interdependencies for Project Delivery

The development of the interdependence matrix A is the key for the IIM approach (Haimes and Jiang, 2001). The IIM applications for infrastructure sectors define the dependence among different sectors as economic input-output relationships, based on the database published by the Bureau of Economic Analysis (BEA). For instance, two infrastructure sectors are related to each other in terms of how many units ($ amount) of sector A's commodity are required as inputs to produce one unit of sector B's commodity, and vice versa. Network theories and analysis method are often used for infrastructure systems like highway and utility lines that form networks due to physical interconnections among the system components. The interdependencies among the physical networks can be examined from the networks' topological features or the system dynamic perspective in responding to disruptive impact (Ouyang, 2014).

Unlike the economic and network constructs, inherent interdependencies for project delivery processes stem from prescribed organizational routines when considering a project as a temporary organization of multiple project parties. Such organizational routines form the input-output relationships between the routines at project and task level (Pentland et al., 2016). In addition to the sequencing logic, these input-output relationships can determine the level of exposure to risks for different project phases along with corresponding project parties. At the

project level, the completion of one project phase's outcome is tied to that of other project phases by the interrelationships regarding how activities performed at earlier stages affect those performed at later stages in either cascading or interactive manner (Hui et al., 2008). For instance, drawings and specifications (outputs for the design phase) can be developed by architects and engineers alone then subsequently adopted by contractors (e.g., D-B-B project delivery), or the collaborative efforts of design and construction professionals (e.g., alternative PDMs like D-B and CM/GC).

The resilience measurement from the system perspective is still in its early stage, which is not because of difficulties in contextualizing the systems but due to a lack of specific guidance and evaluation about how the variables interact in the system (i.e., level of interdependencies) (Linkvo and Trump, 2019). For the phase-based project delivery system, such organizational interdependencies are apparent when a change in the state of one system element could induce changes in the state of another system element (Giachetti, 2006). The change in the system state means the inoperability of project phases as opposed to the intended outcomes. The project delivery interdependencies are applied to the interdependence matrix A for the IIM construct with the assumption that inoperability of one project phase is likely to degrade the performance of other phases if these project phases are interdependent. With the prior example, an incomplete set of construction documentation (outputs) produced from the design phase could lead to defective work put-in-place (outputs) for the succeeding construction phase in the case of D-B-B project delivery. For the IIM construct, the interdependence matrix A for the project delivery scenario represents the strength of the interdependencies in terms of how the inoperability of one project phase caused by disruptive events could lead to a potential inoperability state for other project phases.

This research classifies the interdependencies among project phases based on the interdependence construct researched in the context of patterns of workflows and processes that exist among units in organizations (Kelley and Thibaut, 1978; Victor and Blackbur, 1987). Such input-output relationships from one unit to the other can be described as three requirements for actions: requirements from one's own actions, requirements for actions of other units, and requirements for joint actions of multi-units, as shown in Table 5.1. For D-B-B project delivery, the interdependency type for planning phases is considered as an RC (reflective control) type because the planning outcomes like project scoping and budget are generated solely by owners without inputs from other phases (before design phase begins). The outcomes of succeeding procurement phases are classified as BC (behavior control) type of interdependency with the planning phases because the development of a request for proposal (RFP) for designers and contractors (procurement outcome) is contingent upon the project scoping and budget (planning outcome). And the different outcomes from one project phase could have different types of interdependencies with those of other phases.

Table 5.1 Type of Interdependencies

Interdependency Type	**Remark**	**Degree of Interdependency**
Reflective control (RC)	Phase A has "RC" when phase A's outputs are determined by its own actions.	0
Behavior control (BC)	Phase A has "BC" over phase B when they are contingent upon each other's actions to generate respective outputs.	1
Fate control (FC)	Phase A has "FC" over phase B when phase B's outputs are contingent upon phase A's actions.	2

5.6.2 Interdependence Matrix for Infrastructure Project Delivery Processes

Modeling the deterministic strength of organizational interdependencies could be difficult due to workflow and coordination attributes like urgency, frequency, and delay (Giachetti, 2006). This research simplifies the complex interdependency scenarios by focusing on general patterns and levels of interdependencies during project delivery. The ordinal values of "0" for reflective control (the least interdependent), "1" for behavior control (somewhat interdependent), and "2" for fate control (the most interdependent) are assigned to measure the magnitude for each type of interdependency. The numerical scale with the equal increment of 1 provides an analytical measure that illustrates the increasing strength of the interdependencies, as several researchers recommended when measuring the strength of organizational interdependencies (Victor and Blackburn, 1987; Chinowsky et al., 2010; Christensen and Wirthlin, 2011). The proposed interdependency scale is considered sufficient for the development of the interdependence matrix A in the IIM construct. The scale provides a quantitative metric to distinguish different levels of input-output relationships that induce the system-level propagation of inoperability among the related project phases, which is used to formulate the interdependence matrix for project delivery. The interdependency strength from "0" to "2" also suggests an increasing likelihood of the induced inoperability when a project phase fails to achieve its intended outcomes. If the design phase in D-B-B project delivery is inoperable (defective drawings), the construction phase is more likely to become inoperable by completely relying on the design outcomes to perform the work (FC type interdependency with the strength level of "2"). The construction phase could be less likely to be inoperable if the design and construction professionals co-develop the construction documentation so that

design defects can be detected and fixed early (BC type interdependency with the strength level of "1") in the case of D-B project delivery. In general, this scale acts as a weighting scheme for the measurement of inoperability propagation in the IIM construct based on actual inoperable states of project phases. One project phase which is not directly affected by disruptive events tends to be subject to an inoperable state due to the strong interdependencies with the phases directly hit by the disruptions. The degree of the inoperability propagation is positively related to the weighting level of the interdependencies involved.

In this research, the interdependence matrix for infrastructure project delivery is defined as a 5 x 5 square matrix representing the five typical project phases published by the Construction Industry Institute (CII), including 1) Front End Planning (FEP); 2) Design and Engineering; 3) Procurement; 4) Construction; 5) Commissioning (CII, 2019). There are interdependencies between project phase A and phase B if phase A's outputs are required as the inputs for phase B. The author identified the interdependencies amongst different project phases by conceptualizing typical and direct input-output relationships for D-B-B and D-B project delivery methods, based on input-output measures specific for infrastructure projects, a part of CII's "10-10" performance assessment (CII, 2019). Tables 5.2 and 5.3 show the identified input-output items along with the type and degree of the interdependencies (according to Table 5.1). For simplicity, these phase-specific interdependencies (input-output items) are assumed to remain static under normal (nondisruptive) conditions of the D-B-B and D-B project delivery. One project phase is tied to other phases by the interdependencies specific to the related input-output items. Given the overall degree of interdependencies there is a cumulative effect based on the frequency of interdependent actions (Wybo and Goodhue, 1995). In this research, the author estimated the overall level of interdependencies one phase

contributes to the other phase as the sum of the interdependency level associated with each input-output item. This assumes that the same type of interrelationships has similar patterns of communication and coordination actions.

As shown in Tables 5.2 and 5.3, D-B shows stronger interdependencies among project phases than D-B-B in several cases. Compared to the D-B-B scenario, the enhanced interdependencies for D-B result from extra output items: risk identification/management plan and constructability plan, the required for Procurement, Design Engineering, and Construction phases. For instance, there is a "BC" type of interdependency between the Design Engineering and Construction phases to generate the respective output of the risk identification/management plan. Similarly, another "BC" interdependency is identified between these two phases concerning the outputs of the construction documentation (by Design Engineering) and constructability plan (by Construction). The author identified such interrelationships based on a typical situation for a D-B project that design and construction professionals under a single entity of design-builders are allowed to work together to generate the output items as mentioned above.

Table 5.2 Input-Output Interdependencies for D-B-B Project Delivery

Project Phase	Phase Outputs	Outputs (Inputs) Required from Related Phases	Related Phases	Type/Degree of Interdependency	
Front End Planning	Needs assessment (lifecycle cost analysis, stakeholder involvement)			RC	0
	Land/Right of Way acquisition				
	Project scoping				
	Budget/schedule development				
Procurement	RFP for Architect/Engineer (A/E)/contractor/vendor	Needs assessment (lifecycle cost analysis, stakeholder involvement)	Front End Planning	FC	2
	Proposals (bid) prep/review/award	Land/Right of Way acquisition		FC	2
	Contracts for A/E/contractor/vendor	Project scoping		FC	2
		Budget development		FC	2
Design/ Engineering	Existing site/facility condition assessment	Contracts for A/E/contractor/vendor	Procurement	FC	2
	Compliance requirement & permitting	Project scoping	Front End Planning	FC	2
	Environmental impact assessments				
	A/E's preliminary cost estimate	Budget/schedule development		BC	1

	Construction documentation (drawing & specification)				
	Change management (review/approval)	Change management (request/review)	Construction	BC	1
	Quality control (submittals, RFI)	Quality control (submittals, RFI)		BC	1
Construction	Project control/progress monitoring (time, cost estimate, safety, cashflow)	Contracts for A/E/contractor/vendor	Procurement	FC	2
	Change management (request/review)	Construction documentation (drawing & specification)	Design/Engineering	FC	2
	Quality control (submittals, RFI)	Change management (review/approval)		BC	1
	Punch list upon project completion	Quality control (submittals, RFI)		BC	1
Commissioning	Functional testing and deficiencies correction	Punch list upon project completion	Construction	FC	2
	Warranties/operational manuals	Quality control (submittals, RFI)		BC	1
	As-built (record) drawing & specification	Construction documentation (drawing & specification)	Design/Engineering	FC	2
		Quality control (submittals, RFI)		BC	1

Table 5.3 Input-Output Interdependencies for D-B Project Delivery

Project Phase	Phase Outputs	Outputs (Inputs) Required from Related Phases	Related Phases	Type/Degree of Interdependency	
Front End Planning	Needs assessment (lifecycle cost analysis, stakeholder involvement)			RC	0
	Land/Right of Way acquisition				
	Project scoping				
	Budget/schedule development				
Procurement	RFP for Architect/Engineer (A/E)/contractor/vendor	Needs assessment (lifecycle cost analysis, stakeholder involvement)	Front End Planning	FC	2
	Proposals (bid) prep/review/award	Land/Right of Way acquisition		FC	2
	Contracts for A/E/contractor/vendor	Project scoping		FC	2
		Budget/schedule development		FC	2
	Risk identification/management plan	Risk identification/management plan	Design/Engineering	BC	1
		Risk identification/management plan	Construction	BC	1
Design/ Engineering	Existing site/facility condition assessment	Contracts for A/E/contractor/vendor	Procurement	FC	2
	Compliance requirement & permitting	Project scoping	Front End Planning	FC	2

	Environmental impact assessments				
	A/E's preliminary cost estimate	Budget development		BC	1
	Construction documentation (drawing & specification)				
	Change management (review/approval)	Change management (request/review)	Construction	BC	1
	Quality control (submittals, RFI)	Quality control (submittals, RFI)		BC	1
	Risk identification/management plan	Risk identification/management plan	Construction	BC	1
Construction	Project control/progress monitoring (time, cost estimate, safety, cashflow)	Contracts for A/E/contractor/vendor	Procurement	FC	2
	Change management (request/review)	Construction documentation (drawing & specification)	Design/Engineering	BC	1
	Quality control (submittals, RFI)	Change management (review/approval)		BC	1
	Constructability plan	Construction documentation (drawing & specification)		BC	1
	Risk identification/management plan	Risk identification/management plan		BC	1
	Punch list upon project completion	Quality control (submittals, RFI)		BC	1

Commissioning	Functional testing and deficiencies correction	Punch list upon project completion	Construction	FC	2
	Warranties/operational manuals	Quality control (submittals, RFI)		BC	1
	As-built (record) drawing & specification	Construction documentation (drawing & specification)	Design/Engineering	FC	2
		Quality control (submittals, RFI)		BC	1

The author converted the input-output interdependencies mentioned above (Tables 5.2 and 5.3) to interdependence matrices for quantitative demonstrations in Tables 5.4 and 5.5, where each row represents one project phase, and the columns consist of the degree of interdependency contributed from other project phases. For instance, the D-B-B case shows that the overall level of interdependency between Procurement and Front End Planning can be estimated as 4 (the number of the input-output items, such as “needs assessment” and “land/right of way acquisition” in the row of Procurement multiplied by 2 (FC type of interdependency level for each item), which is equal to 8.

To obtain comparable results of the TI metric in percentage values for the IIM construct, the author normalized the degree of interdependency associated with the five project phases (represented as rows in the matrix). The normalization was done by dividing each interdependency scale value by the sum of all the interdependency values involved in respective project phases (in the same rows), as shown in Tables 5.6 and 5.7. When looking into the row of the Procurement phase for D-B-B (Table 5.6), there is only one interdependent relationship between Procurement and Front End Planning, which can be normalized as 1 which equals the aforementioned interdependency level between Procurement and Front End Planning (i.e., “8”) divided by the corresponding row-sum of the interdependencies (i.e., “8”). In contrast with D-B-B, the Procurement phase for D-B involves increased interdependencies with Design Engineering (i.e., “1”) and Construction (i.e., “1”), in addition to Front End Planning (i.e., “8”). Thus, the interdependency level between Procurement and those three phases can be normalized as 0.8, 0.1, and 0.1. This change, the distributed interdependency, means that Procurement for D-B undergoes an increased level of risk exposure associated with

the inoperability of Design Engineering and Construction even though the relative interdependency level with Front End Planning declines.

Table 5.4 Baseline Interdependence Matrix for D-B-B Project Delivery

	Front End Planning	Procurement	Design Engineering	Construction	Commissioning
Front End Planning	0	0	0	0	0
Procurement	8	0	0	0	0
Design Engineering	3	2	0	2	0
Construction	0	2	4	0	0
Commissioning	0	0	3	3	0

Table 5.5 Baseline Interdependence Matrix for D-B Project Delivery

	Front End Planning	Procurement	Design Engineering	Construction	Commissioning
Front End Planning	0	0	0	0	0
Procurement	8	0	1	1	0
Design Engineering	3	2	0	3	0
Construction	0	2	5	0	0

Commissioning	0	0	3	3	0

Table 5.6 Normalized Interdependence Matrix for D-B-B Project Delivery

	Front End Planning	Procurement	Design Engineering	Construction	Commissioning
Front End Planning	0	0	0	0	0
Procurement	1	0	0	0	0
Design Engineering	0.43	0.29	0	0.29	0
Construction	0	0.33	0.67	0	0
Commissioning	0	0	0.50	0.50	0

Table 5.7 Normalized Interdependence Matrix for D-B Project Delivery

	Front End Planning	Procurement	Design Engineering	Construction	Commissioning
Front End Planning	0	0	0	0	0
Procurement	0.80	0	0.10	0.10	0
Design Engineering	0.38	0.25	0	0.38	0
Construction	0	0.29	0.71	0	0
Commissioning	0	0	0.50	0.50	0

The normalized interdependence matrices, $A_{Org.}$ (Tables 5.6 and 5.7) illustrate the weightings of the input-output interdependencies across the five phases. For the IIM construct, the interdependency level is used to evaluate the degree of impact propagation, which is how the disruptive impact on one (inoperable) project phase gets distributed to other related phases even if those phases are not affected directly by the disruption. The inoperability of one project phase (shown in the rows) could completely or partially result from the interdependencies with the project phases (shown in the columns), based on a cumulative result of different input-output items and the relevant degree of interdependencies. In the case of D-B-B, for example, several implications can be drawn from the normalized interdependence matrix in Table 5.6. All 0 values in the row of Front End Planning mean that this phase can generate outputs independent of the inputs from other project phases. For Procurement phase, the normalized interdependency value of 1 associated with Front End Planning phase suggests that the output of the Procurement phase is contingent on that of Front End Planning. In other words, the failure of project scoping and budget development (outputs from Front End Planning) can lead to 100% inoperability for RFP(s) and contracts (outputs from Procurement). The non-zero values in the normalized independence matrix indicate the contribution towards the inoperability of one phase based on the interdependency with other phases (Haimes and Jiang, 2001). Thus, the failure of the Procurement and Design Engineering phases could lead to 33% and 67% inoperability for the Construction phase.

It is worth noting that the interdependence matrices only show a baseline level of interdependency under the normal (e.g., no disruption) delivery scenario. The magnitude of the interdependencies tends to increase for project phases involved in recovery activities

against a disruptive event. In the case of restoring unfulfilled design deliverables from the disruption of scope changes, engineers and owners would work together and modify the drawings, project scope, and budget to ensure that the scope changes are reflected in both the design and planning phase outcomes. During this process, the interdependencies between the two phases become more intense compared to the non-disruptive state due to increased communications, such as information review, revision, and approval. Accordingly, one adjustment to the original DIIM equation is that the author proposed an alterable normalized interdependence matrix, $A_{IOrg.}$ to capture increased interdependencies caused by the recovery activities. The original IIM and DIIM applications assume that the interdependencies among infrastructure sectors remain economically constant (Santos, 2006). The coordinating activities for the pre-existing organizational interdependencies involved in the recovery will determine the enhanced strength of such organizational interdependencies in terms of the increased coordination load (Nunez et al., 2009). This adjustment of interdependency strength is consistent with the "multiplier effect" of the interdependence matrix in IIM and DIIM constructs, which means enhanced interdependency strength could contribute to higher tendency of inoperability for the related project phases if the enhanced coordinating activities fail to restore the inoperable phase outcomes (Haimes and Jiang, 2001).

To capture this enhanced interdependence for the recovery scenario, a coefficient can be applied to the pre-existing interdependency strength in the baseline interdependence matrices (Tables 5.4 and 5.5). Still, use the D-B-B case as the example and suppose the Design Engineering phase is interrupted by an owner-driven change that requires recovery by reworking the existing project scope and budget (the outputs for the Front End Planning phase). The recovery causes an enhanced interdependency between Design Engineering and Front End

Planning, which is assumed to be twice that of the pre-existing interdependency value of 3 (Table 5.4). In this case, an enhancement coefficient of 2 is applied to the baseline matrix (Table 5.4) by multiplying the existing interdependency value of 3 by 2. The updated matrix is re-normalized to reflect the increased strength of interdependency between the two phases as follows:

$$Enhanced\ Normalized\ Interdependence\ Matrix\ (A_{IOrg.}) = \begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.6 & 0.2 & 0 & 0.2 & 0 \\ 0 & 0.33 & 0.67 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 \end{matrix}$$

5.7 Measurement of Project Delivery Resilience by Inoperability Input-Output Approach

5.7.1 Measurement of Resistance & Recovery Effect Using IIM & DIIM-Based Approach

In response to disruptions, the resistance aspect of resilience for project delivery comes from proactive and preventative measures (e.g., pre-planning and in-process monitoring) which can alleviate but not eliminate the resulting inoperability for the phase-specific outcomes. The result of the resistance measures indicates a level of equilibrium in the related phase outcomes before any recovery process starts. Once the recovery measures begin, the inoperable phase outcomes remaining at the conclusion of the resistance measures begin to recover until another equilibrium state is reached. Due to possible time, budget, and regulatory constraints, this equilibrium state may be an incomplete recovery to a level less than the originally intended outcomes. In this scenario, the related project phases would proceed with a lesser degree of inoperability. Such equilibrium of the phase states resembles the scenario of IIM and DIIM applications that can be formulated to solve the effect of the resistance and

recovery measures in terms of inoperability tendency, as shown in Equations 5.4 and 5.5. All the notations in Equations 5.4 and 5.5 remain similar in meaning as the original IIM and DIIM Equations 5.2 and 5.3.

$$q = (I - A_{Org.})^{-1} c^{*} \tag{5.4}$$

$$q(t) = e^{-K(I - A_{IOrg.})t} q(0) \tag{5.5}$$

The key notations are interpreted in the context of project delivery as follows: 1) Normalized *Interdependence matrices* $A_{Org.}$ and $A_{IOrg.}$ reflect the strength of organizational input-output relationships amongst the project phases; 2) *Impact of disruption, c***, is the phase-specific perturbation vector which refers to the gap between the actual and intended phase outcomes, and can be estimated based on the percent completion related to cost, time, and quantity of work metrics; 3) *Coefficient matrix, K*, is a diagonal matrix in which the non-zero element values represent the event-specific speed of recovery for the restoring project phases (Lian and Haimes, 2006). For a disrupted project phase, *i*, *Ki* = 0.2 indicates that 20% of the corresponding inoperability is reduced within one unit of time (hours, days, or weeks); 4) *Recovery time, t*, is the time duration taken or available to recover. The available recovery time is often limited by the schedule constraint if the affected tasks are on the critical path. It can be observed from Equation 5.5 that if *t* goes to infinite, inoperability *q (t)* tends to level off toward zero, which means the inoperable project state should diminish toward the intended outcomes; and 5) *Inoperability transition, q (0)*, is a transitional inoperable state of *t* = 0, for the phase states to shift from resistance to recovery which represent a) the “worst-case” scenario for the

disrupted phase states, albeit the implementation of proactive and preventative measures; and b) the start of the following recovery process. Thus, *q (0)* equals to the result for the inoperability tendency solved from the resistance effect via Equation 5.4.

The phase-specific inoperability tendency for the resistance and recovery effect can be determined using Equations 5.4 and 5.5. Then by using Equation 5.1, the one can solve the reduced magnitude of the inoperability tendency for the phase-based resilience of project delivery processes. The results in the form of a matrix show the resilience state (in percentage values) for the different project phases holistically in response to a disruptive event.

5.7.2 An Illustrative Example: Design Change During D-B-B Project Delivery for A Wastewater Treatment Project

An example of the proposed resilience measurement approach is presented using a wastewater treatment facility expansion project with a traditional D-B-B delivery method. The project was designed to increase the discharge capacity from 4542 cubic meters per day (cmd) to 5148 cmd. For a D-B-B project, the design is supposed to be fully completed before the project moves forward to the construction phase. However, a disruptive event hit the design phase as a mismatch of the drawings and actual site conditions was identified when the construction phase progressed to the related work. This issue made the design phase inoperable as the completed design was equivalent to 80% of the expected design deliverables. In response to the disruption, the engineers were forced to revisit the capacity design for the groundwater disposal system. The engineers also worked with the contractors to update the drawings and specifications related to the design change. The rework (recovery activities) allowed the engineers to complete the remaining 20% design scope but caused a budget overrun for the construction phase during which five change orders were issued with a value of $300,000.

The rest of this section presents how the proposed inoperability-based approach is used to analyze the impact of the design change on the ability of the design and construction phases to perform the intended work. Since the example project is a D-B-B project, the author assumed that it was delivered in the five phases identified in Table 5.2 with the same input-output relationships as the normalized interdependence matrix in Table 5.4.

Resistance effect

The resistance scenario is that the engineers performed regular prep work like investigating the existing conditions of the wastewater facilities to reduce potential risks of unknown conditions. However, the prep work did not avoid the design issue, which caused 20% inoperability in the outcomes for the Design Engineering phase (e.g., the combined workload of the site visit, load calculation, and drawing and specification development). Table 5.4 is converted and used as the interdependence matrix $A_{Org.}$, along with the perturbation vector c* in five project phases, as shown below.

$$A_{Org.} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.43 & 0.29 & 0 & 0.29 & 0 \\ 0 & 0.33 & 0.67 & 0 & 0 \\ 0 & 0 & 0.50 & 0.50 & 0 \end{bmatrix} \qquad c^* = \begin{bmatrix} 0 \\ 0 \\ 0.2 \\ 0 \\ 0 \end{bmatrix}$$

With Equation 5.4, the inoperability tendency vector for the resistance effect in response to the design change issue can be solved as:

$$q = \left(\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.43 & 0.29 & 0 & 0.29 & 0 \\ 0 & 0.33 & 0.67 & 0 & 0 \\ 0 & 0 & 0.50 & 0.50 & 0 \end{bmatrix} \right)^{-1} \times \begin{bmatrix} 0 \\ 0 \\ 0.2 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0.25 \\ 0.17 \\ 0.21 \end{bmatrix}$$

The outcome for the vector q represents the TI metric. This vector shows that the design change (disruption) will result in a tendency toward inoperability for the Construction and Commissioning phases of 17% and 21% respectively, if no recovery measures are taken to fix the inoperable portion of the design outcome. This effect of inoperability propagation is due to the organizational interdependencies among the related phases, even if the design change issue did not directly affect those two phases. Also, the TI metric for the Design Engineering phase is estimated to increase to 25% exceeding the actual impact of 20% on the design outcomes because of the interdependencies with the other two phases. In this case, the 25% of the TI represents a leading indicator for the realized impact of 20%, merely suggesting an increased tendency that the Design Engineering fails to achieve the intended design outcomes.

Recovery effect

For the recovery scenario, the engineers reworked the drawings and corrected the 20% portion of the problematic design. To apply the proposed DIIM-based approach in Equation 5.5, the transitional inoperability $q\ (0)$ represents the phase-specific inoperability tendency before the recovery, and reads as the outcome of the resistance effect.

$$q(0) = \begin{bmatrix} 0 \\ 0 \\ 0.25 \\ 0.17 \\ 0.21 \end{bmatrix}$$

Since the design change involved extra work with the contractors such as change orders, quality control, and record drawings, the coordination efforts by the Design Engineering and Construction phases increase and are assumed to be doubled. For the case of this recovery process, the author doubled and normalize the interdependency strength associated with these two phases and obtain the enhanced interdependence matrix as follows:

$$A_{IOrg.} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0.33 & 0.22 & 0 & 0.44 & 0 \\ 0 & 0.20 & 0.80 & 0 & 0 \\ 0 & 0 & 0.50 & 0.50 & 0 \end{bmatrix}$$

For the example project, the recovery rate and timing should be specific to the Design Engineering phase and the design change issue. Since the data regarding how long it took to restore the inoperable (20%) design outcome is unavailable, the author assumed that the recovery process was tracked in weeks (the unit of timing for *t*) and the recovery time was one month (t = 4 weeks). The recovery rate is assigned to the diagonal matrix K in which the only element value for the Design Engineering phase (K_{design}) equals 5% per week (20% unfulfilled outcomes divided by four weeks). By the end of the recovery, the inoperability tendency vector (the TI metric) for the recovery effect can be solved using Equation 5.5 as follows:

$$q(4) = e^{-K_{0.05}(I - A_{IOrg.})4} q(0) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0.06 & 0.04 & 0.82 & 0.08 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ 0.25 \\ 0.17 \\ 0.21 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0.22 \\ 0.17 \\ 0.21 \end{bmatrix}$$

After the recovery efforts, the value of the TI metric for the Design Engineering phase drops from 0.25 to 0.22, which indicates the effect of the recovery measures to achieve the intended design outcomes. The value of the TI metric for the two related phases remains unchanged since no recovery efforts were associated with these phases. Based on Equation 5.1, the difference in the value of the TI metric between the resistance and recovery efforts shows the phase-related resilience for the example D-B-B project delivery as follows:

$$Resilience_{phase} = \begin{bmatrix} 0 \\ 0 \\ 0.25 \\ 0.17 \\ 0.21 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0.22 \\ 0.17 \\ 0.21 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0.03 \\ 0 \\ 0 \end{bmatrix}$$

For the Design Engineering phase, the reduced value of TI is 0.03. The limited improvement for the inoperability tendency of this phase reflects a realistic challenge for project delivery processes; namely, the TI for a disrupted project phase continues to exist and reveals the inadequacy of the original project resources, even if the actual phase outcomes bounce back. For typical recovery scenarios, it often requires additional resources to bring the disrupted project phases back to their intended state, which can be considered as the cost of resilience. In other words, the TI that remains after recovery can be explained as the inoperable ability of the project phases to achieve their intended outcomes without extra project resources.

5.8 Discussion

The outcomes for the illustrative example show that the resilience effect due to resistance and recovery is highly driven by the interdependencies among the project phases.

The contribution to the body of knowledge provided by this research is the measure of the interdependencies within project delivery processes which have been infrequently addressed in existing literature, as an indicator of complexity for large project delivery. For known disruptions, researchers and practitioners can perform an impact analysis focused on the deterministic project outcomes, such as cost and schedule deviations (El Asmar et al., 2013). The in-depth discussion about organizational interdependencies is critical in the context of project delivery resilience since interrelated project phases distribute vulnerability to each other. The input-output relationships for different project phases make the impact (inoperability) of one phase affect the ability of the interrelated phases to produce the intended outcomes, even though those phases were not disrupted directly.

The distribution of disruptive consequences also triggers a discussion about if the project delivery process benefits from such interdependent relationships from a resilience perspective. The illustrative example examines the D-B-B project delivery process with which the project phases are sequentially delivered and have less complex and frequent interdependencies than those carried by other delivery methods such as D-B, CM/GC, and Integrated Project Delivery (IPD). Given the recent trend toward collaborative relationships among project stakeholders, there could be increased integration of project resources for early detecting and preparing for potential disruptions, which could increase resistance for the project delivery process against disruptions. For inevitable disruptions, the collaborative relationship could distribute the resulting impact to all the stakeholders involved, or even slow down the recovery speed and effect. For D-B project delivery, collaborative design via Building Information Modeling (BIM) is a case in point when participating entities (owners, engineers, and contractors) could shift obligations for updating the BIM models in the case of

clash detection. This situation highlights that there exists a need to assess the recovery effect when different types and degrees of interdependencies are taken into account, which introduces a point of departure when comparing different project delivery methods for future research.

Inoperability and its tendency can be used as the basis for resilience measurement, which can then be used to facilitate decision-making in two ways. First, inoperability shows a deterministic consequence of the disruptive events on the phase-related outcomes, which provides a consistent metric for the loss evaluation for various project objectives. Secondly, given the delay to obtain data for actual losses, stochastic data like the inoperability tendency become useful for providing decision-makers with a proactive insight about the potential impact on the performance of project phases. Especially for project phases indirectly hit by disruptions, the TI metric is meaningful for decision-makers to realize and respond to the latent inoperable and recovery state, which is consistent with the resilience concept related to the ability of different project phases to withstand and bounce back from disruptions.

5.9 Conclusions

This research contributes to the body of knowledge by presenting a quantitative approach to measure resilience in the context of infrastructure project delivery. Resilience for project delivery is interpreted as the combined ability for project phases to resist and recover from disruptive events by reducing the inoperability for phase-specific outcomes. Inoperability, as a performance-driven concept, accommodates the vulnerability of the disruption-prone project delivery process. For infrastructure projects, an impact-based approach is essential to addressing resilience as the consequences of minor deviations from the intended project

outcomes could be large. This research proposes a TI metric that can be used to holistically evaluate potential performance gaps for the project delivery system. A gain in resilience is realized as the difference between the TI metric after resistance and the TI metric after recovery. To solve the TI difference, a quantitative approach is proposed based on existing inoperability input-output models. An illustrative example is presented showing how to apply the proposed approach to an example D-B-B project.

While this study lays a foundation for resilience measurement for infrastructure project delivery, there are several limitations. The organizational interdependencies for D-B-B and D-B project delivery are mapped based on conceptualized input-output relationships which may alter for particular project scenarios. Further justifications (e.g., via industry expert review) are needed to identify the universal and unique interdependencies for different project delivery scenarios. Due to the limited example project data regarding timing and rates for the recovery measures, the illustrative example for the IIM & DIIM-based approach is limited to one disruption which occurred to one phase of the project. More projects and disruptive scenarios are needed to test the approach by comparing the pattern of inoperability tendency and actual impact caused by disruptive events. For future research, the discussion about how the phase-related interdependencies could affect the inoperability distribution should be extended to other delivery methods, such as CM/GC, P3, and IPD, that have been adopted for infrastructure project delivery.

CHAPTER VI

DISCUSSIONS AND CONCLUSIONS

6.1 Introduction

The overall objective of this research is to contribute to the current state of knowledge about the concept of project delivery (PD) resilience by developing a theoretically sound and empirically valid measure of PD resilience. Several steps were taken to accomplish this task. This chapter discusses those steps by reviewing the six research questions outlined in Chapter I and summarizes the major findings. By the end of this chapter, the author highlights conclusions with a summary of the theoretical and practical implications of the research. Lastly, this chapter concludes by briefing the limitations of this study and formulating some recommendations for future research.

6.2 Discussions

As outlined in Chapter I, this research aimed to achieve four technical objectives. This section revisits each objective with respect to the steps in conceptualizing and measuring the resilience performance for infrastructure construction project delivery.

6.2.1 Defining Resilience of Infrastructure Project Delivery

The first objective was to define resilience in the context of infrastructure project delivery and how resilience can be conceptually measured related to different project aspects. The rationale for this objective was to provide the theoretical foundation for developing specific methods and tools to evaluate the PD resilience.

The author began the study with a comprehensive review of the multidisciplinary resilience definitions and conceptual attributes, as listed in Tables 2.1 and 2.2. The findings suggest that (1) there is no consensus about what resilience refers to across the board, but the different highlight on specific contexts (e.g., property of materials for structure resiliency vs. capacity of lifeline systems for disaster resiliency); (2) resilience is not a new idea, but a composite concept related to existing theories about risk, sustainability, and lean.

Based on the literature review, several comparisons of resilience and those theories were provided to advance the understanding of the resilience concept and ensure an integrated research agenda. Meanwhile, such comparisons clarify the preliminary point of depart for this research: why resilience is essential to infrastructure PD in light of existing theories about risk management and project controls. For instance, resilience is fundamentally distinct from but supplementary to risk management. The focus of resilience highlights the shift from risks to system performance variation due to the risk-induced impact. Not knowing this distinction is considered one of the major barriers for practitioners to implement resilience in parallel with the existing risk paradigm (Linkov et al., 2016, 2014, 2013).

Given the multifaced outlook of resilience, this research conceptualized the resilience of project delivery as a system capability encompassing three commonly cited resilience attributes: resistance, recovery, and adaptation. Based on the resilience definition, the author developed a resilience framework (Figure 2.4) to integrate resilience with infrastructure PD processes. Specifically, resilience is examined throughout PD processes that involve the five dimensions for infrastructure projects, including context (C), financing (F), technical (T), budget (B), and schedule (S) aspects of a project (Shane et al., 2014). The three resilience

stages, resistance, recovery, and adaptation, represent PD systems' response to disruptions in proactive/preventive and reactive/restorative modes before and after the disruptive events.

6.2.2 Qualitative Resilience Criteria for Infrastructure Project Delivery

The second objective of the research aimed to develop resilience criteria based on the conceptual resilience framework for infrastructure PD. The resultant resilience criteria involve seven primary resilience criteria with subordinate resilience factors (Tables 3.6, 3.7, and 3.8) in the context of road construction project delivery. The resilience criteria were derived from the same list of the seventeen resilience factors for three resistance stages: resistance, recovery, and adaptation.

Given the uniqueness of projects and disruptions, the proposed resilience factors highlight the "generality" of their usefulness and are considered best practices and guidelines applicable for different phases of a project. Moreover, the identified resilience criteria/factors and their significance are virtually explanatory based on the opinions of the industry experts using PCA, a factor analysis approach. The PCA results indicate that the most significant resilience criteria (and the associated resilience stage) are *Continuity of Project Alignment* (resistance), *Contingency-Oriented Planning and Design* (recovery), and *Performance-Informed and Industrialized Project Delivery* (adaptation). Another "generality" aspect of the resilience criteria is that they were not intended to address specific disruptive events to PD projects but accommodate various disruptions to project delivery, encompassing shocks (e.g., broken supply chain due to a pandemic outbreak) and slow-moving stresses (e.g., threats of sea-level rise).

6.2.3 Resilience Index for Infrastructure Project Delivery

The third objective of the research was to develop an applied resilience tool to rate the PD resilience. The PDRI was developed for each resilience stage act as a weighted sum of the ratings for the resilience factors. The key results of the PDRI constructs are the varying priorities of the same set of resilience factors when they are evaluated in the context of different resilience stages. To that end, the ANP networks that encompass the resilience factors and priority-based interrelationships were established to determine the factors' weights. The ANP results show that the most significant (i.e., highest weight) resilience factors for resistance, recovery, and adaptation are F13 – *Consistent and accountable decision-making from public agencies*; F17 – *Established claim and emergency response plans and measures*; F11 – *Virtual design and construction*. By applying the resilience indices to different PDMs, the results suggest that D-B outperforms CM/GC and traditional D-B-B based on industry experts' empirical ratings of those three PDMs.

6.2.4 Inoperability-Based Metric for PD Resilience Measurement

The fourth objective of this research was to propose a quantitative resilience metric and approach that can be associated with some universal performance measure that can be used to evaluate the completeness of different phases of a project. Tendency toward Inoperability (TI) was proposed as the resilience metric for two reasons. Frist, inoperability embraces the core idea of resilience by acknowledging the vulnerability of PD processes, say a project phase cannot be completed as intended due to disruptions. Second, inoperability represents a performance-driven measure to estimate the potential impact of disruptive events on the project phases' intended outcome.

The gain in resilience is measured as a decreased TI for affected project phases between resistance and recovery stages using the IIM & DIIM-based model. In addition to the TI metric, another critical finding is the interdependence matrices for different PDMs, which identify and measure the organizational and operational input-output relationships among project phases on a quantitative scale (i.e., RC, BC, and FC) to estimate the strength of interdependencies in the ascending order. Then, the illustrative example of the design change issue to a D-B-B project showed that we could successfully measure resilience as anticipated using the proposed TI metric and its measurement approach.

6.3 Conclusions

Resilience is essential for civil infrastructure systems not only to the system reliability for hazard management but also to the processes that plan, design, and construct the structures and facilities. This research re-defined resilience as a capability of the project phase-based PD systems to accommodate the impact of various disruptions to PD processes so that the intended project results can be achieved. The advantages of formulating resilience as a system approach in different resilience attributes are threefold: (1) synthesizing the multi-elements of the resilience concept into the same system boundary; (2) making the resilience attributes pragmatically relevant to the system performance measures (e.g., resistance and recovery as the different stages of the system response to disruptive events); (3) establishing a resilience measurement structure consisting of system performance measures that can be inversely associated with the different resilience stages.

Resilience for PD processes is measurable. The first part of the findings in this regard is the resilience factors applicable through the PD processes to establish the resilience criteria. Given the qualitative nature of the factors' contents, factoring is considered a useful technique that can create theoretical connections of the best practices in PD (the case of this research) with the abstract ideas of resilience (i.e., resistance, recovery, and adaptation). With the resilience factors, the subsequent step created categories/clusters of these factors (i.e., resilience criteria with subordinate factors) with an assumption that the identified resilience factors are interrelated in terms of their effectiveness of leading to the resilience attributes. Also, the practical implication for categorizing the resilience factors is that evaluators can obtain a well-organized perspective when reviewing this relatively lengthy list of those factors. Another reason for the factor categorization is that the factors under the same categories often represent the common themes that are difficult to observe when being evaluated individually.

Owing to the multifaceted nature of the PD resilience, a list of resilience criteria and subordinate factors alone does not easily support the adoption of those criteria for resilience assessment. The resilience criteria as a construct of the resilience factors were further combined into the respective resilience indices associated with resistance, recovery, and adaptation. With PDRI, resilience for PD processes can be measured consistently. PDRI was applied to three commonly used PDMs for infrastructure projects: D-B-B, CM/GC, and D-B. The results showed that D-B was rated with a higher PDRI score than D-B-B and CM/GC. Another consideration for using the composite index is its understandability when results are presented as comparable scores that project stakeholders can easily comprehend.

In addition to the resilience criteria/indices, this research proposed a quantitative resilience metric – Tendency toward Inoperability (TI) to make resilience more relevant to actual PD performance measure – the project completeness estimation in percentage. TI-based resilience measurement is intended to enhance project performance in the disruptive built environment. TI embraces the deterministic consequence of the disruptive events on the phase-related outcomes, which provides a consistent metric for the loss evaluation for various project objectives. Since there is often a lag between disruption occurrence and the deterministic loss realization, the stochastic data of TI become useful for infrastructure owners and stakeholders by providing them with a proactive insight about the potential impact on the performance of project phases. Especially for project phases indirectly hit by disruptions, the TI metric helps practitioners realize and respond to the latent inoperable and recovery state for those project phases. Moreover, the propagation of disruptive consequences revealed in this research also triggers a discussion about whether the project delivery process can always benefit from such interdependent relationships that are often characterized by trendy PDMs such as CM/GC, D-B, and IPD, from the resilience perspective.

6.4 Theoretical Contribution and Practical Implications

In summary, the theoretical contribution of this research is considered significant from the following aspects. The author defined the PD resilience which is barely addressed in the literature. The performance-driven interpretation of resilience for PD distinguishes resilience from traditional risk management, which theoretically clarifies the confusion about relationships and the necessity of introducing resilience to project management on top of existing risk-based approaches. Also, the proposed resilience criteria/factors (i.e., best

practices in PD processes) add new knowledge to the construction literature for their extended scope of usefulness. In other words, the resilience factors can be used to assess projects' responses to disruptions at different stages (i.e., resistance and recovery) instead of assessing the final project outcome (i.e., time or cost metrics) alone, as we can observe in conventional construction literature. Another novelty of this research is the measurement of the interdependencies within project delivery processes by identifying and determining the strength of input-output relationships among different project phases, which has been less frequently addressed but critical to investigate the complexity of infrastructure projects.

As far as the practical implications for this research, several considerations are listed below. The proposed resilience criteria/factors can be used as a preliminary checklist and baseline for practitioners to review the readiness of their projects at the early stages of the projects and refine the criteria to the specific project scenarios. For resilience evaluators, the proposed PDRI can be useful for them to establish the standard resilience tool which involves step-by-step rating procedures from resilience factor structuring, factor weight development to factor rating and index score presentation. The PDRI results (i.e., D-B is rated with the relatively high PD resilience score) obtained in this research can provide public agencies insight about granting priority on integrated PDMs over traditional D-B-B in the increasingly disruptive built environment. The long-term advantage of practicing project resilience assessment is to support the recent needs and requirements of public agencies in the U.S. (e.g., USDOT) to incorporate resilience into transportation project development as a part of regular project practices (USDOT FHWA, 2018). The TI-based resilience metric can make resilience operational in infrastructure PD for both practitioners and researchers from two aspects. Practitioners can use the TI-based resilience assessment as a tool that is supplementary to

existing project control techniques (e.g., Earned Value Management) to foresee the potential impact of disruptions to their projects before the deterministic impact is realized. The TI also provides a new perspective and performance metric for the comparison of different PDMs, especially when the "trade-offs" of project phased-related interdependencies (i.e., rapid problem solving via successful collaborative relationships vs. inoperability propagation due to shared obligations between collaborative project parties) are taken into account.

6.5 Recommendations for Future Research

Despite the significance of the research mentioned above, the author admits that several limitations were encountered in conducting this research. The following highlight some of these limitations, which also introduce directions for future research.

- The proposed resilience criteria are explanatory results from the exploratory factor analysis – PCA. The PCA results could be sensitive to changes in survey sample size, survey respondents, and their areas of expertise. Thus, the proposed resilience factors can be further verified via confirmative factor analysis and adjusted for specific project scenarios and disruptive events. For instance, one research direction is that each resilience factor can be refined to its subordinate factors that are used to address considerably distinct disruptions (e.g., sea-level rise vs. labor shortage).
- The resilience factors were identified in the context of road construction, which limits the variety of resilience practices and technologies applicable for other types of infrastructure (e.g., data centers and utility lines). Since different infrastructure are vulnerable to certain kinds of threats (e.g., cyber security to data centers),

corresponding resilience measures should be investigated and taken during the project development.

- The PDRI, as an extended application of the resilience factors, is subject to the limitation mentioned above. Also, the PDRI is considered a "top-down" approach. The rating results are still fuzzy in terms of low, medium, and high scale and highly dependent on resilience evaluators, so the subjective bias associated with the evaluators' opinions may exist. For the follow-up research, there exists a need to determine the metrics that can link the effectiveness of resilience factors to the project performance measures (e.g., time and cost growth). So, the PDRI results can be validated by the effectiveness in actual project outcomes in a bottom-up manner.
- While this study lays a foundation for measuring the organizational interdependencies for PD processes, such interdependencies were mapped based on conceptualized input-output relationships which may alter for particular project scenarios. Further justifications (e.g., via industry expert review) are needed to identify the unique interdependencies for different PDM scenarios, such as CM/GC, P3, and Integrated Project Delivery (IPD), which have been adopted for infrastructure project delivery. Due to the limited example project data regarding timing and rates for the recovery measures, the illustrative example for the IIM & DIIM-based approach is limited to one disruption which occurred to one phase of the project. More projects and disruptive scenarios are needed to test the approach by comparing the pattern of inoperability tendency and actual impact caused by disruptive events.

APPENDICES

APPENDIX I Sample of Survey Questionnaire

From: Dr. Susan Bogus Halter and Mr. Fei Han, Dept. of Civil Engineering, UNM

To: Survey participants

Subject: Survey invitation for research

You are invited to evaluate a list of factors related to resilience for infrastructure project delivery processes. Your opinions will provide valuable inputs for this research to develop a rating tool for project delivery resilience. We are more than pleased to share the results upon requests from the participants.

Please click → **to get started.** The partial completion of the survey is allowed when your response in progress will be saved for you to continue later within two weeks of the survey start. For any questions, please contact: Dr. Susan Bogus Halter, and or Mr. Fei Han, sbogus@unm.edu, fhan96@unm.edu

We thank you for devoting 20 minutes of your time to this survey!

Please describe yourself:

Name:

Company:

Work Titles:

Email:

Resilience Factors for Infrastructure Project Delivery

WHAT

This survey is being conducted as part of a research project investigating the level of importance of various factors that could lead to improved resilience for infrastructure project delivery. Completion of any portion of the survey indicates that you consent to participate in this research and grant us permission to use your anonymized data for research purpose.

WHY

The planning, design, and construction of infrastructure projects in the U.S. are vulnerable to disruptive events, including but not limited to, natural hazards, human-caused incidents, and funding uncertainties. Given the inevitable risks and uncertainties that accompany every project, the idea of resilience within project delivery is important. Resilience refers to the capability of a system to resist disruptions, recover from loss of function, and ultimately adapt to the disruptive environment. In terms of project delivery, resilience reflects the ability of the planning, design, and construction processes to overcome disruptions.

This research aims to develop criteria to rate resilience for infrastructure project delivery. To achieve this goal, we need input on the level of importance of various factors in their ability to influence the resilience of the project delivery process (i.e., the planning, design, and construction of a project).

HOW

The survey asks you to evaluate the level of importance for each resilience factor as it relates to how that factor can contribute to the listed types of resilience (note: **evaluate the**

same list of factors in four different types of resilience scenarios). The survey questions present consistent choices of five importance levels (from “very important” to “not important”). Please select ONE as the most appropriate based on your knowledge and experience. Brief explanations for the four types of resilience are listed below:

Type	Description
Resistance	The ability of project delivery phases to withstand a given level of disruption without the loss of critical project performance.
Resourcefulness	The ability of project delivery phases to detect and prepare for disruptions by allocating resources to meet established priorities and objectives.
Rapidity	The ability of project delivery phases to bounce back from disruptions and recover the lost performance rapidly.
Adaptation	The ability of project delivery phases to extend lessons learned from disruptions and eventually adapt to the disruptions in the future.

At the end of this survey, you are welcome to provide any other resilience factors based on your knowledge and experience. Thank you for your participation!

Please rate the level of importance for the following factors as they relate to the ability of the project delivery process to ***withstand*** ***a given level of*** ***disruption*** ***without the loss of critical project performance*** (e.g., via pre-planning activities).

List of Factors					
	Very Important	Important	Neutral	Less Important	Not Important
Public involvement using focus groups to foster consensus	☐	☐	☐	☐	☐
Regional (multi-state) scenario planning to address future disruptions (e.g., population growth, climate change)	☐	☐	☐	☐	☐
Smooth land acquisition (e.g., Right-Of-Way (ROW) acquisition for highway infrastructure)	☐	☐	☐	☐	☐
Land use restrictions in hazardous (inundation) areas	☐	☐	☐	☐	☐
Innovative financing methods (e.g., toll revenues, fuel taxes, engaging private funds, loan of future funds)	☐	☐	☐	☐	☐
Clearly defined project scope (scoping with timelines for deliverables to avoid project creep)	☐	☐	☐	☐	☐
Design factoring in natural hazards & emergency incidents (e.g., roadway elevation, overdesign, and natural heating/cooling)	☐	☐	☐	☐	☐
Early detection of regulatory & technical constraints (e.g., permitting, jurisdictional overlap, unexpected utility encounters)	☐	☐	☐	☐	☐
Performance-based design (e.g., value engineering and weather-resistant construction materials)	☐	☐	☐	☐	☐
Sensing technology applications for disruption (damage) monitoring and issue resolution	☐	☐	☐	☐	☐
Virtual planning, design, and construction (e.g., GIS and BIM applications)	☐	☐	☐	☐	☐
Modular design and construction	☐	☐	☐	☐	☐
Consistent and accountable decision-making from public agencies	☐	☐	☐	☐	☐
Early involvement of contractors/O&M professionals	☐	☐	☐	☐	☐
Project progress audits on budget, schedule, and scope (e.g., forecasting & issue resolution)	☐	☐	☐	☐	☐
Appropriate contingencies for budget and schedule	☐	☐	☐	☐	☐
Well-established claim and emergency response plans and measures (e.g., post-event analysis)	☐	☐	☐	☐	☐

Please rate the level of importance for the following factors as they relate to the ability of the project delivery process to ***bounce back* from disruptions and *recover* the lost performance rapidly** (e.g., via recovery measures per emergency plans).

List of Factors					
	Very Important	Important	Neutral	Less Important	Not Important
Public involvement using focus groups to foster consensus	☐	☐	☐	☐	☐
Regional (multi-state) scenario planning to address future disruptions (e.g., population growth, climate change)	☐	☐	☐	☐	☐
Smooth land acquisition (e.g., Right-Of-Way (ROW) acquisition for highway infrastructure)	☐	☐	☐	☐	☐
Land use restrictions in hazardous (inundation) areas	☐	☐	☐	☐	☐
Innovative financing methods (e.g., toll revenues, fuel taxes, engaging private funds, loan of future funds)	☐	☐	☐	☐	☐
Clearly defined project scope (scoping with timelines for deliverables to avoid project creep)	☐	☐	☐	☐	☐
Design factoring in natural hazards & emergency incidents (e.g., roadway elevation, overdesign, and natural heating/cooling)	☐	☐	☐	☐	☐
Early detection of regulatory & technical constraints (e.g., permitting, jurisdictional overlap, unexpected utility encounters)	☐	☐	☐	☐	☐
Performance-based design (e.g., value engineering and weather-resistant construction materials)	☐	☐	☐	☐	☐
Sensing technology applications for disruption (damage) monitoring and issue resolution	☐	☐	☐	☐	☐
Virtual planning, design, and construction (e.g., GIS and BIM applications)	☐	☐	☐	☐	☐
Modular design and construction	☐	☐	☐	☐	☐
Consistent and accountable decision-making from public agencies	☐	☐	☐	☐	☐
Early involvement of contractors/O&M professionals	☐	☐	☐	☐	☐
Project progress audits on budget, schedule, and scope (e.g., forecasting & issue resolution)	☐	☐	☐	☐	☐
Appropriate contingencies for budget and schedule	☐	☐	☐	☐	☐
Well-established claim and emergency response plans and measures (e.g., post-event analysis)	☐	☐	☐	☐	☐

Please rate the level of importance for the following factors as they relate to the ability of the project delivery process to ***extend lessons learned* from disruptions and eventually *adapt to* the disruptions in the future** (e.g., via continuous learning and self-adjustment).

List of Factors					
	Very Important	Important	Neutral	Less Important	Not Important
Public involvement using focus groups to foster consensus	☐	☐	☐	☐	☐
Regional (multi-state) scenario planning to address future disruptions (e.g., population growth, climate change)	☐	☐	☐	☐	☐
Smooth land acquisition (e.g., Right-Of-Way (ROW) acquisition for highway infrastructure)	☐	☐	☐	☐	☐
Land use restrictions in hazardous (inundation) areas	☐	☐	☐	☐	☐
Innovative financing methods (e.g., toll revenues, fuel taxes, engaging private funds, loan of future funds)	☐	☐	☐	☐	☐
Clearly defined project scope (scoping with timelines for deliverables to avoid project creep)	☐	☐	☐	☐	☐
Design factoring in natural hazards & emergency incidents (e.g., roadway elevation, overdesign, and natural heating/cooling)	☐	☐	☐	☐	☐
Early detection of regulatory & technical constraints (e.g., permitting, jurisdictional overlap, unexpected utility encounters)	☐	☐	☐	☐	☐
Performance-based design (e.g., value engineering and weather-resistant construction materials)	☐	☐	☐	☐	☐
Sensing technology applications for disruption (damage) monitoring and issue resolution	☐	☐	☐	☐	☐
Virtual planning, design, and construction (e.g., GIS and BIM applications)	☐	☐	☐	☐	☐
Modular design and construction	☐	☐	☐	☐	☐
Consistent and accountable decision-making from public agencies	☐	☐	☐	☐	☐
Early involvement of contractors/O&M professionals	☐	☐	☐	☐	☐
Project progress audits on budget, schedule, and scope (e.g., forecasting & issue resolution)	☐	☐	☐	☐	☐
Appropriate contingencies for budget and schedule	☐	☐	☐	☐	☐
Well-established claim and emergency response plans and measures (e.g., post-event analysis)	☐	☐	☐	☐	☐

Please feel free to provide any comments and or other factors which could lead to improved resilience for infrastructure project delivery.

APPENDIX II Pearson Correlation Matrices

Pearson Correlation Matrix – Resistance

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17
F1	1.000	0.136	0.141	0.080	0.126	0.139	0.209	0.057	0.191	0.349	0.130	-0.018	0.179	0.078	0.088	0.005	0.118
F2	0.136	1.000	-0.002	0.186	0.179	-0.019	0.225	0.101	0.357	0.276	0.043	0.151	0.034	0.077	0.191	0.004	0.226
F3	0.141	-0.002	1.000	0.369	0.285	0.159	-0.199	0.129	-0.011	-0.119	-0.012	0.111	-0.049	0.054	-0.021	-0.041	-0.093
F4	0.080	0.186	0.369	1.000	0.227	0.366	0.220	0.278	0.217	0.124	0.033	0.045	-0.013	0.078	0.023	0.062	0.133
F5	0.126	0.179	0.285	0.227	1.000	0.020	0.085	0.098	0.273	0.203	0.102	0.131	0.169	0.170	0.124	0.150	0.166
F6	0.139	-0.019	0.159	0.366	0.020	1.000	0.090	0.286	0.114	-0.007	0.102	0.159	0.264	0.314	0.284	0.230	0.163
F7	0.209	0.225	-0.199	0.220	0.085	0.090	1.000	0.111	0.424	0.437	0.239	0.254	0.232	0.211	0.250	0.310	0.454
F8	0.057	0.101	0.129	0.278	0.098	0.286	0.111	1.000	0.095	-0.038	0.026	0.163	0.179	0.185	0.255	0.189	0.314
F9	0.191	0.357	-0.011	0.217	0.273	0.114	0.424	0.095	1.000	0.597	0.391	0.342	0.321	0.333	0.361	0.234	0.324
F10	0.349	0.276	-0.119	0.124	0.203	-0.007	0.437	-0.038	0.597	1.000	0.448	0.241	0.333	0.293	0.256	0.240	0.422
F11	0.130	0.043	-0.012	0.033	0.102	0.102	0.239	0.026	0.391	0.448	1.000	0.412	0.321	0.340	0.285	0.308	0.258
F12	-0.018	0.151	0.111	0.045	0.131	0.159	0.254	0.163	0.342	0.241	0.412	1.000	0.348	0.324	0.389	0.249	0.273
F13	0.179	0.034	-0.049	-0.013	0.169	0.264	0.232	0.179	0.321	0.333	0.321	0.348	1.000	0.430	0.474	0.250	0.302
F14	0.078	0.077	0.054	0.078	0.170	0.314	0.211	0.185	0.333	0.293	0.340	0.324	0.430	1.000	0.345	0.290	0.379
F15	0.088	0.191	-0.021	0.023	0.124	0.284	0.250	0.255	0.361	0.256	0.285	0.389	0.474	0.345	1.000	0.538	0.414
F16	0.005	0.004	-0.041	0.062	0.150	0.230	0.310	0.189	0.234	0.240	0.308	0.249	0.250	0.290	0.538	1.000	0.352
F17	0.118	0.226	-0.093	0.133	0.166	0.163	0.454	0.314	0.324	0.422	0.258	0.273	0.302	0.379	0.414	0.352	1.000

Pearson Correlation Matrix – Recovery

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17
F1	1.000	0.391	0.296	0.337	0.395	0.122	0.165	0.087	0.113	-0.078	0.068	0.010	0.138	0.083	0.014	0.033	0.028
F2	0.391	1.000	0.324	0.313	0.418	0.073	0.110	0.055	0.114	0.088	0.141	0.271	0.176	0.334	0.183	0.105	0.055
F3	0.296	0.324	1.000	0.548	0.353	0.105	-0.029	0.093	0.097	-0.102	-0.075	0.101	-0.073	0.082	-0.005	-0.086	-0.085
F4	0.337	0.313	0.548	1.000	0.307	0.192	0.068	0.080	0.096	0.023	0.106	0.144	0.112	0.165	0.070	0.024	0.103
F5	0.395	0.418	0.353	0.307	1.000	0.123	0.137	0.041	0.122	0.081	0.119	0.357	0.152	0.275	0.096	0.151	0.075
F6	0.122	0.073	0.105	0.192	0.123	1.000	0.121	0.255	0.071	0.063	0.011	0.077	0.263	0.160	0.106	0.088	0.050
F7	0.165	0.110	-0.029	0.068	0.137	0.121	1.000	0.224	0.311	0.225	0.243	0.203	0.229	0.154	0.165	0.330	0.509
F8	0.087	0.055	0.093	0.080	0.041	0.255	0.224	1.000	0.325	0.453	0.207	0.184	0.164	0.197	0.257	-0.026	-0.044
F9	0.113	0.114	0.097	0.096	0.122	0.071	0.311	0.325	1.000	0.498	0.392	0.312	0.067	0.196	0.157	0.250	0.157
F10	-0.078	0.088	-0.102	0.023	0.081	0.063	0.225	0.453	0.498	1.000	0.346	0.340	0.292	0.165	0.222	0.201	0.214
F11	0.068	0.141	-0.075	0.106	0.119	0.011	0.243	0.207	0.392	0.346	1.000	0.537	0.160	0.306	0.122	0.167	0.206
F12	0.010	0.271	0.101	0.144	0.357	0.077	0.203	0.184	0.312	0.340	0.537	1.000	0.158	0.202	0.117	0.053	0.084
F13	0.138	0.176	-0.073	0.112	0.152	0.263	0.229	0.164	0.067	0.292	0.160	0.158	1.000	0.343	0.308	0.297	0.382
F14	0.083	0.334	0.082	0.165	0.275	0.160	0.154	0.197	0.196	0.165	0.306	0.202	0.343	1.000	0.334	0.314	0.210
F15	0.014	0.183	-0.005	0.070	0.096	0.106	0.165	0.257	0.157	0.222	0.122	0.117	0.308	0.334	1.000	0.303	0.170
F16	0.033	0.105	-0.086	0.024	0.151	0.088	0.330	-0.026	0.250	0.201	0.167	0.053	0.297	0.314	0.303	1.000	0.544
F17	0.028	0.055	-0.085	0.103	0.075	0.050	0.509	-0.044	0.157	0.214	0.206	0.084	0.382	0.210	0.170	0.544	1.000

Pearson Correlation Matrix – Adaptation

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17
F1	1.000	0.174	0.065	0.113	0.119	0.054	0.128	0.055	0.102	0.043	-0.007	0.054	0.158	-0.029	0.092	0.104	0.090
F2	0.174	1.000	0.004	0.244	0.333	0.116	0.453	0.108	0.209	0.328	0.199	0.170	0.243	0.133	0.202	0.268	0.348
F3	0.065	0.004	1.000	0.414	0.044	0.255	-0.071	0.251	0.006	-0.053	0.023	0.249	-0.078	0.002	0.210	0.173	0.121
F4	0.113	0.244	0.414	1.000	0.173	0.280	0.318	0.375	0.219	0.215	0.229	0.268	0.148	0.068	0.147	0.187	0.346
F5	0.119	0.333	0.044	0.173	1.000	0.129	0.355	0.146	0.252	0.249	0.221	0.340	0.178	0.268	0.199	0.339	0.317
F6	0.054	0.116	0.255	0.280	0.129	1.000	0.269	0.405	0.120	0.093	0.041	0.153	0.078	0.074	0.180	0.285	0.226
F7	0.128	0.453	-0.071	0.318	0.355	0.269	1.000	0.398	0.399	0.535	0.318	0.306	0.228	0.296	0.222	0.260	0.311
F8	0.055	0.108	0.251	0.375	0.146	0.405	0.398	1.000	0.197	0.395	0.177	0.245	0.064	0.244	0.380	0.313	0.399
F9	0.102	0.209	0.006	0.219	0.252	0.120	0.399	0.197	1.000	0.505	0.619	0.406	0.173	0.127	0.147	0.233	0.171
F10	0.043	0.328	-0.053	0.215	0.249	0.093	0.535	0.395	0.505	1.000	0.590	0.461	0.182	0.349	0.372	0.262	0.469
F11	-0.007	0.199	0.023	0.229	0.221	0.041	0.318	0.177	0.619	0.590	1.000	0.514	0.024	0.412	0.176	0.166	0.188
F12	0.054	0.170	0.249	0.268	0.340	0.153	0.306	0.245	0.406	0.461	0.514	1.000	-0.071	0.314	0.341	0.314	0.364
F13	0.158	0.243	-0.078	0.148	0.178	0.078	0.228	0.064	0.173	0.182	0.024	-0.071	1.000	0.157	0.118	0.184	0.206
F14	-0.029	0.133	0.002	0.068	0.268	0.074	0.296	0.244	0.127	0.349	0.412	0.314	0.157	1.000	0.240	0.179	0.339
F15	0.092	0.202	0.210	0.147	0.199	0.180	0.222	0.380	0.147	0.372	0.176	0.341	0.118	0.240	1.000	0.358	0.460
F16	0.104	0.268	0.173	0.187	0.339	0.285	0.260	0.313	0.233	0.262	0.166	0.314	0.184	0.179	0.358	1.000	0.556
F17	0.090	0.348	0.121	0.346	0.317	0.226	0.311	0.399	0.171	0.469	0.188	0.364	0.206	0.339	0.460	0.556	1.000

APPENDIX III PDRI Scores for D-B-B, CM/GC, and D-B

PDRI Score for D-B-B

Resilience Stage	Principal Criteria (PC)	Resilience Factor (F)		Weights (W)	Criteria Feasibility ("0" or "1")	Resilience Score (RS)	PDRI
RESISTANCE	#1		**Continuity of Project Alignment**				
		F13	Consistent and accountable decision-making from public agencies	0.099	1	0.33	0.0327
		F14	Early involvement of contractors/O&M professionals	0.092	1	0.33	0.0304
		F15	Project progress audits on budget, schedule, and scope	0.097	1	0.67	0.0650
		F12	Modular design and construction	0.090	1	0.33	0.0297
	#2		**Adaptive Design and Automatic Issue Identification**				
		F10	Sensing technology applications for disruption detection/monitoring	0.041	1	0.33	0.0135
		F11	Virtual design and construction	0.035	1	0.67	0.0235
		F9	Performance-based design	0.040	1	0.33	0.0132
		F7	Design factoring in natural hazards & emergency incidents	0.035	1	0.33	0.0116
	#3		**Contingency Measures**				
		F16	Appropriate contingencies for budget and schedule	0.067	1	0.33	0.0221
		F17	Well-established claim and emergency response plans and measures	0.067	1	0.33	0.0221
	#4		**Constraint & Scope Management**				
		F4	Land use restrictions in hazardous areas	0.034	1	0.33	0.0112
		F6	Clearly-defined project scope	0.034	1	0.33	0.0112

		F8	Early detection of regulatory & technical constraints	0.032	1	0.33	0.0106
	#5		**Scenario Planning**				
		F2	Regional scenario planning to address future disruptions	0.089	1	0.33	0.0294
	#6		**Early Land Acquisition and Innovative Financing**				
		F5	Innovative financing methods	0.038	1	0.33	0.0125
		F3	Early completion of land acquisition	0.038	1	0.33	0.0125
	#7		**Consensus-Driven Project Justification**				
		F1	Public involvement using focus groups to foster consensus	0.072	1	0.33	0.0238
				Subtotal of PDRI			0.3749
RECOVERY	#1		**Contingency-Oriented Planning and Design**				
		F17	Well-established claim and emergency response plans and measures	0.115	1	0.33	0.0380
		F16	Appropriate contingencies for budget and schedule	0.105	1	0.33	0.0347
		F7	Design factoring in natural hazards & emergency incidents	0.103	1	0.33	0.0340
	#2		**Issue Detection and Adaptive Design**				
		F8	Early detection of regulatory & technical constraints	0.061	1	0.33	0.0201
		F9	Performance-based design	0.063	1	0.33	0.0208
		F10	Sensing technology applications for disruption detection/monitoring	0.067	1	0.33	0.0221
	#3		**Industrialized Project Delivery**				
		F12	Modular design and construction	0.069	1	0.33	0.0228
		F11	Virtual design and construction	0.069	1	0.67	0.0462
	#4		**Project Justification and Innovative Financing**				
		F1	Public involvement using focus groups to foster consensus	0.035	1	0.33	0.0116
		F2	Regional (multi-state) scenario planning to address future disruptions	0.036	1	0.33	0.0119
		F5	Innovative financing methods	0.036	1	0.33	0.0119

	#5		**Project Tracking and Team Collaboration**				
		F15	Project progress audits on budget, schedule, and scope	0.047	1	0.67	0.0315
		F14	Early involvement of contractors/O&M professionals	0.047	1	0.33	0.0155
	#6		**Early Land Acquisition and Land-Use Restriction**				
		F3	Early completion of land acquisition	0.039	1	0.33	0.0129
		F4	Land use restrictions in hazardous areas	0.039	1	0.33	0.0129
	#7		**Clear Project Scoping and Owners' Accountability**				
		F6	Clearly-defined project scope	0.036	1	0.33	0.0119
		F13	Consistent and accountable decision-making from public agencies	0.036	1	0.33	0.0119
				Subtotal of PDRI			0.3704
ADAPTATION	#1		**Performance-Informed and Industrialized Project Delivery**				
		F11	Virtual design and construction	0.108	1	0.67	0.0724
		F9	Performance-based design	0.100	1	0.33	0.0330
		F10	Sensing technology applications for disruption detection/monitoring	0.101	1	0.33	0.0333
		F12	Modular design and construction	0.095	1	0.33	0.0314
	#2		**Project Tracking and Contingency Management**				
		F15	Project progress audits on budget, schedule, and scope	0.046	1	0.67	0.0308
		F17	Well-established claim and emergency response plans and measures	0.051	1	0.33	0.0168
		F16	Appropriate contingencies for budget and schedule	0.049	1	0.33	0.0162
	#3		**Scenario Planning and Innovative Financing**				
		F5	Innovative financing methods	0.061	1	0.33	0.0201
		F2	Regional scenario planning to address future disruptions	0.061	1	0.33	0.0201
	#4		**Adaptive Planning/Design and Clear Project Scoping**				
		F6	Clearly-defined project scope	0.032	1	0.33	0.0106
		F8	Early detection of regulatory & technical constraints	0.035	1	0.33	0.0116

		F7	Design factoring in natural hazards & emergency incidents	0.032	1	0.33	0.0106
	#5		**Early Land Acquisition and Land-Use Restriction**				
		F3	Early completion of land acquisition	0.043	1	0.33	0.0142
		F4	Land use restrictions in hazardous areas	0.043	1	0.33	0.0142
	#6		**Owners' Accountability**				
		F13	Consistent and accountable decision-making from public agencies	0.073	1	0.33	0.0241
	#7		**Early and Harmonious Involvement of Project Stakeholders**				
		F1	Public involvement using focus groups to foster consensus	0.035	1	0.33	0.0116
		F14	Early involvement of contractors/O&M professionals	0.035	1	0.33	0.0116
				Subtotal of PDRI			0.3824
				Total of PDRI			1.128

PDRI Score for CM/GC

Resilience Stage	Principal Criteria (PC)	Resilience Factor (F)		Weights (W)	Criteria Feasibility ("0" or "1")	Resilience Score (RS)	PDRI
RESISTANCE	#1		**Continuity of Project Alignment**				
		F13	Consistent and accountable decision-making from public agencies	0.099	1	1	0.0990
		F14	Early involvement of contractors/O&M professionals	0.092	1	0.67	0.0616
		F15	Project progress audits on budget, schedule, and scope	0.097	1	1	0.0970
		F12	Modular design and construction	0.090	1	0.33	0.0297
	#2		**Adaptive Design and Automatic Issue Identification**				
		F10	Sensing technology applications for disruption detection/monitoring	0.041	1	0.67	0.0275
		F11	Virtual design and construction	0.035	1	1	0.0350
		F9	Performance-based design	0.040	1	1	0.0400
		F7	Design factoring in natural hazards & emergency incidents	0.035	1	0.67	0.0235
	#3		**Contingency Measures**				
		F16	Appropriate contingencies for budget and schedule	0.067	1	0.67	0.0449
		F17	Well-established claim and emergency response plans and measures	0.067	1	0.67	0.0449
	#4		**Constraint & Scope Management**				
		F4	Land use restrictions in hazardous areas	0.034	1	0.67	0.0228
		F6	Clearly-defined project scope	0.034	1	1	0.0340
		F8	Early detection of regulatory & technical constraints	0.032	1	0.67	0.0214
	#5		**Scenario Planning**				

		F2	Regional scenario planning to address future disruptions	0.089	1	0.33	0.0294
	#6		**Early Land Acquisition and Innovative Financing**				
		F5	Innovative financing methods	0.038	1	0.67	0.0255
		F3	Early completion of land acquisition	0.038	1	0.67	0.0255
	#7		**Consensus-Driven Project Justification**				
		F1	Public involvement using focus groups to foster consensus	0.072	1	0.67	0.0482
				Subtotal of PDRI			0.7098
RECOVERY	#1		**Contingency-Oriented Planning and Design**				
		F17	Well-established claim and emergency response plans and measures	0.115	1	0.67	0.0771
		F16	Appropriate contingencies for budget and schedule	0.105	1	0.67	0.0704
		F7	Design factoring in natural hazards & emergency incidents	0.103	1	0.67	0.0690
	#2		**Issue Detection and Adaptive Design**				
		F8	Early detection of regulatory & technical constraints	0.061	1	0.67	0.0409
		F9	Performance-based design	0.063	1	1	0.0630
		F10	Sensing technology applications for disruption detection/monitoring	0.067	1	0.67	0.0449
	#3		**Industrialized Project Delivery**				
		F12	Modular design and construction	0.069	1	0.33	0.0228
		F11	Virtual design and construction	0.069	1	1	0.0690
	#4		**Project Justification and Innovative Financing**				
		F1	Public involvement using focus groups to foster consensus	0.035	1	0.67	0.0235
		F2	Regional (multi-state) scenario planning to address future disruptions	0.036	1	0.33	0.0119
		F5	Innovative financing methods	0.036	1	0.67	0.0241
	#5		**Project Tracking and Team Collaboration**				
		F15	Project progress audits on budget, schedule, and scope	0.047	1	1	0.0470

		F14	Early involvement of contractors/O&M professionals	0.047	1	0.67	0.0315
	#6		**Early Land Acquisition and Land-Use Restriction**				
		F3	Early completion of land acquisition	0.039	1	0.67	0.0261
		F4	Land use restrictions in hazardous areas	0.039	1	0.67	0.0261
	#7		**Clear Project Scoping and Owners' Accountability**				
		F6	Clearly-defined project scope	0.036	1	1	0.0360
		F13	Consistent and accountable decision-making from public agencies	0.036	1	1	0.0360
				Subtotal of PDRI			0.7191
ADAPTATION	#1		**Performance-Informed and Industrialized Project Delivery**				
		F11	Virtual design and construction	0.108	1	1	0.1080
		F9	Performance-based design	0.100	1	1	0.1000
		F10	Sensing technology applications for disruption detection/monitoring	0.101	1	0.67	0.0677
		F12	Modular design and construction	0.095	1	0.33	0.0314
	#2		**Project Tracking and Contingency Management**				
		F15	Project progress audits on budget, schedule, and scope	0.046	1	1	0.0460
		F17	Well-established claim and emergency response plans and measures	0.051	1	0.67	0.0342
		F16	Appropriate contingencies for budget and schedule	0.049	1	0.67	0.0328
	#3		**Scenario Planning and Innovative Financing**				
		F5	Innovative financing methods	0.061	1	0.67	0.0409
		F2	Regional scenario planning to address future disruptions	0.061	1	0.33	0.0201
	#4		**Adaptive Planning/Design and Clear Project Scoping**				
		F6	Clearly-defined project scope	0.032	1	1	0.0320
		F8	Early detection of regulatory & technical constraints	0.035	1	0.67	0.0235
		F7	Design factoring in natural hazards & emergency incidents	0.032	1	0.67	0.0214
	#5		**Early Land Acquisition and Land-Use Restriction**				

		F3	Early completion of land acquisition	0.043	1	0.67	0.0288
		F4	Land use restrictions in hazardous areas	0.043	1	0.67	0.0288
	#6		**Owners' Accountability**				
		F13	Consistent and accountable decision-making from public agencies	0.073	1	1	0.0730
	#7		**Early and Harmonious Involvement of Project Stakeholders**				
		F1	Public involvement using focus groups to foster consensus	0.035	1	0.67	0.0235
		F14	Early involvement of contractors/O&M professionals	0.035	1	0.67	0.0235
				Subtotal of PDRI			0.7354
				Total of PDRI			2.164

PDRI Score for D-B

Resilience Stage	Principal Criteria (PC)	Resilience Factor (F)		Weights (W)	Criteria Feasibility ("0" or "1")	Resilience Score (RS)	PDRI
RESISTANCE	#1		**Continuity of Project Alignment**				
		F13	Consistent and accountable decision-making from public agencies	0.099	1	0.67	0.0663
		F14	Early involvement of contractors/O&M professionals	0.092	1	1	0.0920
		F15	Project progress audits on budget, schedule, and scope	0.097	1	0.67	0.0650
		F12	Modular design and construction	0.090	1	0.67	0.0603
	#2		**Adaptive Design and Automatic Issue Identification**				
		F10	Sensing technology applications for disruption detection/monitoring	0.041	1	1	0.0410
		F11	Virtual design and construction	0.035	1	1	0.0350
		F9	Performance-based design	0.040	1	1	0.0400
		F7	Design factoring in natural hazards & emergency incidents	0.035	1	0.33	0.0116
	#3		**Contingency Measures**				
		F16	Appropriate contingencies for budget and schedule	0.067	1	1	0.0670
		F17	Well-established claim and emergency response plans and measures	0.067	1	0.67	0.0449
	#4		**Constraint & Scope Management**				
		F4	Land use restrictions in hazardous areas	0.034	1	0.67	0.0228
		F6	Clearly-defined project scope	0.034	1	0.67	0.0228

		F8	Early detection of regulatory & technical constraints	0.032	1	1	0.0320
	#5		**Scenario Planning**				
		F2	Regional scenario planning to address future disruptions	0.089	1	0.33	0.0294
	#6		**Early Land Acquisition and Innovative Financing**				
		F5	Innovative financing methods	0.038	1	0.33	0.0125
		F3	Early completion of land acquisition	0.038	1	1	0.0380
	#7		**Consensus-Driven Project Justification**				
		F1	Public involvement using focus groups to foster consensus	0.072	1	0.67	0.0482
				Subtotal of PDRI			0.7288
RECOVERY	#1		**Contingency-Oriented Planning and Design**				
		F17	Well-established claim and emergency response plans and measures	0.115	1	0.67	0.0771
		F16	Appropriate contingencies for budget and schedule	0.105	1	1	0.1050
		F7	Design factoring in natural hazards & emergency incidents	0.103	1	0.33	0.0340
	#2		**Issue Detection and Adaptive Design**				
		F8	Early detection of regulatory & technical constraints	0.061	1	1	0.0610
		F9	Performance-based design	0.063	1	1	0.0630
		F10	Sensing technology applications for disruption detection/monitoring	0.067	1	1	0.0670
	#3		**Industrialized Project Delivery**				
		F12	Modular design and construction	0.069	1	0.67	0.0462
		F11	Virtual design and construction	0.069	1	1	0.0690
	#4		**Project Justification and Innovative Financing**				
		F1	Public involvement using focus groups to foster consensus	0.035	1	0.67	0.0235

		F2	Regional (multi-state) scenario planning to address future disruptions	0.036	1	0.33	0.0119
		F5	Innovative financing methods	0.036	1	0.33	0.0119
	#5		**Project Tracking and Team Collaboration**				
		F15	Project progress audits on budget, schedule, and scope	0.047	1	0.67	0.0315
		F14	Early involvement of contractors/O&M professionals	0.047	1	1	0.0470
	#6		**Early Land Acquisition and Land-Use Restriction**				
		F3	Early completion of land acquisition	0.039	1	1	0.0390
		F4	Land use restrictions in hazardous areas	0.039	1	0.67	0.0261
	#7		**Clear Project Scoping and Owners' Accountability**				
		F6	Clearly-defined project scope	0.036	1	0.67	0.0241
		F13	Consistent and accountable decision-making from public agencies	0.036	1	0.67	0.0241
				Subtotal of PDRI			0.7613
ADAPTATION	#1		**Performance-Informed and Industrialized Project Delivery**				
		F11	Virtual design and construction	0.108	1	1	0.1080
		F9	Performance-based design	0.100	1	1	0.1000
		F10	Sensing technology applications for disruption detection/monitoring	0.101	1	1	0.1010
		F12	Modular design and construction	0.095	1	0.67	0.0637
	#2		**Project Tracking and Contingency Management**				
		F15	Project progress audits on budget, schedule, and scope	0.046	1	0.67	0.0308
		F17	Well-established claim and emergency response plans and measures	0.051	1	0.67	0.0342
		F16	Appropriate contingencies for budget and schedule	0.049	1	1	0.0490
	#3		**Scenario Planning and Innovative Financing**				

		F5	Innovative financing methods	0.061	1	0.33	0.0201
		F2	Regional scenario planning to address future disruptions	0.061	1	0.33	0.0201
	#4		**Adaptive Planning/Design and Clear Project Scoping**				
		F6	Clearly-defined project scope	0.032	1	0.67	0.0214
		F8	Early detection of regulatory & technical constraints	0.035	1	1	0.0350
		F7	Design factoring in natural hazards & emergency incidents	0.032	1	0.33	0.0106
	#5		**Early Land Acquisition and Land-Use Restriction**				
		F3	Early completion of land acquisition	0.043	1	1	0.0430
		F4	Land use restrictions in hazardous areas	0.043	1	0.67	0.0288
	#6		**Owners' Accountability**				
		F13	Consistent and accountable decision-making from public agencies	0.073	1	0.67	0.0489
	#7		**Early and Harmonious Involvement of Project Stakeholders**				
		F1	Public involvement using focus groups to foster consensus	0.035	1	0.67	0.0235
		F14	Early involvement of contractors/O&M professionals	0.035	1	1	0.0350
				Subtotal of PDRI			0.7731
				Total of PDRI			2.263

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