A DECISION SUPPORT SYSTEM FOR SUCCESS OF POST-HURRICANE RECONSTRUCTION OF TRANSPORTATION INFRASTRUCTURES

by

ELNAZ SAFAPOUR

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DEDICATION

To Him,

who I trust!

To my love, Behzad,

who stands behind me in all steps!

To my parents, Aroosbanoo & Abolfazl,

who spend their lives building mine!

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NOMENCLUTURE

CDF	Cumulative Density Function
CII	Construction Industry Institute
CM	Construction Management
EBA	Extreme Bound Analysis
OLS	Ordinary Least Square
PRT	Significant Factors for Post-Hurricane Reconstruction of Transportation Infrastructure
PMT	Project Management Team
STA	State Transportation Agency

ABSTRACT

A DECISION SUPPORT SYSTEM FOR SUCCESS OF POST-HURRICANE RECONSTRUCTION OF TRANSPORTATION INFRASTRUCTURES

Elnaz Safapour, Ph.D.

The University of Texas at Arlington, 2020

Supervising Professor: Dr. Sharareh Kermanshachi

In the aftermath of hurricanes, when reliable transportation systems are vital, the chaotic and complex environment creates multiple uncertainties and risks in the reconstruction of transportation infrastructures. Damaged transport infrastructures decrease the timeliness of emergency responses and recovery procedures, and make it difficult for authorities, who are under excessive pressure and are struggling to find the financial resources to reconstruct them on time and within budget. The aim of this research was to develop a decision support system that would improve the cost and schedule performance, as well as reduce the number and extent of reworks in post-hurricane reconstruction of transportation infrastructures.

Significant factors that contribute to cost overruns, schedule delays, and the cost of reworks in post-hurricane reconstruction of transportation infrastructures (PRT) were statistically determined in this research. The results demonstrated that 26, 23, and 25

PRTs were statistically significant for cost escalations, schedule delays, and reworks of the mentioned projects, respectively.

Three models were developed to predict the cost performance, schedule performance, and cost of reworks, and a stepwise multiple regression method was adopted. The results revealed that seven, nine, and ten PRTs were significant predictors of cost performance, schedule performance, and cost of reworks, respectively. The results demonstrated that frequency of on-site inspection, information management, and safety/environment issues were recorded as influential predictors in all three developed models to predict cost performance, schedule performance, and reworks in post-hurricane reconstruction of transport infrastructures.

The extreme bounds analysis (EBA) method proposed by Leamer and Sala-i-Marin was adopted, and the criteria proposed by Sala-i-Martin was used. It was concluded from the results that four, six, and five significant predictors were robustly connected to cost performance, schedule performance, and the cost of reworks of the regression model, respectively. The results revealed that information management was a robust predictor shared between reconstruction cost performance and rework. Moreover, frequency of on-site inspection was the shared robust predictor between reconstruction cost and schedule performance in post-hurricane reconstruction of transportation infrastructures.

It is believed that the findings of this research can provide a decision support system to stakeholders, decision makers, and project managers that will improve the success of post-hurricane reconstruction of transportation infrastructures. Additionally,

this research provides accurate knowledge and information that will be helpful in effectively allocating limited resources after hurricanes and mitigating schedule delays, cost overruns, and reworks in reconstruction of transportation infrastructures.

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1. INTRODUCTION

1.1. Problem Statement

In the last two decades, a remarkable number of natural disasters have occurred (Eid et al. 2015), causing many fatalities and substantial losses in various parts of the world (Fuchs 2010; Eid and El-Adaway 2017). Hurricanes are among the most powerful and destructive disasters, as was demonstrated by Hurricanes Harvey, Katrina, and Ike. Hurricane Harvey struck in the southern part of Texas and destroyed a number of structures in 2017 (Picou and Marshal 2007), Hurricane Katrina caused losses of more than $160 billion (Josephson et al. 2017), and Hurricane Ike resulted in at least seven deaths in Texas and losses of nearly $30 billion (Careem et al. 2006).

The recovery process needs to begin very soon after a natural disaster so that the affected community can return to its pre-disaster condition (Chang 2010); however, the damaged transportation infrastructures such as highways lower the pace of emergency response teams and disrupt the traffic flow, which often result in challenges associated with supply chains of necessary products and resources (Werner et al. 1997; Chang and Nojima 2001; Peeta et al. 2010; Du and Peeta 2014). For instance, traffic on critical transport infrastructure was disrupted at four locations in the northwestern Los Angeles metropolitan area by the 1991 Northridge disaster (Chang and Nojima 1998), leading to substantial disruptions in the movement of people, and the closure of parts of Interstate 10 (i.e., Santa Monica Freeway) led to economic losses that were estimated at $1 million per day (Zamichow and Ellis 1994). After the disaster in Aceh and Nias, (Bappenas 2005), the damages to the transportation systems accounted for 19.7% of the total estimated damages. Similarly, in 2004, in Sri Lanka, losses and damages to transportation sector due to the natural disaster there accounted for 22% of the total damages. Damaged transportation systems need to be restored to their pre-event state within the least amount of time to mitigate these socioeconomic disruptions, as they play critical roles in public mobility, access, the economy, safety, and the environment after disasters (Mallela and Sadasivam 2011).

The number of natural disasters, especially hurricanes, has increased over the last two decades (Ku and Ma 2015), and authors and practitioners have responded by conducting studies that investigate the serious challenges and risks that are incurred during the reconstruction of transportation sector (Hayat and Amaratunga 2017; Zamanifar and Seyedhoseyni 2017; Hayat et al. 2019; Gajanayake et al. 2019; Gajanayake et al. 2020a; Gajanayake et al. 2020b). These researchers and practitioners believe that the reconstruction process following a disaster is different from routine construction jobs because of the unique and dynamic nature of expedited reconstruction.

The rehabilitation of transportation infrastructures often requires significant funds (Hayat and Amaratunga 2011; Vu et al. 2016; Zhang et al. 2017; Baek 2018; Hayat et al. 2019), and a lack of adequate funding seriously affects the likelihood of post-hurricane reconstruction projects being completed on time and within budget (Comerio 2006; Freeman 2007; Safapour et al. 2020a). Local governments are subjected to additional pressure from the public when contractors are not able to deliver their services on time. Hidayat and Egbu (2010) and Chang et al. (2011) espoused that prices are commonly inflated and labor, materials, and equipment are in short supply after hurricanes, all of which lead to cost overruns, schedule delays, and even failure of some of the reconstruction projects.

Many of the challenges and risks incurred during post-hurricane reconstruction of transport infrastructures arise from the complex and chaotic aftermath of the disaster and merit further study (Zamanifar and Seyedhoseyni 2017; Mojtahedi and Lan 2017; Hayat et al. 2019; Gajanayake et al. 2019; Gajanayake et al. 2020a; Gajanayake et al. 2020b; Safapour et al. 2020b). A few studies have been conducted to determine the influential predictors associated with cost performance, schedule performance, and cost of reworks pertaining to transport infrastructure projects after hurricanes, but the existing literature suffers from a lack of applicable predictive models.

1.2. Research Goal and Objectives

The goal of this research was to determine the factors that significantly contribute to success of reconstruction of transport infrastructures after a hurricane, with the focus on reducing the number and extent of reworks and minimizing cost overruns and schedule delays, which are endemic problems in these projects. The objectives described below were designed to accomplish these goals.

Objective 1: Determine the significant factors that affect the cost overruns, schedule delays, and reworks in the post-hurricane reconstruction of transport infrastructures.

Objective 2: Develop models to predict the cost and schedule performance, and cost of reworks in the post-hurricane reconstruction of transport infrastructures.

Objective 3: Determine how robustly each of the predictors is related to the predictive models in post-hurricane reconstruction of transport infrastructures.

1.3. Research Contributions

The present research is pivotal to improving the success of post-hurricane reconstruction of transport infrastructures and serves as the foundation for integrating different project parties across a wide range of disciplines, such as engineering, construction, and management. It will contribute to a better understanding of the factors that influence cost overruns, schedule delays, and reworks, as well as their impacts on project performance and success. Decision makers and project managers will be able to utilize the predictive models as a decision support system to quantitatively assess projects’ risks in a chaotic and dynamic post-hurricane environment, which will enable them to make plans and adopt strategies that will prevent and/or mitigate undue expenses and delays, and reduce the number and cost of reworks.

1.4. Research Limitations

Although substantial efforts have been made to obtain valid and reliable results, this research contains several limitations, which are presented below.

Limitation 1: The influential factors were identified through a careful review of the existing literature, but there may be other critical PRTs that are applicable in construction practice.

Limitation 2: The process of collecting the surveys coincided with the COVID-19 pandemic and its consequences, which resulted in a limited number of data being collected.

Limitation 3: This study was conducted only on hurricane-related disasters.

Limitation 4: This study relied solely on the environmental and geographical context of the United States.

1.5. Dissertation Outline

This dissertation is presented in nine chapters. The current chapter, "Introduction," focuses on the problem statement, research goal and objectives, and the research's contributions and limitations. The second chapter presents information related to the existing literature on natural disasters; reconstruction of transportation infrastructures; and the cost, schedule performance, and reworks endemic to reconstruction projects. In the third chapter, the research methodology is systematically described, and in the fourth chapter, the process of survey development and collection is explained in detail. Chapter 5 focuses on descriptive and preliminary data analyses, such as the comparative analyses of projects' cost, schedule, and cost of reworks. The statistical test conducted to determine the significant PRTs affecting cost and schedule performance and rework in reconstruction projects is presented and explained in Chapter 6. The process and ability of the three models to predict cost and schedule performance, as well as cost of reworks for post-hurricane reconstruction of transport infrastructures, are described in Chapter 7. The results of a residual analysis for each of the developed predictive models are also presented in this chapter. In Chapter 8, the procedure and results of a sensitivity analysis to determine the robust/fragile relationships between the influential predictors and the predictive models are described. In the ninth chapter, the process of implication of results obtained by this research that can be adopted by practitioners and researchers explains in detail. The last chapter describes the conclusions that were drawn from this research and makes recommendations for further future research.

2. LITERATURE REVIEW

2.1. Natural Disasters

The number of natural disasters has increased considerably in the last three decades, a fact confirmed by a report published by the Center for Research on the Epidemiology of Disasters (CRED 2009). Shaluf and Ahmadun (2006) and Vos et al. (2010) defined disaster as *"a serious disruption of the functioning of the society that leads to environmental and human losses on a scale that exceeds the capacity of the affected community to cope with its own resources*." Hayat and Amaratunga (2011) defined natural disasters as "*disasters caused by the event of natural hazards where occurrences are out of human control*."

The losses and damages have not increased proportionally with the increased number of natural disasters (Noy and Vu 2010), as the average total losses and damages increased from roughly $10 billion in 1975 to roughly $90 billion in 2009 (Hayat and Amaratunga 2011). A report, published by the EM-DAT database stated that 25 natural disasters occurred from 1900 to 2011 and resulted in more than 50,000 deaths (Lindell 2013).

A natural disaster usually results in a major disruption of the way that society functions (Sun and Xu 2011). It causes serious human and environmental issues, including physical damage and psychological trauma, at a time when the affected community does not have the resources necessary to cope with the incurred losses

(Shaluf and Ahmadun 2006; Karunasena et al. 2009; Vos et al. 2010; Hayat and Amaratunga 2011; Kermanshachi et al. 2019). The physical damages such as death, injuries, and property damages are clearly visible and quantifiable; the social damages are less so and include physiological, political, and economic harm (Lindell 2013).

Among all of the types of natural disasters, hurricanes are the biggest cause of disruptions, losses, and damages in the U.S. (Horners and Downs 2010). For instance, Hurricane Andrew in 1992 caused $26.5 billion in losses and damages in Florida (Chavériat 2000). Hurricanes Katrina and Rita led to tremendous socioeconomic damages, with total costs far exceeding what was predicted. The direct and indirect economic losses and damages after Hurricane Katrina were estimated to be $160 billion, but in actuality were roughly $1,845 billion (Knabb et al. 2006a). The economic losses and damages from Hurricane Rita were predicted to the $10 billion, but amounted to $120 billion (Knabb et al. 2006b).

2.2. Post-Disaster Reconstruction of Transportation Infrastructures

The losses and damages to the transport sector are among the largest following a disaster, thus reconstruction is costly (Hayat and Amaratunga 2011). There are many examples of such losses, but to cite a few, Aceh and Nias, Bappenas experienced losses and damages to their transportation infrastructure that amounted to 19.7% of their investment after a natural disaster in 2005. After a disastrous event in Sri Lanka, the transportation sector experienced a 22% loss. Hurricane Katrina wreaked havoc on coast of Louisiana in 2005, and repairs of the extensive damage sustained by bridges were estimated to cost more than $1 billion (TCLEE 2006). In addition, due to severe storm surges that affected the coastal area, many roads were damaged, and a plethora of debris delayed recovery activities for several weeks. The economic losses related to the debris removal were estimated at about $200 million (Padget et al. 2008).

The period of time immediately following a disaster is considered the emergency phase. A functioning transportation system has a crucial role in rescuing the affected community by evacuating them when necessary and rapidly distributing items essential to their health and wellbeing. Damaged transportation systems usually disrupt traffic flows and the pace of emergency responses, and result in more indirect losses than direct ones (Rose et al. 2011). After a disaster, a non-functioning transportation system leads to substantial increases in transportation costs and duration for reconstruction (Orabi et al. 2010; Change et al. 2011), and results in considerable increases in schedule delays and in the cost of materials (Rose and Huyck 2016). Complex reconstruction procedures can prolong the length of time that a community is without adequate transportation and may lead to remarkable capital losses (Rose et al. 2011).

Post-hurricane reconstruction of transportation infrastructures is a continuous procedure that needs to begin immediately after the disaster. The time required to implement it is usually much longer than what was estimated (Jha and Duyne 2010) because it is complex, dynamic, and chaotic (Alexander 2004). Multiple researchers and authors believe that cost overruns in reconstruction projects are one of the most serious issues and challenges that governments face in these projects (Odeck 2004; Wichen et al. 2009; Kaliba et al. 2009), and they usually require more funds and take longer to complete than estimated (Jha and Duyne 2010). Thus, it is important to identify the factors that affect the cost of these projects (Choudhary and Mehmood 2013).

2.3. Success Criteria in the Construction Industry

A successful project in the construction industry is defined by a number of criteria that are mentioned in the existing literature. In 1987, Pinto and Slevin stated that a project could be considered successful if it was completed on time and on budget, met all of its objectives, and satisfied the client. In 2007, Jha and Iyer espoused that not only time, cost, and quality are important for a project to be considered successful, but commitment, coordination, and competence are vital as well throughout the execution of a project. Various studies have been conducted on successful construction projects, using the mentioned definition (Nixon et al. 2012; Carvalho and Junior 2015; Wang et al. 2015; Davis 2016; Wang et al. 2017; Karunakaran et al. 2019; Ghribi et al. 2019).

From the start of the construction industry, project managers have had concerns about delivering high quality projects on time and within budget (Ika 2009; Santoso and Soeng 2016; He et al. 2019). Almost all researchers believe that staying within the budget, adhering to the schedule, and achieving a quality project performance, referred to as “the iron triangle” by Atkinson (1999), is necessary for the success of a construction project (Nguyen and Hadikusumo 2017; Kissi et al. 2019; Viswanathan et al. 2019; Narayan and Tan 2019; Silva et al. 2019).

Multiple authors and practitioners have mentioned schedule delays as one of the main challenges of project managers (Westerveld 2003; Barnes 2013; Marzo and El-Rasas 2014; Alias et al. 2014). In 2002, Ahmed et al. indicated that schedule delays are a universal issue in the construction industry. In 2010, Thomsen et al. explained that roughly 50% of construction projects in the U.S experience serious schedule delays and have serious impacts on the relationships of owners with other project parties.

Cost overruns occur when actual costs exceed the estimated budget (Leavitt et al. 1993; Sohu et al. 2018). This issue has been mentioned by different authors and practitioners as a common issue that negatively affects projects' success (Ogunlana 2010; Mishra et al. 2011; Ebbesen and Hope 2013; Aggor 2017; Love et al. 2019; Kermanshachi and Safapour 2020). In 2009, Flyvbjerg et al. stated that approximately 90% of construction projects experience cost overruns. In 2009, Shane et al. said that about 50% of large-scale projects in the U.S. construction industry experience cost overruns. An increase in the cost of a construction project might have negative impacts on other aspects of the project such as safety and/or quality (Siemiatycki 2009; Aggor 2017).

Reworks are inevitable in all types of construction projects. They impact the cost of a project, create scheduling delays, decrease productivity, and play an important role in a project's success or failure (Wu et al. 2005; Sunday 2010; Li and Taylor 2014; Desai 2015). Reworks have the potential to create serious challenges for owners, designers, and contractor stakeholders, and may also cause conflicts among the project stakeholders (Wu et al. 2005; Desai 2015; Safapour and Kermanshachi 2019). The literature contains several definitions and interpretations of rework in the area of construction management (Love 2002). In 2001, the Construction Industry Institute (CII) characterized rework in the construction phase as activities that have to be done more than once, or activities that remove previous work installed as part of a project.

2.4. Critical Success Factors in Post-Disaster Reconstruction Projects

Every post-hurricane reconstruction project is unique in its determinants for success. Among the factors could be differences in the safety and environmental issues, the uniqueness of the project, and the attitudes of the decision makers (Toor and Ogunlana 2008; Reissman and Howard 2008). Multiple studies have been conducted to identify the root causes of the success and failure of reconstruction projects (Tierney and Bevc 2007; Chang et al. 2010; Chang et al. 2011; Brunsdon et al. 2012; Moloney 2014; Safapour and Kermanshachi 2020; Safapour et al. 2020c), and some of these factors are presented in Table 1. As shown in Table 1, Ika et al. (2012) believed that ineffective designs are one of the main reasons for failure, and multiple authors have stated that delays in delivering resources are one of the crucial challenges that affect the success of reconstruction projects after disasters (Rouhanizadeh and Kermanshachi 2019a, and b).

Many obstacles are encountered by those facilitating the reconstruction of infrastructures after a disaster. In 2012, Brunsdon et al. and IPEZ cited severe damage as a common challenge, Table 1 shows that shortages of workers and materials are challenges (King et al. 2014; Chang-Richards et al. 2017), and Taylor et al. (2012) and Marquis et al. (2015) stated that delays in decision-making during different stages of post-disaster reconstruction projects cause delays that ultimately affect their success.

Table 1. Challenges Affecting Success of Post-Disaster Reconstruction Projects

Challenge	Previous Study
Delay in delivering resources	Nazara and Resosudarmo 2007; Matsumaru et al. 2012; Iwai and Tabuchi 2013; Moloney 2014
Finance and limitation of funds	Comerio 2006; Freeman 2007; Hidayat and Egbu 2010; UNDP 2011
Inappropriate assessment	Kennedy et al. 2008
Communication and coordination	Chang et al. 2010
Ineffective design	Ika et al. 2012
Transportation	Matsumaru et al. 2012
Temporary paths	Choudhary and Mehmood 2013
Inadequacy of resource procurement	Chang et al. 2011
Difficulties in damage evaluation	Brunsdon et al. 2012; IPENZ 2012
Unavailability of human resources	King et al. 2014; Chang-Richards et al. 2017; Rouhanizadeh et al. (2020a)
Unavailability of material resources	King et al. 2014; Chang-Richards et al. 2017
Low pace of decision-making	Iuchi 2010; Taylor et al. 2012; Marquis et al. 2015; Rouhanizadeh et al. (2020b, c)
Number and Quality of Inspection	Almufti and Willford 2013
Engineering mobilization	Almufti and Willford 2013
Inability in relocation of functions	Comerio 2006
Inflation	Chang et al. 2011; Pamidimukkala et al. 2020
Permitting and consenting	Chang-Richards et al. 2017

2.5. Summary

The chapter covering the literature review consists of four main parts: (1) natural disasters, (2) post-disaster reconstruction of transportation infrastructures, (3) success criteria in the construction industry, and (4) critical success factors in post-disaster reconstruction projects. The main criteria for considering a construction project successful are studied from different points of view of researchers, authors, and practitioners. This chapter also investigates the critical root causes of schedule delays and cost overruns in the post-disaster reconstruction of transportation infrastructures that are covered in the literature. In the next chapter, the research framework is presented, with detailed explanations of every step of the current study.

3. RESEARCH METHODOLOGY

3.1. Research Framework

A structured research framework of seven main phases was designed to fulfill the aims of this research. Figure 1 presents the phases of this research; an explanation of each one is presented in the following.

Phase 1: The research problem, objectives, and questions were defined and are explained in detail in the Introduction.

Phase 2: A comprehensive literature review was conducted to identify potential PRTs affecting the cost performance, schedule performance and reworks in the post-hurricane reconstruction of transport infrastructures. More than 75% of the 200 journal articles, conference papers, dissertations, and research reports were from peer-reviewed journal articles that were obtained from five databases: Google Scholar, JSTOR, ProQuest, and Science Direct. All of the articles were carefully reviewed; the most relative ones were used, and the rest were excluded.

Phase 3: A structured survey was designed according to the potential PRTs that were identified through the literature and affect cost performance, schedule performance, and reworks of reconstruction projects. The survey was distributed to professionals and experts involved in reconstruction projects, to collect project-based information and data. After three follow-up emails, 30 completed surveys were collected.

Phases 4 & 5: The collected surveys were analyzed to investigate the distribution of the hurricanes based on the state of origin and the damage level. The baseline budgets/schedules and actual costs/durations were comparatively analyzed, then the costs of the reworks were descriptively analyzed. The collected project-based data was analyzed to: (1) determine the significant PRTs that affect schedule and cost performance of reconstruction projects, (2) compare the mean scores of the PRTs of high and low cost/schedule performance, and (3) determine the significant PRTs that affect the cost performance/schedule performance of transport infrastructure projects that sustained a high level of damage and those that sustained a low level of damage. The outcomes were achieved by qualitatively analyzing the collected project-based data to: (1) determine the significant PRTs affecting the cost of reworks, (2) compare the mean scores of PRTs with high and low costs of reworks, and (3) determine the significant PRTs affecting the cost of reworks in both highly and minimally damaged projects.

Phase 6: Stepwise multiple regression was adopted to develop three predictive models to estimate cost performance, schedule performance, and the cost of reworks for post-hurricane reconstruction of transport infrastructures. The method of residual analysis was conducted to validate the three models.

Phase 7: A sensitivity analysis was conducted to analyze the robustness or fragility of predictors for the schedule performance, cost performance, and cost of reworks of post-hurricane reconstruction of transport infrastructures. The extreme bound analysis method was adopted to determine which of the influential predictors were robust.

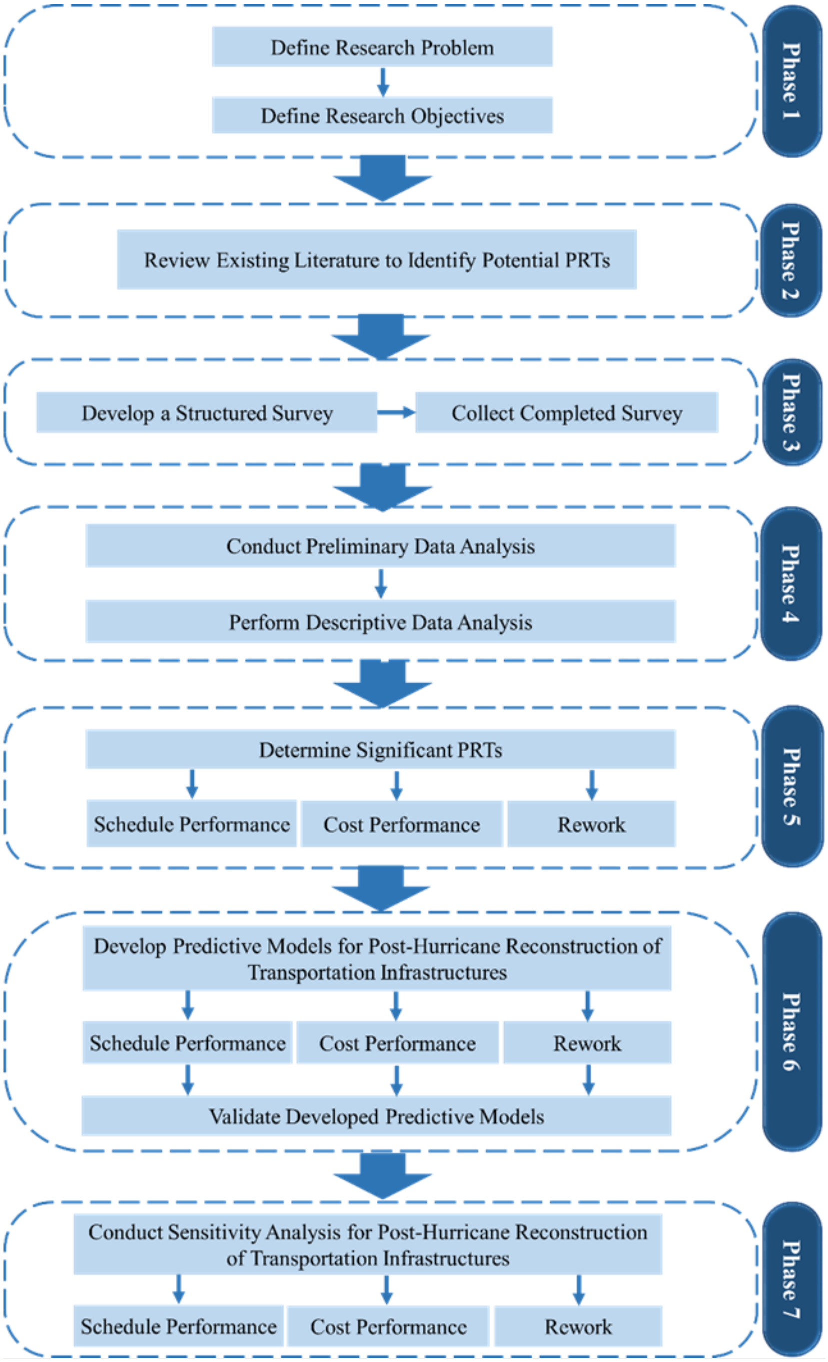


Figure 1. Research framework

3.2. Summary

The research framework is explained in detail in this chapter. The research was conducted in seven phases: (1) definition of the problem statement; (2) literature review; (3) survey development and data collection; (4) preliminary data analysis and statistical analysis tests; (5) development of three predictive models to estimate cost performance, schedule performance, and cost of reworks; and (6) sensitivity analysis of predictors to determine their robustness or fragility. In the next chapter, the procedures followed for survey development and data collection are described in detail.

4. DATA COLLECTION

4.1. Survey Development

The approach adopted for the literature review is presented in Figure 2. It was initiated by entering the following keywords into various search engines to collect relevant scholarly works on post-disaster reconstruction, reconstruction of transportation systems, cost performance of post-hurricane reconstruction of transportation systems, schedule performance of post-hurricane reconstruction of transport infrastructures, cost value of reworks in reconstruction of transportation projects, etc.

As shown in Figure 2, over 200 relevant peer-reviewed journal articles, conference papers, dissertations, and research reports published on post-disaster reconstruction of transportation system were reviewed. More than three-quarters of the articles selected were journal articles because of the rigorousness of their review process. The research team established the following inclusion criteria to establish an appropriate database for this study:

(1) The scholarly works must be published in English,
(2) The scholarly works must have been published after the year 2000,
(3) The scholarly works must have been published by one of the distinguished publishers such as ASCE, Taylor & Francis, Science Direct, etc.

(4) The scholarly works must be associated with post-disaster reconstruction of transportation infrastructures, and

(5) The scholarly works must be associated with engineering areas.

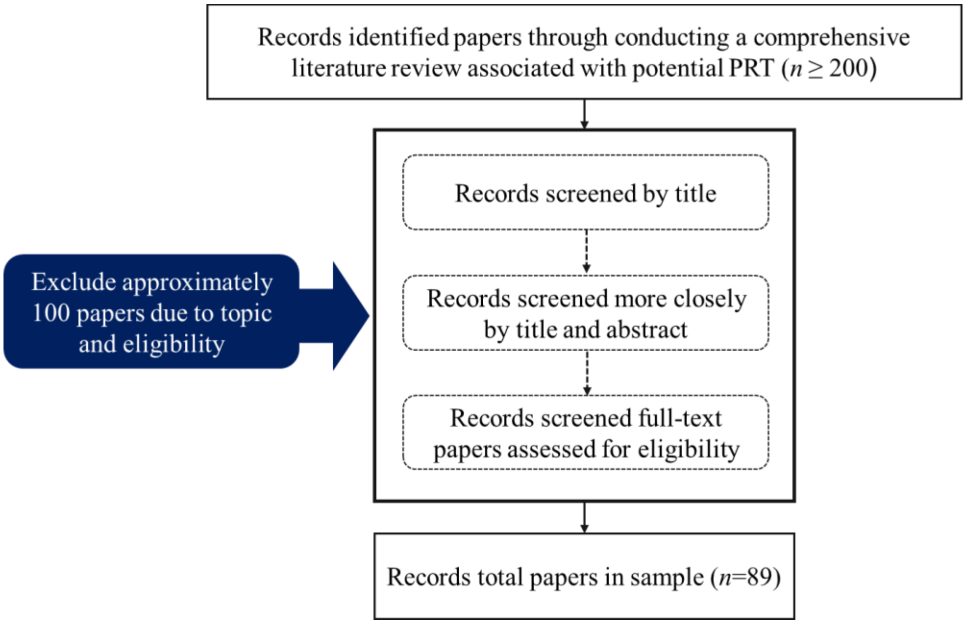


Figure 2. Process of including and excluding articles

After the articles were screened to assess their quality and eligibility, the 89 remaining articles were reviewed in depth to investigate the potentially influential PRTs that affect the cost performance, schedule performance, and cost of reworks for post-hurricane reconstruction of transport infrastructures. The process of identifying the PRTs consisted of two main steps:

(1) Identifying the potential PRTs affecting cost performance, schedule performance, and cost of reworks for post-hurricane reconstruction of transport infrastructures, and

(2) Determining which of the identified potential PRTs were most frequently cited, and retaining those, while excluding the others.

Thirty (30) PRTs were identified as being influential factors, and a structured survey was developed based on them. One question in the survey was devoted to each PRT. The survey consisted of three main parts: (1) respondent information, (2) area transportation network, and (3) project-based information. The questions belonging to the last category were classified into eight categories: general information, physical characteristics of the project, damage level, resources, environment and safety, project management, locality, and legal. The survey consisted of 46 questions, two of which are presented in Figure 3.

I. How many number of main/trunk lines did the selected reconstruction project consist of? (Main/trunk line refers to the primary linkage serving main arteries of interaction and commerce in transportation networks.)

Number:________________

II. What was the total lengths of the selected reconstruction project?

Number:________________

Figure 3. Two sample questions from the survey

The survey respondents were asked to answer the questions based on their involvement in a reconstruction project of transport infrastructures that was damaged by a recent natural disaster. They were also asked to consider the following in their selection of a project:

(1) The reconstruction of transport infrastructures whose damages are due to a hurricane is an acceptable project, and

(2) A reconstruction project with a minimum cost of $1M is highly desirable, as the focus of this study is larger-size projects.

To avoid confusion and collect consistent data, the definitions of the professional words used in each question were included at the end of each question in the survey.

4.2. Institutional Review Board (IRB) Approval

In December 2019, the research team submitted the survey, along with all of the required documents, to UTA's Institutional Review Board (IRB). The members of IRB provided multiple comments on the survey questions and asked the research team to make revisions. After two rounds of comments, the survey was approved for distribution in January of 2020.

4.3. Survey Collection

The research team developed a list of potential respondents, including experts and professionals who have been involved in the post-hurricane reconstruction of transport infrastructures. The list consisted of the name and contact information of more than 500 policy makers, project managers, design and construction engineers, etc. who are working and involved in governmental and private agencies, such as State Transportation Agencies (STA), departments of transportation, and city officials located in the USA. The research team invited the potential respondents to participate in the survey by emailing them an invitation letter and the survey, asking them to complete and return it by February 2020. Roughly 30 completed surveys were collected after three follow-up emails. Unfortunately, the COVID-19 pandemic proved to be a huge obstacle to the process of data collection.

4.4. Survey Respondents

The demographic information of the survey respondents is presented in Table 2, which shows that about 70% of the respondents had work experience of more than 20 years and roughly 35% of the respondents had work experience of less than 20 years. Approximately 25% of the respondents were program managers or directors, and the rest of them were project managers or engineers. All of the participants had been involved as owner stakeholders.

Table 2. Demographic Information of Respondents

Years of Experience	Percentage (%)	Current Role in the Company	Percentage (%)
Less than 10 years	12.5%	Program Manager	8%
Between 10 and 20 years	21%	Director	17%
Between 21 and 30 years	37.5%	Project Manager	30%
More than 30 years	29%	Engineer	45%

4.5. Summary

This chapter explains the procedures followed to collect the data so that it could be analyzed to achieve the aims of this research. The procedure consisted of three steps: (1) development of a structured survey, (2) distribution of the survey, and (3) collection of the completed surveys. The potential PRTs affecting cost performance, schedule performance, and cost of reworks for post-hurricane reconstruction of transport infrastructures were used to develop the survey. In the next chapter, the results of the preliminary data analysis are described in detail, and the outcomes of the statistical analysis that was conducted to determine the PRTs that significantly affect the cost performance, schedule performance, and cost of reworks for reconstruction projects are explained.

5. PRELIMINARY DATA ANALYSIS

5.1. Distribution of Hurricanes

The regions and the associated frequency (i.e., percentage) of the survey responses are presented in Figure 4. Approximately 20% of the surveys completed were from those who had worked on post-hurricane reconstruction of transport infrastructures in Ohio, and approximately 30% were from respondents who had been involved in the reconstruction of transport infrastructures damaged by hurricanes that had occurred in Florida or Alaska.

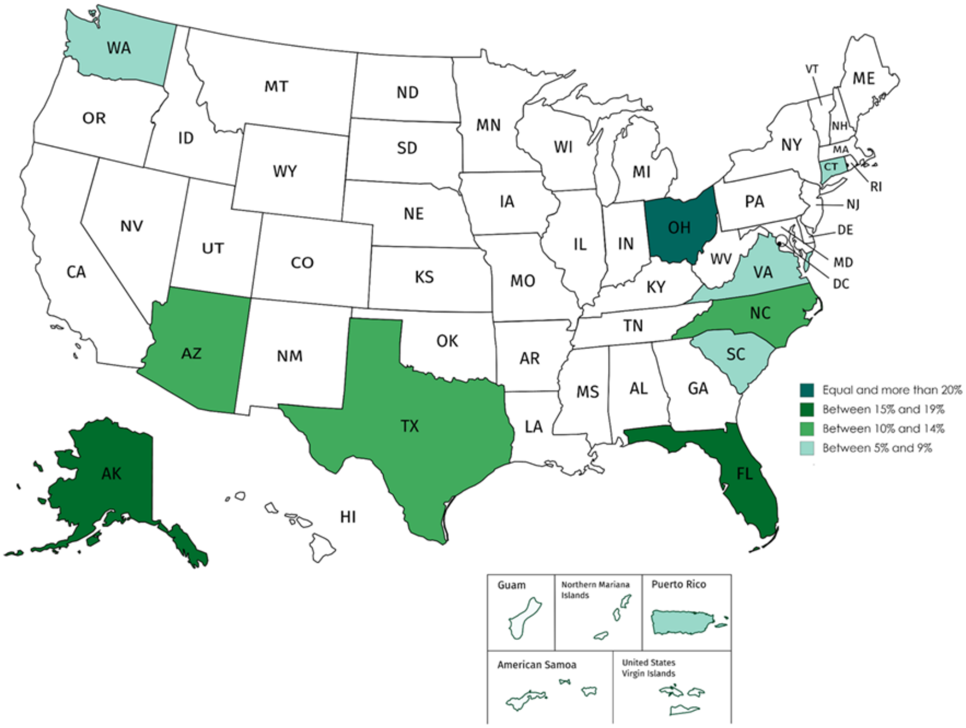


Figure 4. Distribution of hurricanes based on the state of origin

As indicated in Figure 4, more than 9% of the responses were from those who had been involved with damages from hurricanes that occurred in Arizona, Texas, North Carolina, Virginia, Connecticut, South Carolina, Washington, or Puerto Rico.

5.2. Damaging Level of Hurricanes

The respondents were asked to provide information about the level of damage to the transport infrastructures that they were involved in after the hurricane. The results are shown in Figure 5, which illustrates that about 45% of the hurricanes damaged more than 60% of the transport infrastructures, and roughly 35% of the transport infrastructures sustained damages of 30% to 60% of their infrastructure. Figure 5 shows that the minimum level of damage sustained by transport infrastructures was 21%.

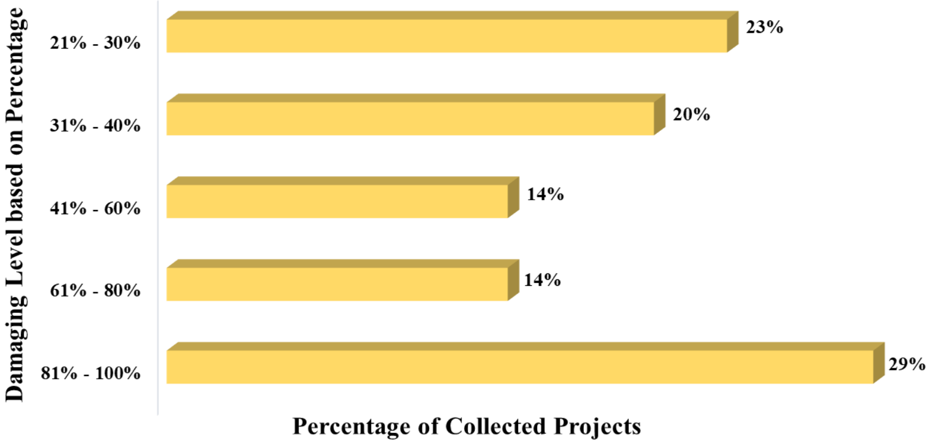


Figure 5. Damaging level of transport infrastructures by hurricanes

5.3. Comparison of Projects’ Baseline Budgets and Actual Costs

As shown in Figure 6, box plots were used to demonstrate the baseline budgets and actual costs of the selected reconstruction projects for which the respondents provided information. The maximum values of the projects’ actual cost and baseline budget were roughly \$150M and \$100M, respectively. The same analysis of the cost values indicated that the median of the projects’ actual cost was about double that of the median of the baseline budget, and the actual cost of reconstruction was substantially higher than the baseline budget.

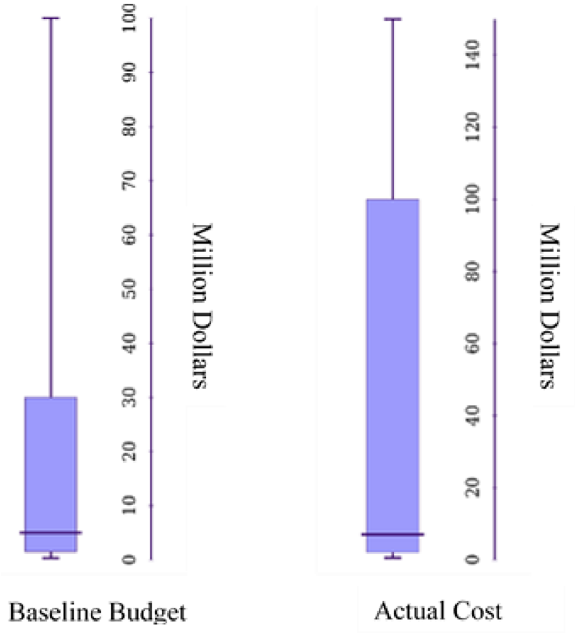


Figure 6. Comparison of projects’ baseline budget and actual cost

5.4. Comparison of Projects’ Baseline Schedule and Actual Time

Box plots were used to demonstrate the baseline schedule and actual duration of the reconstruction projects for which the respondents provided information. The results are presented in Figure 7 and show that the baseline schedules and actual durations of the reconstruction projects were remarkably different. The maximum values of the projects’ actual time and baseline schedules were about 90 months and 60 months, respectively, and the actual time and baseline schedule were roughly 12 months and 20 months, respectively.

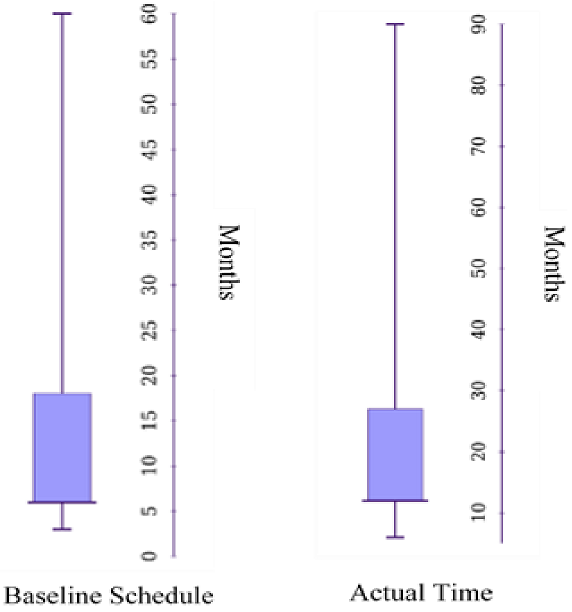


Figure 7. Comparison of projects’ baseline schedule and actual time

5.5. Descriptive Data Analysis

The descriptive data from the analyses associated with baseline and actual budgets and schedules, as well as the rework costs corresponding to the 30 reconstruction projects, is provided in Table 3.

As illustrated in Table 3, the means of the baseline and actual budgets were roughly \$25 million and \$35 million, respectively. Table 3 shows that the means of the baseline and actual schedules were 11 months and 18 months, respectively. The mean and maximum cost values of reworks were roughly \$270 K and \$1 million, respectively.

Table 3. Descriptive Data Analysis

Category		Minimum	Mean	Maximum	Standard Deviation
Cost	Baseline Budget	\$300K	\$22,930K	\$100,000K	\$33,200K
	Actual Cost	\$500K	\$36,540K	\$150,000K	\$53,110K
Schedule	Baseline Schedule	3 Months	11 Months	30 Months	9 Months
	Actual Time	6 Months	18 Months	42 Months	12 Months
Rework	Cost	\$50K	\$264K	\$1,000K	\$361K

5.6. Summary

Chapter 5 describes the preliminary data analysis that was conducted and presents the results of: (1) the distribution of hurricanes, (2) the damage level of the infrastructure after hurricanes, (3) a comparison of projects' baseline budgets and actual costs, (4) a comparison of projects' baseline schedules and actual time, and (5) a descriptive data analysis. The next chapter describes the process of statistical data analysis and presents the results that determined the statistically significant PRTs that affect cost performance, schedule performance, and cost of reworks in the reconstruction of transport infrastructures after hurricanes.

6. STATISTICAL DATA ANALYSIS

6.1. Statistical Analysis Methods

Statistical tests were performed according to the type of data that was collected from the survey. Table 4 summarizes the basic formal statistical methods that were used for the quantitative analysis in this study. *P*-Values that indicated the statistical significance of differences between the two groups were generated through the relevant tests.

Table 4. Statistical Analysis Methods

Statistical Test	Assumptions
Two-sample *t*-test: This test was used where the response is a count or numerical value.	• The two groups follow a normal distribution. • Each Project was independent from other projects.
Kruskal-Wallis: This test was used for Likert scale questions (ordinal seven-point scale), where it could not necessarily be assumed that the data follows a normal distribution.	• The two groups follow an identically scaled distribution. • Each Project was independent from other projects.
Chi-squared test: This test was used for survey questions with binary responses ("Yes" or "No" response), testing whether the observed frequencies of "Yes" or "No" are equal for both targeted groups.	• Each Project was independent from other projects.

Since three types of data were collected from the survey, three different types of statistical analyses were conducted to determine the significant PRTs. As presented in Table 4, for continuous and Likert scale data, the two-sample t-test and the Kruskal-

Wallis test were adopted to determine the significant PRTs. The chi-squared statistical test was implemented for binary questions with “yes” and “no” responses.

6.2. Significant PRTs Affecting Reconstruction Cost Performance

The *P*-Values corresponding to the significant PRTs affecting reconstruction cost performance of transport infrastructures after hurricanes are shown in Table 5. As mentioned earlier, three types of data (continuous, seven-point Likert scale, and binary) were collected from the survey, and the two-sample *t*-test, the Kruskal-Wallis test, and the chi-squared test were performed.

Through the literature, 30 potential PRTs affecting cost and schedule performance and reworks of post-hurricane reconstruction of transport infrastructures were initially identified. As presented in Table 5, the identified PRTs were classified into eight categories: (1) physical characteristics, (2) damage level, (3) resources, (4) quality, (5) project management, (6) environment and safety, (7) legal, and (8) locality.

The first, second, and third columns of Table 5 consist of the names of the main categories, a list of identified PRTs, and the corresponding *P*-values, respectively. This study initially conducted the statistical analysis at the 0.05 significance level, then raised it to 0.1 to include more PRTs. Table 5 presents that 26 of the 30 PRTs were determined statistically significant for the cost performance of reconstruction projects.

Table 5. Results of Significant PRTs Affecting Reconstruction Cost Performance

Category	List of PRTs	*P*-Value
Physical Characteristics	PRT1. Number of main/truck lines	0.051*
	PRT2.Total length	0.049**
	PRT3. Level of complexity	0.036**
	PRT4. Distance from highly-populated area	0.078*
Damaging Level	PRT5. Level of damage	0.044**
	PRT6. Level of traffic disturbance	0.196
Resource	PRT7. Shortage of experts	0.011*
	PRT8. Shortage of field labors	0.054**
	PRT9. Productivity level of contractors	0.069*
	PRT10. Shortage of materials	0.077*
	PRT11. Shortage of equipment	0.017**
	PRT12. Inflation of labor wage	0.096*
	PRT13. Availability level of on-site infrastructure	0.080*
	PRT14. On-site accommodation level for staff	0.066*
	PRT15. Shortage of supplier	0.065*
Quality	PRT16. Quality issues of materials	0.018**
	PRT17. Quality issues of equipment	0.011**
Project Management	PRT18. Frequency level of logistics management issues	0.013**
	PRT19. Quality of on-site inspection	0.072*
	PRT20. Frequency of on-site inspection	0.022**
	PRT21. Information management	0.045*
	PRT22. Pace of decision-making process	0.020**
	PRT23. Implementation level of risk management	0.012**
	PRT24. Coordination	0.046**
	PRT25. Pace of workers’ mobilization	0.258
Environment & Safety	PRT26. Volume of debris	0.082*
	PRT27. Environmental/safety issues prior starting execution of the project	0.033**
	PRT28. Work suspension	0.060*
Legal	PRT29. Regulatory requirement	0.205
Local	PRT30. Availability of required temporary pathways	0.163

*** denotes significant differences with 95% confidence*

** denotes significant differences with 90% confidence*

Table 5 presents that in the case of PRT-3, which belongs to the category of project characteristics, if the reconstruction project is complex, an increased number of reworks that are caused by deficiencies in the workers' knowledge and/or experience is more probable. Ultimately, these reworks might increase the cost of materials so that cost of reconstruction will increase. Since there are commonly financial limitations after a disaster, the stated PRT significantly decreases the cost performance.

Table 5 shows that low-quality materials (PRT-16, belonging to the category of quality) and low-quality equipment (PRT-17, belonging to the category of quality) lead to replacement of them during the reconstruction process, which causes serious shortages in material and equipment resources and increases cost overruns.

Since various organizations are commonly involved in the process of reconstruction, ineffective coordination is a major factor in decreasing workers' productivity and project cost performance. Thus, as shown in Table 5, effective coordination plays a critical role in completing a project within a budget. A slow decision making process (PRT-22, belonging to the category of project management) also often causes delays in the reconstruction of transport infrastructures and increases the probability of cost overruns.

As indicated in Table 5, the implementation of risk management (PRT-23) decreases cost overruns. The timely adoption of risk assessment and management in a reconstruction project helps project managers identify any issues and prevent their consequences by mitigating serious cost overruns.

6.3. Descriptive Comparison of PRTs Affecting Reconstruction Cost Performance

Descriptive comparisons of the mean values of two groups of projects associated with continuous data, one with good cost performance and one with poor cost performance, are presented in Table 6. It is important to mention that good cost performance is considered as less than 10%, and cost performance above 10% is considered a poor cost performance (Sun and Xu 2011).

Table 6. Comparative Analysis of PRTs Affecting Reconstruction Cost Performance – Continuous Data

List of PRTs	Average	
	Good Performance	Poor Performance
PRT1. Number of main/truck lines	5	10
PRT2. Total length	37.85 mi	177.45 mi
PRT4. Distance from highly-populated area	20 mi	34 mi
PRT5. Level of damage	40%	65%
PRT26.Volume of debris	51,200 cy	279,166 cy
PRT27. Environmental/safety issues	1 week	3 months
PRT28. Work suspension through execution of the project	1 week	1 month

Table 6 presents the significant difference between the mean values of the two above-mentioned groups. For instance, the mean of the damage level (PRT-5) as compared with the pre-hurricane condition, was 40% for the projects with good performance, while it was 65% for projects with poor performance. Table 6 presents that the mean volumes of debris for projects with good performance and bad performance were roughly 50,000 CY and 280,000 CY, respectively. The results of

Table 6 indicate that reconstruction projects with poor performance were more complicated than the projects with good performance.

Figure 8 depicts the difference in the mean scores of the two groups of reconstruction projects (those with good cost performance and those with poor cost performance) and associates them with the seven-point Likert scale responses. The mean scores of the Likert-scale data were converted to percentages to make them more readable.

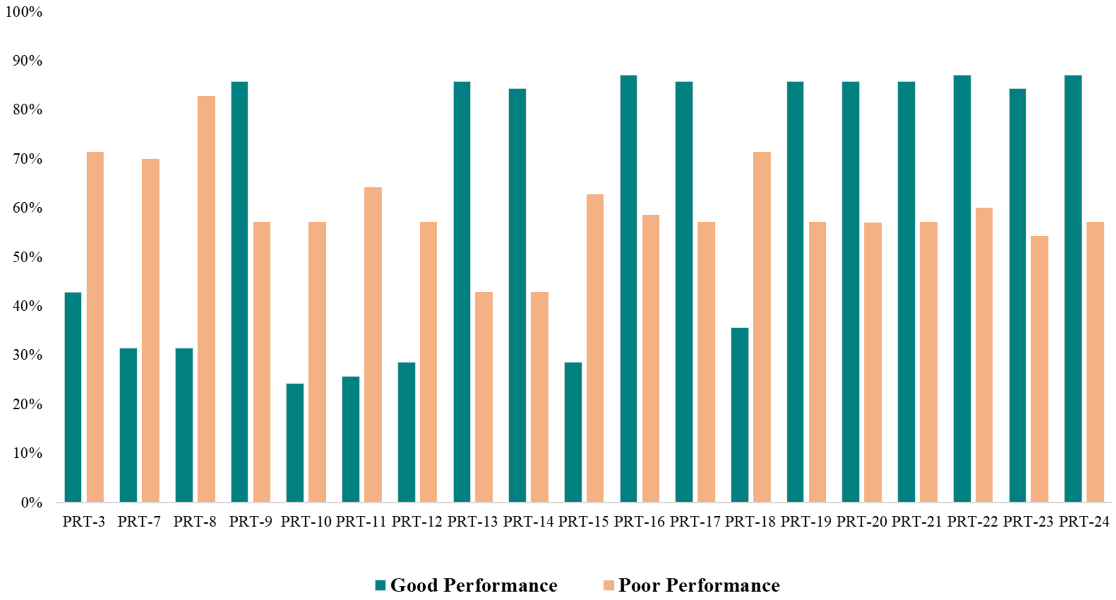


Figure 8. Comparative Analysis of PRTs Affecting Reconstruction Cost Performance–Likert Data

Figure 8 illustrates that the mean scores of the two groups of reconstruction projects (i.e., good performance and poor cost performance) were significantly different. As an example, the mean scores of PRT-10 (shortage of materials) and PRT-11 (shortage of equipment) for projects with good cost performance were considerably lower than the same ones with poor cost performance. As indicated in Figure 8, the mean scores of the implementation level of risk management (PRT-23) and level of effective coordination (PRT-24) in reconstruction projects with poor cost performance were considerably lower than those of good cost performance.

6.4. Determine Significant PRTs Affecting Cost Performance in Highly Damaged and Minimally Damaged Reconstruction Projects

The results of the *P*-Values of the PRTs significantly affecting cost performance for different levels of damage are shown in Table 7. Appropriate statistical tests were performed for the three types of data in the survey (continuous, seven-point Likert scale, and binary). The first and second columns of Table 7 contain the names of the main categories and a list of identified PRTs, respectively. The last two columns of Table 7 present the results of the *P*-values of significant PRTs affecting cost performance associated with the damage level of the reconstruction projects.

Table 7 indicates that this study initially conducted the statistical analysis at the 0.05 significance level, and then raised it to 0.1 to include more indicators of manageable rework causes. Twenty-six (26) out of 30 PRTs were determined statistically significant for highly damaged reconstruction projects; 19 PRTs were recorded as statistically significant for minimally damaged reconstruction projects.

Table 7. Results of Significant PRTs Affecting Cost Performance in Highly Damaged and Minimally Damaged Reconstruction Projects

Category	List of PRTs	*P*-Value	
		Highly Damaged	Minimally Damaged
Physical Characteristics	PRT1. Number of main/truck lines	0.040**	0.022**
	PRT2. Total length	0.025**	0.034**
	PRT3. Level of complexity	0.068*	0.534
	PRT4. Distance from highly-populated area	0.056*	0.036*
Damaging Level	PRT6. Level of traffic disturbance	0.011**	0.397
Resource	PRT7. Shortage of experts	0.001**	0.017**
	PRT8. Shortage of field labors	0.022**	0.075*
	PRT9. Productivity level of contractors	0.078*	0.041**
	PRT10. Shortage of materials	0.081*	0.082*
	PRT11. Shortage of equipment	0.065*	0.037**
	PRT12. Inflation of labor wage	0.055*	0.031**
	PRT13. Availability of on-site infrastructure	0.063*	0.061*
	PRT14. On-site accommodation level for staff	0.325	0.197
	PRT15. Shortage of supplier	0.035**	0.487
Quality	PRT16. Quality issues of materials	0.012**	0.059*
	PRT17. Quality issues of equipment	0.062*	0.085*
Project Management	PRT18. Logistics management issues	0.010**	0.063*
	PRT19. Quality of on-site inspection	0.078*	0.021**
	PRT20. Frequency of on-site inspection	0.085*	0.258
	PRT21. Information management	0.058*	0.089*
	PRT22. Pace of decision-making process	0.071*	0.073*
	PRT23. Risk management	0.008**	0.014**
	PRT24. Coordination	0.001**	0.051*
	PRT25. Pace of workers' mobilization	0.061*	0.357
Environment & Safety	PRT26. Volume of debris	0.044**	0.526
	PRT27. Environmental/safety issues	0.055*	0.070*
	PRT28. Work suspension	0.091*	0.357
Legal	PRT29. Regulatory requirement	0.258	0.278
Local	PRT30. Availability of required temporary pathways	0.195	0.355

*** denotes significant differences with 95% confidence*
** denotes significant differences with 90% confidence*

When PRT-27 (environment/safety issues existing prior to execution of the project) and PRT-28 (delays in beginning the process of reconstruction) occur on highly damaged transportation systems, excessive pressure is often put on the management team and staff to complete the project and return the system to its pre-hurricane condition. Consequently, an increase in the number and cost of reworks might occur due to decreased labor productivity, which would affect the overall cost performance of the project. As shown in Table 7, shortages of experts (PRT-7) and field laborers (PRT-8) are significant factors in the cost of reconstructing both highly damaged and minimally damaged transportation systems. These shortages increase the probability of additional risks and uncertainties in the reconstruction projects and significantly affect their cost performance.

6.5. Determination of Significant PRTs Affecting Reconstruction Schedule Performance

The significant PRTs affecting the schedule performance of post-hurricane reconstruction of transport infrastructures were statistically determined, and the results of the *P*-Values, presented in Table 8, showed that 23 of 30 of the identified PRTs were statistically significant. Three PRTs of PRT-1 (high number of main lines), PRT-3 (level of complexity), and PRT-4 (distance from highly-populated area), belonging to the category of project characteristics, commonly result in complex plans and schedules. In addition, the availability of the mentioned PRTs in a reconstruction project might increase the number of discussions between stakeholders and cause delays. Therefore, these three PRTs had substantial impacts on schedule performance.

Table 8. Results of Significant PRTs Affecting Reconstruction Schedule Performance

Category	List of PRTs	*P*-Value
Physical Characteristics	PRT1. Number of main/truck lines	0.022**
	PRT2. Total length	0.850
	PRT3. Level of complexity	0.042**
	PRT4. Distance from highly-populated area	0.078*
Damaging Level	PRT5. Level of damage	0.011**
	PRT6. Level of traffic disturbance	0.061*
Resource	PRT7. Shortage of experts	0.011**
	PRT8. Shortage of field labors	0.012**
	PRT9. Productivity level of contractors	0.025**
	PRT10. Shortage of materials	0.037**
	PRT11. Shortage of equipment	0.017**
	PRT12. Inflation of labor wage	0.019**
	PRT13. Availability level of on-site infrastructure	0.750
	PRT14. On-site accommodation level for staff	0.410
	PRT15. Shortage of supplier	0.020**
Quality	PRT16. Quality issues of materials	0.081*
	PRT17. Quality issues of equipment	0.021**
Project Management	PRT18. Frequency level of logistics management issues	0.013**
	PRT19. Quality of on-site inspection	0.032**
	PRT20. Frequency of on-site inspection	0.022**
	PRT21. Information management	0.068*
	PRT22. Pace of decision-making process	0.041**
	PRT23. Implementation level of risk management	0.082*
	PRT24. Coordination	0.046**
	PRT25. Pace of workers’ mobilization	0.258
Environment & Safety	PRT26. Volume of debris	0.124
	PRT27. Environmental/safety issues prior starting execution of the project	0.078*
	PRT28. Work suspension through execution of the project	0.001**
Legal	PRT29. Regulatory requirement	0.205
Local	PRT30. Availability of required temporary pathways	0.163

*** denotes significant differences with 95% confidence*

** denotes significant differences with 90% confidence*

Table 8 shows that shortages of materials (PRT.10) and shortages of equipment (PRT.11) significantly lead to time delays in reconstruction projects. They cause multiple challenges and issues in the execution of projects, so that stretching the time required to complete the project and decreasing the schedule performance is a real possibility after a hurricane disaster.

As indicated in Table 8, ineffective coordination (PRT-24) indicates a lack of alignment between reconstruction project organizations and/or team members. In addition, communication among the mentioned teams can be time-consuming and affect the schedule performance. Frequent inspections of construction sites (PRT-20) substantially improve schedule performance of the reconstruction of transport infrastructures after hurricanes and help project managers identify problems and issues in the project and make plans to resolve them in a timely manner, thereby preventing serious time delays.

Table 8 illustrates that a slow pace of decision-making by project managers and/or decision makers significantly decreases schedule performance in post-hurricane reconstruction of transport infrastructures. It leads to failure to accomplish and deliver certain tasks and services on time so that the other related services which are to follow also fall behind and schedule performance is diminished. Suspension of work during execution of reconstruction projects (PRT-28) directly extends the duration required to accomplish the project and impacts the schedule performance of the project.

6.6. Descriptive Comparison of PRTs Affecting Reconstruction Schedule Performance

Descriptive comparisons of the mean values of two groups of projects associated with continuous data, one with good schedule performance and one with poor schedule performance, are presented in Table 9. It is important to mention that good schedule performance is considered as less than 20%, and cost performance above 20% is considered a poor cost performance (Sun and Xu 2011).

Table 9. Comparative Analysis of PRTs Affecting Reconstruction Schedule Performance – Continuous Data

List of PRTs	Average	
	Good Performance	Poor Performance
PRT1. Number of main/truck lines	4	11
PRT4. Distance from highly-populated area	16 mi	32 mi
PRT5. Level of damage	35%	60%
PRT27. Environmental/safety issues	2 weeks	3.5 months
PRT28. Work suspension	2 week	1.5 month

Table 9 presents the significant difference between the mean values of the groups with good schedule performance and poor schedule performance in reconstruction projects. As presented in Table 9, the mean of the damage level (PRT-5) was 35% for the projects with good schedule performance, compared with the pre-hurricane conditions, while it was 60% for projects with poor schedule performance. As shown in Table 9, the post-hurricane reconstruction of transport infrastructures with poor schedule performance was more complex than it was for those with good schedule performance.

Figure 9 shows the difference in the mean scores of the group of reconstruction projects with good schedule performance and the group with poor schedule performance according to the seven-point Likert scale responses. In order to make the data more understandable and readable, the mean scores of the Likert-scale data were converted to percentages.

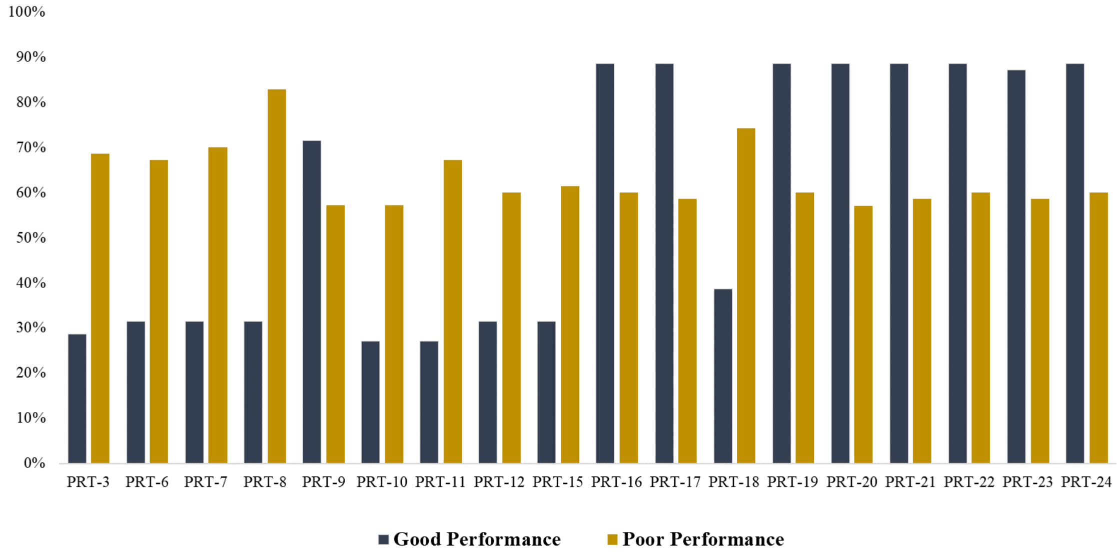


Figure 9. Comparative Analysis of PRTs Affecting Reconstruction Schedule Performance - Likert Data

Figure 9 illustrates that the mean score of reconstruction projects with good schedule performance was significantly different from that of the reconstruction projects with poor schedule performance. For instance, the mean scores of PRT-10 (shortage of materials) and PRT-11 (shortage of equipment) for projects with poor schedule performance were substantially higher than the same ones with good schedule performance. Figure 9 shows that the mean scores of the implementation level of risk management (PRT-23) and level of effective coordination (PRT-24) in reconstruction projects with good schedule performance were considerably higher than those with poor schedule performance.

6.7. Determine Significant PRTs Affecting Schedule Performance in Highly Damaged and Minimally Damaged Reconstruction Projects

The result of the *P*-Values of the significant PRTs affecting schedule performance associated with reconstruction projects with highly damaged as well as minimally transport infrastructures due to hurricanes is presented in Table 10. As explained earlier, responses to three types of questions were collected, so three appropriate statistical tests were conducted of the data. The first and second columns of Table 10 contain the names of the main categories and a list of identified PRTs, respectively. The last two columns of Table 10 present the results of the *P*-values of significant PRTs affecting schedule performance of reconstruction projects in which transport infrastructures were highly damaged and minimally damaged.

As presented in Table 10, 26 of the 30 PRTs were determined statistically significant for the schedule performance of reconstruction of highly damaged transport infrastructures due to hurricanes; 19 PRTs were recorded as statistically significant for the schedule performance of reconstruction of minimally damaged transport infrastructures after hurricanes.

Table 10. Results of Significant PRTs Affecting Schedule Performance in Highly Damaged and Minimally Damaged Reconstruction Projects

Category	List of PRTs	*P*-Value	
		Highly Damaged	Minimally Damaged
Physical Characteristics	PRT1. Number of main/truck lines	0.040**	0.022**
	PRT2. Total length	0.025**	0.034**
	PRT3. Level of complexity	0.068*	0.534
	PRT4. Distance from highly-populated area	0.056*	0.036*
Damaging Level	PRT6. Level of traffic disturbance	0.011**	0.397
Resource	PRT7. Shortage of experts	0.001**	0.017**
	PRT8. Shortage of field labors	0.022**	0.075*
	PRT9. Productivity level of contractors	0.078*	0.041**
	PRT10. Shortage of materials	0.081*	0.082*
	PRT11. Shortage of equipment	0.065*	0.037**
	PRT12. Inflation of labor wage	0.055*	0.031**
	PRT13. Availability of on-site infrastructure	0.063*	0.061*
	PRT14. On-site accommodation	0.325	0.197
	PRT15. Shortage of supplier	0.035**	0.487
Quality	PRT16. Quality issues of materials	0.012**	0.059*
	PRT17. Quality issues of equipment	0.062*	0.085*
Project Management	PRT18. Logistics management issues	0.010**	0.063*
	PRT19. Quality of on-site inspection	0.078*	0.021**
	PRT20. Frequency of on-site inspection	0.085*	0.258
	PRT21. Information management	0.058*	0.089*
	PRT22. Pace of decision-making process	0.071*	0.073*
	PRT23. Risk management	0.008**	0.014**
	PRT24. Coordination	0.001**	0.051*
	PRT25. Pace of workers' mobilization	0.061*	0.357
Environment & Safety	PRT26. Volume of debris	0.044**	0.526
	PRT27. Environmental/safety issues	0.055*	0.070*
	PRT28. Work suspension	0.091*	0.357
Legal	PRT29. Regulatory requirement	0.258	0.278
Local	PRT30. Availability of temporary pathways	0.195	0.355

*** denotes significant differences with 95% confidence*

** denotes significant differences with 90% confidence*

Table 10 presents that shortages of experts (PRT-7) and field laborers (PRT-8) are significant factors in the schedule performance of reconstructing transport infrastructures that were highly or minimally damaged by hurricanes. Shortages of experts and field laborers increase the probability of risks and unknowns/uncertainties in the mentioned projects and remarkably affect the schedule performance of reconstruction projects.

As illustrated in Table 10, environment/safety issues (PRT-27) and delays in beginning the process of reconstruction (PRT-28) occur on highly damaged transport infrastructures due to hurricanes, resulting in additional pressure/force being put on project managers and team members to accomplish the reconstruction project and deliver the services on time. Consequently, the productivity of craft labors might decrease and the probability of delays might increase.

6.8. Determine Significant PRTs Leading to Reconstruction Rework

The results of the PRTs that significantly lead to reworks in reconstruction projects are shown in Table 11. As mentioned earlier, the two-sample *t*-test, Kruskal-Wallis test, and chi-squared test were performed according to the type of data. To avoid any bias created by including large projects in the results, the cost of the issued rework was normalized based on project size. To calculate the normalized cost of rework, the cost of the rework was divided by the baseline budget for the construction phase. These costs were recorded and used for the remainder of the analyses conducted for this study. Table 11 shows that 25 PRTs were recorded as significant in causing reworks in reconstruction projects.

Table 11 indicates that when the reconstruction of a transportation project is complex (PRT-3, belonging to physical characteristics), skilled and experienced site laborers and project managers are vital to its success. After a disaster, clients are usually faced with a shortage of human resources; therefore, when the reconstruction is complex, the probability of reworks being needed due to a dearth of knowledgeable experts might remarkably increase.

As presented in Table 11, the lack of frequent on-site inspections (PRT-20, belonging to the category of project management) and low quality of on-site inspections (PRT-19, belonging to the category of project management) leads to decreased productivity and waste of limited post-hurricane resources. In addition, the lack of sufficient quality and quantity of on-site inspections results in inadequate documentation and records, and often causes duplications of efforts and an increase in the number and cost of reworks.

Suspending work during the execution of a reconstruction project (PRT-28) leads to wasting time and might cause schedule delays. Because project managers commonly make major efforts to mitigate schedule delays and deliver a service on time, they ask team members to work harder to accomplish their tasks in the shortest time. Consequently, the productivity of the team members might be affected and the number and cost of reworks would increase in the project.

Table 11. Results of Significant PRTs Leading to Reconstruction Rework

Category	List of PRTs	*P*-Value
Physical Characteristics	PRT1. Number of main/truck lines	0.021**
	PRT2. Total length	0.256
	PRT3. Level of complexity	0.062*
	PRT4. Distance from highly-populated area	0.011**
Damaging Level	PRT5. Level of damage	0.018**
	PRT6. Level of traffic disturbance	0.637
Resource	PRT7. Shortage of experts	0.033**
	PRT8. Shortage of field labors	0.014**
	PRT9. Productivity of contractors	0.072*
	PRT10. Shortage of materials	0.054*
	PRT11. Shortage of equipment	0.036**
	PRT12. Inflation of labor wage	0.333
	PRT13. Availability of on-site infrastructure	0.044*
	PRT14. On-site accommodation level for staff	0.078*
	PRT15. Productivity of supplier	0.002**
Quality	PRT16. Quality issues of materials	0.029**
	PRT17. Quality issues of equipment	0.066*
Project Management	PRT18. Number of logistics management issues	0.088*
	PRT19. Quality of on-site inspection	0.034**
	PRT20. Number of on-site inspection	0.019**
	PRT21. Information management	0.093*
	PRT22. Pace of decision-making process	0.080*
	PRT23. Implementation level of risk management	0.019**
	PRT24. Coordination	0.077*
	PRT25. Pace of workers' mobilization	0.155
Environment & Safety	PRT26. Volume of debris	0.474
	PRT27. Environmental/safety issues prior starting execution of the project	0.045**
	PRT28. Work suspension through execution of the project	0.085*
Legal	PRT29. Regulatory requirement	0.001**
Local	PRT30. Availability of required temporary pathways	0.011**

*** denotes significant differences with 95% confidence*

** denotes significant differences with 90% confidence*

6.9. Descriptive Comparison of PRTs Leading to Reconstruction Rework

Table 12 shows a descriptive comparison of the mean values of reconstruction projects with low costs of reworks and high costs of reworks associated with continuous data. The mean values of PRTs 1, 4, and 5 are significantly different. For instance, the average distance of a project's location from a highly populated area (PRT-4) in a project with a low cost of reworks is very different from the same project with a high cost of rework. Additionally, the mean of the damage level for reconstruction projects with a low cost of rework was found to be 50%, while the mean of the damage level for projects with a high cost of rework was found to be 70%. Therefore, it was concluded from Table 12 that the reconstruction projects with poor performance were more complicated than those with good performance.

Table 12. Comparative Analysis of PRTs Leading to Reconstruction Rework – Continuous Data

List of PRTs	Average	
	Low Cost of Rework	High Cost of Rework
PRT1. Number of main/truck lines	9	3
PRT4. Distance from highly-populated area	12.5 mi	30.5 mi
PRT5. Level of damage	50%	70%

The differences in the mean scores associated with the data on low cost of rework and high cost of rework for the seven-point Likert scale responses are shown in

Figure 10. The mean scores were converted to percentages to make them more understandable and readable.

Figure 10 indicates that the mean scores of the mentioned two groups are significantly different. Figure 10 shows that the mean scores of the seven PRTs in the reconstruction projects with high cost of rework are considerably higher than those of the projects with low cost of reworks. These factors are PRT-3 (level of complexity), PRT-7 (shortage of experts), PRT-10 (shortage of materials), PRT-11 (shortage of equipment), PRT-18 (number of logistics management issues), and PRT-29 (regulatory requirement).

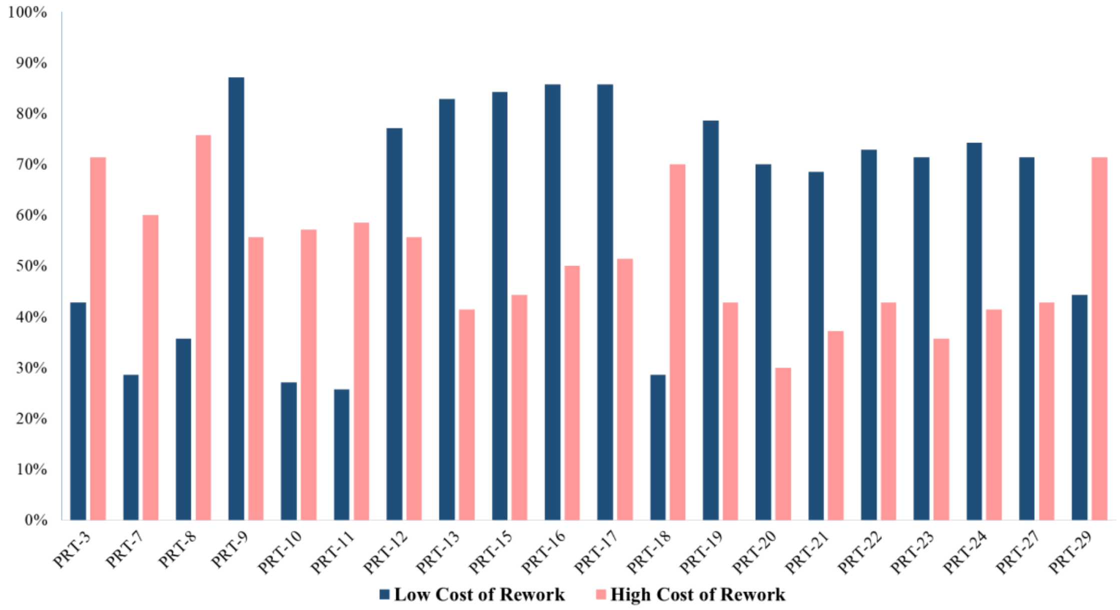


Figure 10. Comparative analysis of PRTs Leading to Reconstruction Rework – Likert Data

6.10. Determine Significant PRTs Leading to Reconstruction Rework in Highly Damaged and Minimally Damaged Transport infrastructures

The PRTs significantly affecting the cost of reworks associated with the two groups (highly damaged and minimally damaged) were statistically determined and are presented in Table 13. Three types of statistical analysis methods, the two-sample *t*-test, chi-Square test, and Kruskal-Wallis test, were adopted and administered according to the type of data. Table 13 indicates that 24 of the 30 PRTs were determined statistically significant for highly damaged reconstruction projects, and 20 PRTs were recorded as statistically significant for minimally damaged reconstruction projects.

As presented in Table 13, the availability of PRT-1 (number of main lines), PRT-3 (level of complexity), and PRT-4 (distance from highly-populated area), belonging to the category of physical characteristics in the highly damaged post-hurricane reconstruction of transport infrastructures, make projects more complicated and increase the number of uncertainties and risks. These issues may lead to suspension of the projects, frustration of the team members, and the fostering of low productivity, thereby increasing the number and cost of reworks.

Table 13. Results of Significant PRTs Leading to Reconstruction Rework in Highly Damaged and Minimally Damaged Transport infrastructures

Category	List of PRTs	*P*-Value	
		Highly Damaged	Minimally Damaged
Physical Characteristics	PRT1. Number of main/truck lines	0.029**	0.025**
	PRT2. Total length	0.254	0.359
	PRT3. Level of complexity	0.092*	0.083*
	PRT4. Distance from highly-populated area	0.028**	0.013**
Damaging Level	PRT6. Level of traffic disturbance	0.634	0.179
Resource	PRT7. Shortage of experts	0.011**	0.016**
	PRT8. Shortage of field labors	0.091*	0.055*
	PRT9. Productivity of contractors	0.071*	0.059*
	PRT10. Shortage of materials	0.020**	0.089*
	PRT11. Shortage of equipment	0.014*	0.001**
	PRT12. Inflation of labor wage	0.199	0.435
	PRT13. Availability of on-site infrastructure	0.007**	0.031**
	PRT14. On-site accommodation for staff	0.088*	0.633
	PRT15. Productivity of supplier	0.059*	0.074*
Quality	PRT16. Quality issues of materials	0.016**	0.027**
	PRT17. Quality issues of equipment	0.037**	0.015**
Project Management	PRT18. Number of logistics management issues	0.056*	0.072*
	PRT19. Quality of on-site inspection	0.066*	0.028**
	PRT20. Number of on-site inspection	0.080*	0.017**
	PRT21. Information management	0.069*	0.077*
	PRT22. Pace of decision-making process	0.022**	0.759
	PRT23. Implementation level of risk management	0.082*	0.032**
	PRT24. Coordination	0.022**	0.075*
	PRT25. Pace of workers' mobilization	0.058*	0.153
Environment & Safety	PRT26. Volume of debris	0.195	0.174
	PRT27. Environmental/safety issues prior starting execution of the project	0.647	0.357
	PRT28. Work suspension	0.019**	0.754
Legal	PRT29. Regulatory requirement	0.033**	0.001**
Local	PRT30. Availability of temporary pathways	0.391	0.351

*** denotes significant differences with 95% confidence*
** denotes significant differences with 90% confidence*

Information management (PRT-21) also plays a critical role in the reconstruction of both highly and minimally damaged transport infrastructures after hurricanes by tracking projects' resources, improving budgeting and cost analyses, and mitigating risks. Lack of information management seriously affects the quality of project management and results in more reworks. Moreover, the lack of effective coordination (PRT-24) significantly increases the number of reworks, as well as the cost of reworks in reconstruction of both highly and minimally damaged transport infrastructures. Ineffective coordination of a project leads to inconsistent performance of tasks and/or services and propagates unnecessary reworks.

6.11. Summary

This chapter consisted of three categories of post-hurricane reconstruction of transport infrastructures: (1) cost performance, (2) schedule performance, and (3) reworks. Each category included four sub-categories: (1) statistical tests to determine significant PRTs, (2) descriptive analyses for Likert responses and numerical responses, and (3) statistical analysis test to determine the PRTs that are significant in the reconstruction of transport infrastructures highly and minimally damaged by hurricanes. As three types of responses (binary, continuous, and Likert-scale) were collected by the survey, three types of statistical analyses were conducted: chi-squared, two-sample *t*-test, and Kruskal-Wallis test. The following chapter describes the process of developing predictive models for cost performance, schedule performance, and cost of reworks.

7. DEVELOPMENT OF PREDICTION MODELS

7.1. Data Z-Transformation

Since the survey was designed based on three types of questions (continuous, Likert-scale, and binary), three types of data were collected, which necessitated converting the data to a dimensionless quantity (Larsen and Marx 1981). The auto-scaling method, which is also called z-transformation, was adopted to normalize the data because it is a useful technique that allows using different types of data without considering their original scales.

The equation of z-transformation (Eq.1) is presented as follows:

$$z = \frac{x - \mu}{\sigma} \qquad \text{Eq.1}$$

where x is an observation, μ is the mean of the distribution, and σ is the standard deviation. The positive and negative values of z-score, which are obtained from Eq.1, indicate that the observation (x) is larger and smaller than the value of the mean, respectively.

7.2. Stepwise Multiple Regression Data Reduction

The regression analysis method is recognized as an efficient tool for researchers and practitioners (Armestrong 2012). Stepwise multiple regression was adopted to investigate the relationships between the influential factors and dependent variable. This method generates a prediction model from a series of influential variables by adding and removing the variables (Lowe et al. 2006). The purpose of the stepwise regression method is to generate an equation by combining the influential variables to successfully predict the dependent variables. It is important to note that some, but not all, of independent variables might be entered into the generated equation. To clarify how stepwise regression works, each independent variable is entered into the generated equation at each step, with the one that contributes the most to the generated regression equation, based on higher multiple correlation, R, entered first. This procedure is continued until adding the independent variable would not increase the value of R-squared (i.e. coefficient of determination) of the regression equation. In other words, if adding an independent variable could not increase the value of R-squared, the process would be terminated.

7.3. Stepwise Multiple Regression for Reconstruction Cost Performance

The stepwise multiple regression method was adopted to develop a predictive model for cost performance of post-hurricane reconstruction of transport infrastructures. The results are presented in Table 14, which illustrates that the cost performance predictive model, based on 30 observations, received an *R*-Squared of 0.953 (95.3%). This value indicates that 95.3% of the cost performance is described by the obtained equation of regression.

Table 14. Results of Stepwise Multiple Regression for Reconstruction Cost Performance

Model Parameter	Value
R	0.976
R^2	0.953
Adjusted R^2	0.924
Standard Error	0.2012
Significance	0.000
F-Value	32.215
Durbin-Watson	1.639

The final predictors of the cost performance model were obtained by stepwise multiple regression and are presented in Table 15, which shows that the results consisted of unstandardized regression coefficients (B) and standardized coefficient (Beta). Regression coefficients indicate a change in the mean of the dependent variable for one unit of change in each predictor, while the rest of predictors remain constant. In addition, Table 15 presents the value of standard errors of the regression coefficients and the significance levels (*P*-Value) associated with predictors of a cost performance model.

Seven independent variables were recorded as influential predictors in the prediction model and are shown in Table 15. These seven predictors are: (1) inflation of labor wages (PRT.12), (2) on-site accommodation level for staff (PRT.14), (3) frequency level of logistics management issues (PRT.18), (4) frequency of on-site inspections (PRT.20), (5) information management (PRT.21), (6) pace of decision-making process (PRT.22), and (7) environment/safety issues existing prior to execution of the project (PRT.27).

Table 15. Summary of Predictive Model for Reconstruction Cost Performance

Independent Variables	Coefficient B	Standard Error	Beta	T	*P*-Value
Constant	0.106	0.007	-	14.174	0.000
PRT.12	-0.061	0.008	-0.524	-7.350	0.000
PRT.22	-0.046	0.011	-0.588	-4.354	0.001
PRT.27	-0.068	0.010	-0.505	-6.785	0.000
PRT.20	-0.026	0.006	-0.306	-4.545	0.001
PRT.18	0.061	0.010	0.472	5.893	0.000
PRT.14	0.032	0.013	0.306	2.369	0.037
PRT.21	0.017	0.007	0.185	2.280	0.044

PRT.12: Inflation of labor wage
PRT.14: On-site accommodation level for staff
PRT.18: Frequency level of logistics management issues
PRT.20: Frequency of on-site inspection
PRT.21: Information management
PRT.22: Pace of decision-making process
PRT.27: Environmental/Safety issues prior starting execution of the project

Table 15 shows that information management (PRT.21) directly improves the cost performance of post-hurricane reconstruction of transport infrastructures. It helps by providing all of the parties involved in the project with important information and data in a timely manner so that duplication of tasks does not occur. Consequently, it has the potential for reducing overruns.

Conducting frequent on-site inspections (PRT.20) helps project managers detect probable issues and/or identify reconstruction risks in a timely manner so that they are able to assess and manage the problems and mitigate or eliminate cost overruns. As shown in Table 15, inflation of labor wages (PRT.12) directly increases the budget for completing the reconstruction project, which affects the overall cost performance.

The presence of environment/safety issues (PRT.27) before a reconstruction project commences requires additional funds to correct the problem and prevent cost overruns. Table 15 indicates that logistic management (PRT.18) is one of the influential predictors that affects the cost of post-hurricane reconstruction projects. After disasters, there is commonly a shortage of transportation of facilities for transferring required materials and equipment, as well as a shortage of the most effective routes for facility transportation to occur. Resolving these issues increases the cost of the projects, thereby decreasing the cost performance.

The predictive model for the cost performance of post-hurricane reconstruction of transport infrastructures was validated by verifying the homogeneity of variances with an analysis of residuals. The results are presented in Figures 11 and 12.

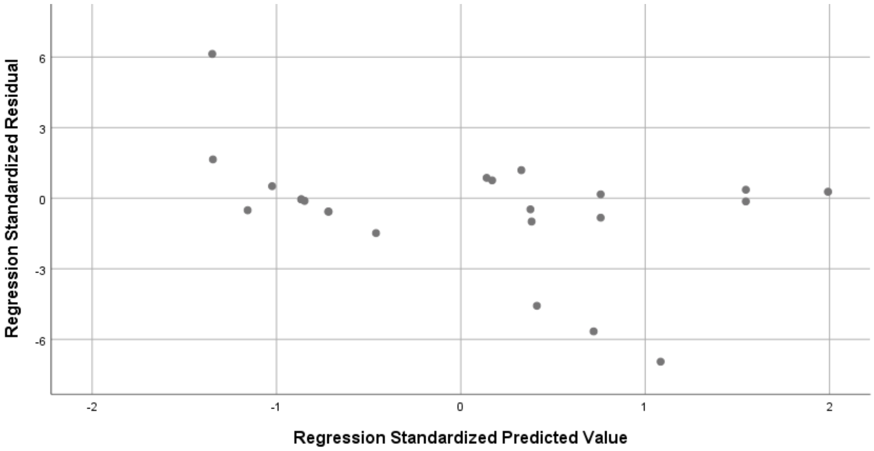


Figure 11. Scatter Plot of the Residuals against the Predicted Value for Reconstruction Cost Performance

Figure 11 depicts the scatter plot of the residuals shows that the residuals behave randomly and the model fitted the data well. In other words, residual analysis was implemented to confirm the goodness of the fit to the model. Figure 11 indicates that there is no relationship between residuals and predicted values, so the assumptions of linearity and homogeneity of variance were met.

The normal probability plot of regression standardized residual for reconstruction cost performance is shown in Figure 12. This figure presents that the points are located close to a straight line, confirming that the residuals are mostly normally distributed.

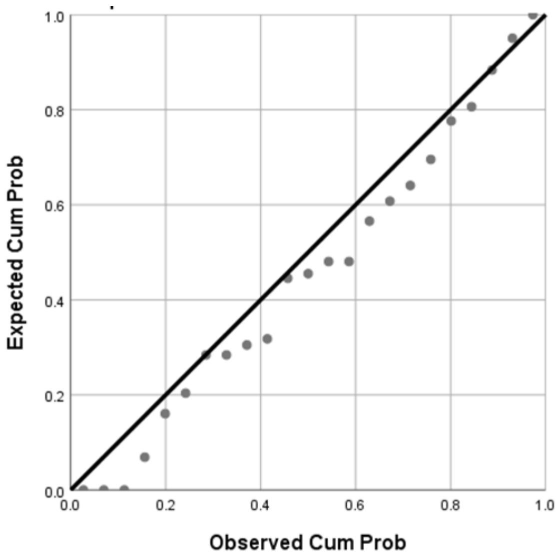


Figure 12. Normal Probability of Regression Standardized Residual for Reconstruction Cost performance

7.4. Stepwise Regression for Reconstruction Schedule Performance

A stepwise multiple regression method was adopted to develop a predictive model for the schedule performance of post-hurricane reconstruction of transport infrastructures. Table 16 shows the results and presents that the predictive model for schedule performance, based on 30 observations, received an *R*-Squared of 0.996 (99.6%). The value of *R*-Squared means that 99.6% of the schedule performance is described by the obtained equation of regression.

Table 16. Results of Stepwise Multiple Regression for Reconstruction Schedule Performance

Model Parameter	Value
R	0.998
R^2	0.996
Adjusted R^2	0.992
Standard Error	0.00395
Significance	0.000
F-Value	265.088
Durbin-Watson	1.738

Table 17 presents the list of final predictors of a schedule performance model that was obtained by implementing the stepwise multiple regression method. Table 17 contains the results of both the unstandardized regression coefficients (B) and standardized coefficients (Beta). Regression coefficient indicates the change of mean in dependent variable for one unit of change in each predictor, while the rest of the predictors remain constant.

The influential predictors obtained by the stepwise multiple regression method are presented in Table 17, which shows nine influential predictors: (1) level of project complexity (PRT.03), (2) level of traffic disturbance (PRT.06), (3) shortage of materials (PRT.10), (4) shortage of equipment (PRT.11), (5) inflation of labor wages (PRT.12),

(6) shortage of suppliers (PRT.15), (7) frequency of onsite inspections (PRT.20), (8) information management (PRT.21), and (9) environment/safety issues present prior to executing the project.

Table 17. Summary of Model Variables for Reconstruction Schedule Performance

Independent Variables	Coefficient B	Standard Error	Beta	T	*P*-Value
Constant	0.099	0.001	-	68.369	0.000
PRT.12	-0.050	0.004	-0.606	-11.647	0.000
PRT.20	-0.063	0.003	-0.844	-23.311	0.000
PRT.06	-0.045	0.003	-0.600	-13.377	0.000
PRT.27	-0.046	0.003	-0.547	-13.965	0.000
PRT.03	0.017	0.002	0.193	7.000	0.000
PRT.15	0.031	0.003	0.375	9.527	0.000
PRT.11	0.025	0.004	0.281	5.651	0.000
PRT.10	0.012	0.003	0.159	4.309	0.002
PRT.21	-0.009	0.003	-0.100	-3.303	0.009

PRT.03: Level of complexity
PRT.06: Level of traffic disturbance
PRT.10: Shortage of materials
PRT.11: Shortage of equipment
PRT.12: Inflation of labor wage
PRT.15: Shortage of supplier
PRT.20: Frequency of on-site inspection
PRT.21: Information management
PRT.27: Environmental/Safety issues prior starting execution of the project

As presented in Table 17, increasing complexity in a reconstruction project (PRT.03) requires experts and professionals to execute the project with minimum errors and mistakes. However, it is common for reconstruction projects to experience a lack of these types of workers after disasters, which results in delays.

Table 17 indicates that heavy traffic and traffic disturbances (PRT. 06) are strong predictors of the schedule performance for post-hurricane reconstruction projects.

Traffic disturbances increase the frequency of accidents so that delivering materials and equipment at the right time might not be possible and the schedule performance of the projects would be affected.

Shortages of materials (PRT.10) and shortages of equipment (PRT.11) were recorded as two influential predictors for the schedule performance of post-hurricane reconstruction projects since they extend the completion of the projects past the estimated and budgeted time. As shown in Table 17, a lack of sufficient suppliers after disasters significantly increases the time required for completing the projects and, therefore, seriously affects schedule performance.

Table 17 shows that the frequency of on-site inspections is another predictor that influences the schedule performance of post-hurricane reconstruction. More frequent on-site inspections lead to timely identification and management of reconstruction risks, thus mitigating schedule delays.

To validate the predictive model for post-hurricane reconstruction of schedule performance in transport infrastructures, the homogeneity of variances was verified in an analysis of residuals, and the results are presented in Figure 13. This figure indicates that the residuals do not completely behave randomly. Accordingly, further studies would be conducted using the method of extreme bound analysis to determine the influential predictors who were robustly connected to the regression model. The process of adopting the mentioned method and their results is presented in the next chapter.

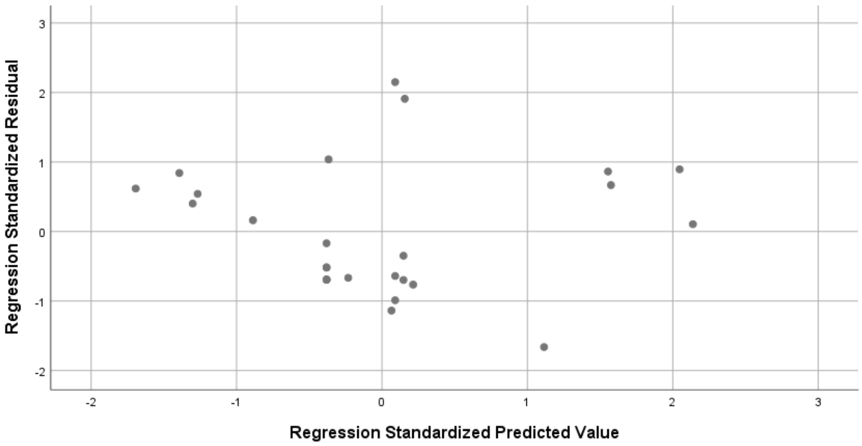


Figure 13. Scatter Plot of the Residuals against the Predicted Value for Reconstruction Schedule Performance

Figure 14 presents the normal probability plot of regression standardized residual for a reconstruction schedule performance and shows that the points are positioned close to a straight line, which confirms that the residuals are mostly normally distributed.

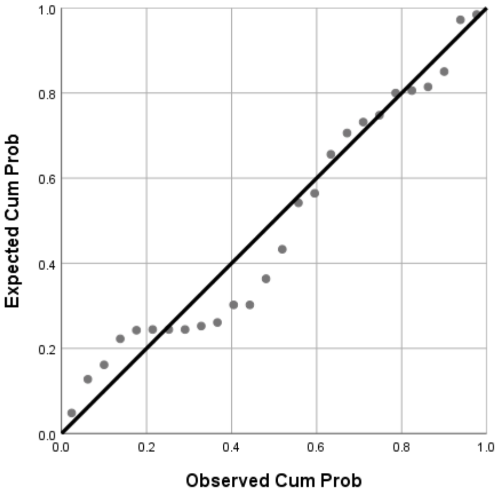


Figure 14. Normal Probability of Regression Standardized Residual for Reconstruction Schedule performance

7.5. Stepwise Regression for Reconstruction Rework

The stepwise multiple regression method was implemented to develop a predictive model for the cost of reworks for post-hurricane reconstruction of transport infrastructures. The results presented in Table 18 show that the predictive model for the cost of reworks, based on 30 observations, recorded an *R*-Squared of 0.998 (99.8%). The value of *R*-Squared meant that 99.8% of the cost of reworks in post-hurricane reconstruction projects can be explained by the generated equation of regression.

Table 18. Results of Stepwise Multiple Regression for Reconstruction Rework

Model Parameter	Value
R	0.999
R^2	0.998
Adjusted R^2	0.996
Standard Error	0.04615
Significance	0.000
F-Value	639.996
Durbin-Watson	2.055

The list of influential predictors obtained by the stepwise multiple regression method is given in Table 18 and illustrates the results of unstandardized regression coefficients (B) and standardized coefficients (Beta). Regression coefficients describe the change of means in the cost of reworks for one unit of change in each influential predictor, while the rest of predictors remain constant. Table 18 shows the value of standard errors of the regression coefficients and the significance levels (*P*-Value) associated with the predictors of the cost of reworks model.

Table 19 clearly shows that ten independent variables were recorded as influential predictors in the predictive model. The stated influential predictors are: (1) distance from highly-populated area (PRT.04), (2) shortage of field laborers (PRT.08), (3) frequency level of logistics management issues (PRT.18), (4) frequency of on-site inspection (PRT.20), (5) information management (PRT.21), (6) coordination (PRT.24), (7) environmental/safety issues prior starting execution of the project (PRT.27), (8) work suspension through execution of the project (PRT.28), (9) regulatory requirement (PRT.29), and (10) availability of required temporary pathways (PRT.30).

Table 19. Model Variables Summary for Reconstruction Rework

Independent Variables	Coefficient B	Standard Error	Beta	T	*P*-Value
Constant	1.454	0.021	-	70.343	0.000
PRT.28	-1.728	0.032	-1.983	-53.754	0.000
PRT.20	-0.935	0.020	-0.710	-45.930	0.000
PRT.30	0.404	0.023	0.319	17.643	0.000
PRT.29	0.302	0.024	0.240	12.804	0.000
PRT.04	0.622	0.033	0.390	19.105	0.000
PRT.24	0.532	0.027	0.593	19.894	0.000
PRT.08	-0.548	0.036	-0.317	-15.423	0.000
PRT.18	-0.345	0.031	-0.215	-11.286	0.000
PRT.27	0.156	0.040	0.086	3.906	0.008
PRT.21	-0.048	0.020	-0.450	-2.457	0.049

PRT.04: Distance from highly-populated area
PRT.08: Shortage of field labors
PRT.18: Frequency level of logistic management issues
PRT.20: Frequency of on-site inspection
PRT.21: Information management
PRT.24: Coordination
PRT.27: Environmental/Safety issues prior starting execution of the project
PRT.28: Work suspension through execution of the project
PRT.29: Regulatory requirement
PRT.30: Availability of required temporary pathways

An insufficient number of laborers (PRT.08) substantially increases the number of reworks in a post-hurricane reconstruction project, as shown in Table 19. It also puts added pressure on the laborers to complete the project on time, which has the potential to increase the number of mistakes, necessitate reworks, and increase the cost of the project.

Table 19 shows that both ineffective information management (PRT.21) and ineffective coordination (PRT.24) increase reworks in the post-hurricane reconstruction of transport infrastructures. Effective coordination and information management lead to a transfer of needed knowledge, data, and information at the right time among the project management team (PMT) and staff. Conversely, ineffective coordination and information management can increase the number of mistakes and errors made in a reconstruction project, thereby increasing the number of reworks and project cost.

Ineffective logistic management (PRT.18) causes issues that increase the frequency and cost of reworks in the post-hurricane reconstruction of transport infrastructures. A lack of effective logistic management leads to the inability to anticipate logistic risks and issues, and unexpected risks add pressure to team members and project managers to accomplish the project on time. As a result, the number of errors made by the laborers increases which directly affects cost of the reworks.

The homogeneity of variances was verified by an analysis of residuals in order to validate the predictive model for post-hurricane reconstruction rework in transport infrastructure projects, and the results are shown in Figure 15. This figure presents that the residuals behave randomly, indicating that the predictive model for reconstruction rework fits the data well.

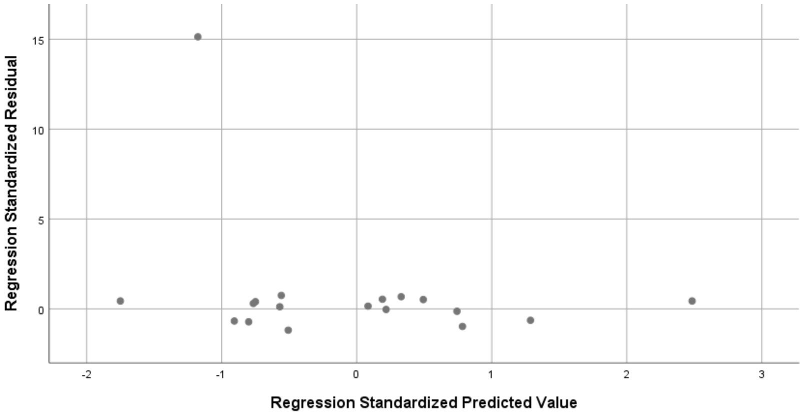


Figure 15. Scatter Plot of the Residuals against the Predicted Value for Reconstruction Rework

The normality of the response was verified by investigating the normal probability plot associated with the regression standardized residual for reconstruction rework in transport infrastructure projects after hurricanes, and the result is plotted in Figure 16. As shown, the probability distribution is recorded as normal because the scatters are located close to the straight line.

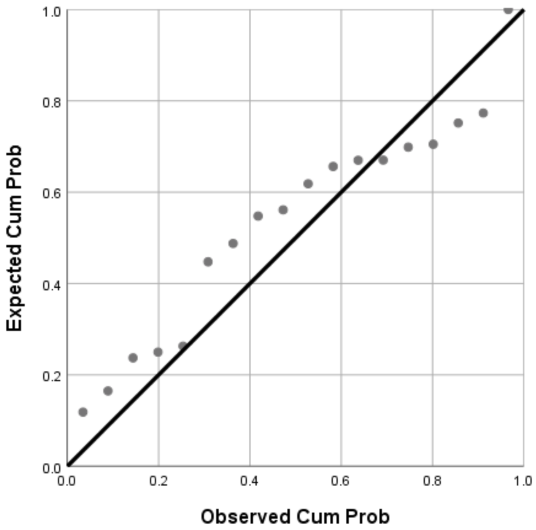


Figure 16. Normal Probability of Regression Standardized Residual for Reconstruction Rework

7.6. Comparative Analysis of the Significant Predictors

In this section, significant predictors contributing cost performance, schedule performance, and rework in post-hurricane reconstruction of transportation infrastructures were comparatively analyzed and the results are schematically presented in Figure 17. This figure indicates that frequency of on-site inspection (PRT.20), information management (PRT.21), and safety/environment issues (PRT.27) were recorded as influential predictors in all three developed models to predict cost performance, schedule performance, and reworks.

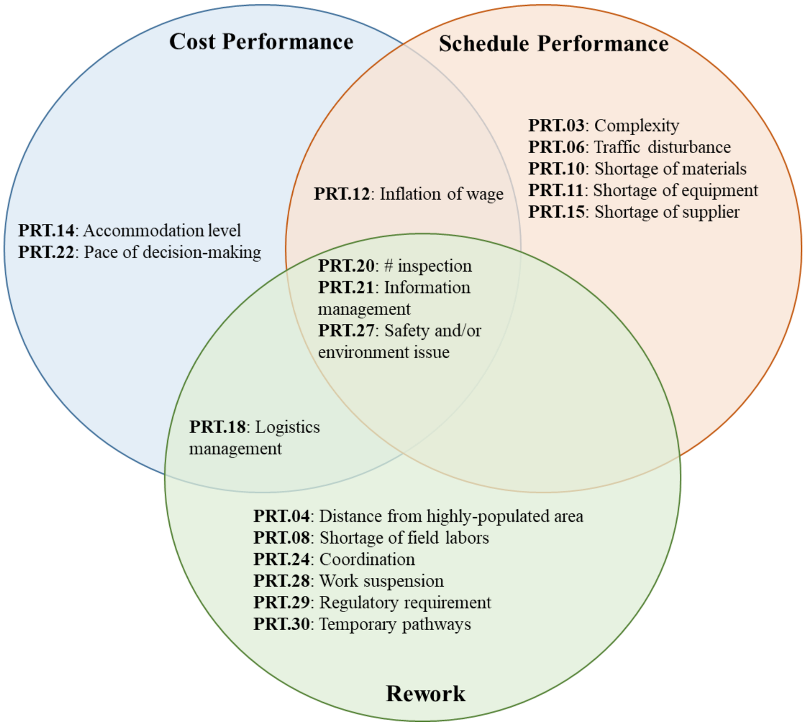


Figure 17. Schematic Results of Comparative Analysis for Significant Predictors

As presented in Figure 17, frequent on-site inspection through execution of reconstruction project is one of the shared PRTs that substantially help project management team identify any available and/or probable issues and problems at the right time. Thus, project management team could adopt effective strategies to resolve the identified issues. As a result, reconstruction cost and schedule performance as well as reconstruction reworks would increase in the mentioned projects.

Figure 17 shows that information management (PRT.21) is one of the shared PRTs considerably contributing cost and schedule performance as well as rework in post-hurricane reconstruction of transportation infrastructures. Information management in a reconstruction project leads to transferring knowledge, data, and information at the right time among the project's parties. Therefore, project managers could effectively manage project in order to prevent and/or mitigate any major issues and/or mistakes so that considerable schedule delays, cost overruns, and reworks would be avoidable.

Moreover, environment and/or safety issues (PRT.27) through post-hurricane reconstruction of transportation infrastructure would seriously contribute to cost escalations, time delays, and reworks in these projects. Availability of safety and/or environment issues in a project causes multiple challenges and risks through execution of the project and leading to cost and duration of the project. In addition, with increasing risks, different errors and mistakes might be derived in the project.

7.7. Summary

This chapter describes the process of developing three models to predict the cost performance, schedule performance, and cost of reworks for the reconstruction of transport infrastructures damaged by hurricanes. Stepwise multiple regression was used to develop the models. In the equations of predictive models, seven, nine, and ten predictors were recorded as significant to the reconstruction cost performance, schedule performance, and rework, respectively. The homogeneity of variances associated with the three predictive models was verified in an analysis of residuals in order to validate that the residuals behave randomly. The normality of the response belonging to three predictive models was verified by investigating the normal probability plot associated with the regression standardized residual for reconstruction cost performance, schedule performance, and cost of reworks in transport infrastructures after hurricanes. Next, comparative analysis was conducted to identify the shared influential predictors which contribute to cost overruns, schedule delays, and rework in these projects. In the next chapter, the process of conducting a sensitivity analysis to determine which of the predictors are robustly related to predictive models and equations is described, and the results are given.

8. EXTREME BOUND ANALYSIS

8.1. Overview of the EBA Method

Formally, adoption of the regression method helps researchers and authors investigate the relationship between dependent and independent variables. Unfortunately, the results may be vague, so the EBA method was proposed to deal with the mentioned issue by addressing model uncertainty in regression analysis. The EBA method assists in determining which influential predictors are robust and which are fragile, as it was designed to answer the following question: “Which influential predictors are robustly connected with dependent variable?”

Leamer (1983) and Leamer and Leonard (1983) proposed the method of EBA as a tool for measuring the sensitivity of regression estimates. In 1985, Leamer explained the fragility of the regression method for making arbitrary decisions regarding the selection of control variables. Afterwards, other researchers and authors such as Levine and Renelt (1992) and Sala-i-Martin (1997) adopted EBA to conduct robustness and sensitivity analyses associated with influential predictors.

Adopting the EBA method helps researchers determine the robustness of the influential predictors (Chanegriha et al. 2014; Chanegriha et al. 2017). It changes the subset of control variables included in the regression to determine the broadest range of coefficient estimates of the influential predictors that standard hypothesis tests do not reject. If the coefficients remain statistically significant, the influential predictors are considered robust (Changeriha et al. 2014; Changeriha et al. 2017).

The concept of EBA is simple. It is adopted to determine which variables from the set of $\boldsymbol{X}$ have robust relationships with the dependent variable of *y*. The process of EBA starts with running a large number of regression models. Each regression model consists of a dependent variable (*y*), a set of standard exploratory variables ($\boldsymbol{F}$), and a different subset ($\boldsymbol{D}$) of the variables in $\boldsymbol{X}$**.** Accordingly to the existing literature, $\boldsymbol{F}$ and $\boldsymbol{X}$ refer to free variables and doubtful variables, respectfully. In the method of EBA, the doubtful variables (i.e., $\boldsymbol{X}$) whose regression coefficients remain statistically significant in a sufficient number of estimated models, are considered as robust, while the others are labeled fragile. To clarify, consider a focus variable $v \epsilon \boldsymbol{X}$ in Eq. 2, which needs to determine whether there is a robust relationship with the dependent variable. The above-mentioned set of regression models are estimated with the following form:

$$y = \alpha_i + \beta_i v + \gamma_i \boldsymbol{F} + \delta_i \boldsymbol{D}_i + \varepsilon \qquad \text{Eq. 2}$$

where *i* indexes regression models, $\boldsymbol{F}$ refers to a set of standard exploratory variables including those in every regression model, $\boldsymbol{D_i}$ is a vector consisting of *k* variables taken from $\boldsymbol{X}$ (i.e. set of doubtful variables), and ε refers to the error term. Furthermore, β_i refers to estimated coefficients of the focus variable (*v*).

Originally, the ordinary least square (OLS) method was used to estimate regressions in the EBA method; however, other types of regression models have been adopted by other researchers and authors (Bjornskov et al. 2008; Moser and Sturm 2011; Gassebner et al. 2013).

8.2. A Version of EBA Method Proposed by Leamer

Extreme bound analysis, proposed by Leamer, focuses only on the extreme bounds of the regression coefficients to determine whether an influential predictor is robust or fragile (Leamer 1985). For each focus variable, *v*, the lower and upper extreme bounds are described as the lowest and highest values of $\hat{\beta}_i \pm \alpha \hat{\sigma}_i$ across the *N* number of estimated regression models, while α is the critical value for the requested confidence level. For instance, α would be equal to roughly 1.96 regarding the conventional 95 percent (95%) confidence level. While the lower and upper extreme bounds would have the same sign, the focus variable *v* is considered as a robust predictor. On the contrary, while the upper and lower extreme bounds would have different signs, the focus variable *v* is considered as a fragile predictor.

The interval between the upper and lower extreme bounds indicates the set of values, which are not statistically significantly distinguishable from the coefficient estimate $\hat{\beta}_i$. The method of EBA proposed by Leamer considers a large number of model specifications for the minimum and maximum values that the β_i parameter could take at the asked confidence level. Consequently, the variables consisting of the same and opposite signs would be named fragile and robust, respectively, considering the stated extreme bounds.

Leamer's EBA method has a strict criterion for robust predictors because the results from a single regression model are sufficient to label a predictor as fragile. To further clarify, a focus variable would be labeled fragile even if its extreme bounds have the same sign in all of the estimated models except one. As a result, it is obvious that most of the predictors obtained by the EBA method proposed by Leamer are fragile (Levine and Renelt 1992; Levine and Zervos 1993; Sala-i-Martine 1997).

8.3. A Version of EBA Method Proposed by Sala-i-Martin

In 1997, Sala-i-Martin proposed another form of EBA method that focuses on the entire distribution of regression coefficients instead of just extreme bounds. He assigned a level of confidence to the robustness of each variable instead of applying a binary level of fragile or robust and considered the value of CDF (0), the fraction of the variable's cumulative distribution located on each side of zero. In other words, a predictor would be considered robust if a greater portion (95%) of its coefficient estimate was on the same side of zero.

The coefficients in each individual model have an asymptotic normal distribution; however, the coefficient estimates that were recorded from different regression models could be scattered in less certain patterns and not follow any specific distribution or pattern. To this end, Sala-i-Martin (1997) proposed two assumptions of his EBA method, which are presented as follows:

Assumption 1: Estimated regression coefficients are assumed to follow a normal distribution across the estimated models, and

Assumption 2: Estimated regression coefficients are assumed to follow a generic distribution model across the estimated models and not assume any specific distribution of regression coefficients.

8.4. EBA Analysis of Cost Performance Predictors

EBA method was adopted to determine the robustness and fragility of cost performance predictors for post-hurricane reconstruction of transport infrastructures. Two forms of the EBA method proposed by both Leamer and Sala-i-Martin were adopted, and the results are presented in Table 20. This table illustrates that the four robust predictors are: (1) inflation of labor wage (PRT.12), (2) frequency level of logistics management issues (PRT.18), (3) frequency of on-site inspection (PRT.20), and (4) information management (PRT.21).

Wages for laborers commonly increase after a disaster, which leads to inflation (PRT.12) in reconstruction projects. The cost of completing the projects increases significantly so that the recorded results, in which PRT.12 was obtained as robust for reconstruction cost performance, is justifiable.

As presented in Table 20, the frequency of logistics management issues (PRT.18) impacts post-hurricane reconstruction projects. A lack of effective logistics management increases shipping costs due to orders being rushed and/or the use of inappropriate transporting materials, which increases the probability of overruns.

On-site inspection plays a critical role in post-hurricane reconstruction projects, as inspectors have the ability to observe potential risks and act proactively to prevent major issues. An insufficient number of on-site inspections (PRT.20) often leads to a need for an increased budget for completing the project. Thus, it is clear that on-site inspections are considered robust.

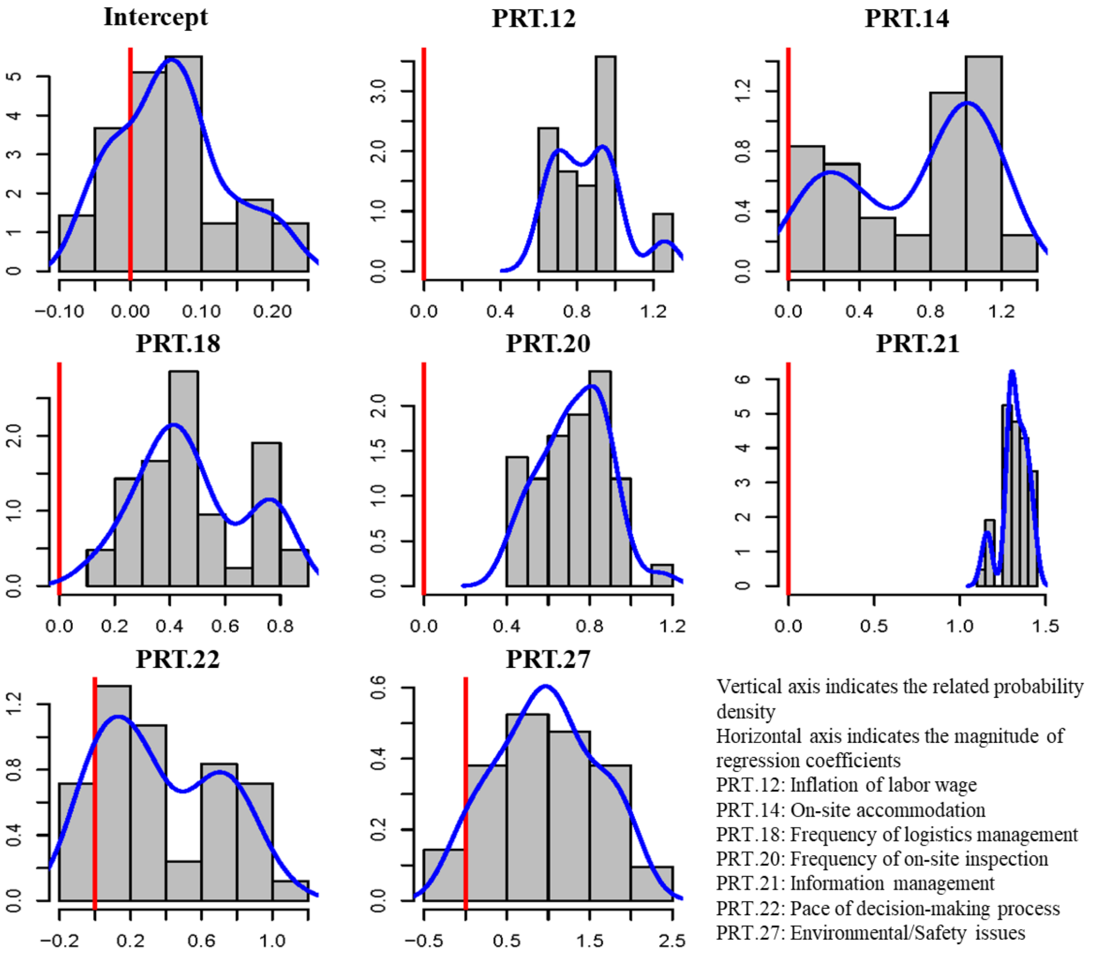
Table 20. Results of EBA Analysis for Cost Performance Predictors

Predictor	Leamer's EBA Result		Sala-i-Martin's EBA Result				Type of Predictor
	Lower Extreme Bound	Upper Extreme Bound	Normal CDF ($\beta \leq 0$)	Normal CDF ($\beta > 0$)	Non-Normal CDF ($\beta \leq 0$)	Non-Normal CDF ($\beta > 0$)	
Intercept	-0.358	0.469	30.705	69.295	33.344	66.656	Fragile
PRT.12	-0.192	1.916	0.549	99.451	1.342	98.658	Robust
PRT.14	-0.431	1.735	0.223	99.777	7.053	92.947	Fragile
PRT.18	-0.442	1.569	6.965	93.035	9.517	95.483	Robust
PRT.20	-0.721	2.017	5.241	94.759	6.901	98.099	Robust
PRT.21	0.716	1.879	0.000	100.000	0.000	100.000	Robust
PRT.22	-1.029	1.853	17.519	82.481	22.884	77.116	Fragile
PRT.27	-1.823	4.084	17.786	82.214	21.614	78.386	Fragile

PRT.12: Inflation of labor wage
PRT.14: On-site accommodation level for staff
PRT.18: Frequency level of logistics management issues
PRT.20: Frequency of on-site inspection
PRT.21: Information management
PRT.22: Pace of decision-making process
PRT.27: Environmental/Safety issues

As indicated in Table 20, information management (PRT.21) was recorded as a robust predictor for cost performance. Ineffective information management can seriously increase risks to the strategic plans for reconstruction projects and result in an increase in the cost of the projects and a decrease in the cost performances.

The graphical results of the EBA analysis proposed by Sala-i-Martin are presented in Figure 18, which clearly shows that four PRTs (PRTs 12, 18, 20, and 21) were recorded as robust predictors, while the rest of the predictors were recorded as fragile. This figure shows that the PRTs were recorded as robust predictors, as at least 95% of their coefficient estimates were on the same side of zero.



Vertical axis indicates the related probability density
Horizontal axis indicates the magnitude of regression coefficients
PRT.12: Inflation of labor wage
PRT.14: On-site accommodation
PRT.18: Frequency of logistics management
PRT.20: Frequency of on-site inspection
PRT.21: Information management
PRT.22: Pace of decision-making process
PRT.27: Environmental/Safety issues

Figure 18. Schematic Results of EBA Proposed by Sala-i-Martin for Reconstruction Cost Performance Predictors

8.5. EBA Analysis of Schedule Performance Predictors

A sensitivity analysis was performed to identify the fragility and robustness of schedule performance predictors for post-hurricane reconstruction of transport infrastructures. The EBA method proposed by both Leamer and Sala-i-Martin was implemented, and the results are shown in Table 21 and Figure 19.

Table 21. Results of EBA Analysis for Schedule Performance Predictors

Predictor	Leamer's EBA Result		Sala-i-Martin's EBA Result				Type of Predictor
	Lower Extreme Bound	Upper Extreme Bound	Normal CDF ($\beta \leq 0$)	Normal CDF ($\beta > 0$)	Non-Normal CDF ($\beta \leq 0$)	Non-Normal CDF ($\beta > 0$)	
Intercept	-0.434	0.817	20.831	79.169	24.487	75.513	Fragile
PRT.03	-0.143	2.750	0.025	99.975	0.499	99.501	Robust
PRT.06	0.453	1.999	0.000	100.000	0.001	99.999	Robust
PRT.10	-0.406	2.289	0.005	99.995	0.535	99.465	Robust
PRT.11	-0.946	4.011	0.604	99.396	3.439	96.561	Robust
PRT.12	-7.146	5.428	71.083	28.917	62.761	37.239	Fragile
PRT.15	-1.119	4.238	0.204	99.796	2.231	97.769	Robust
PRT.20	-1.185	4.495	0.229	99.771	2.209	97.791	Robust
PRT.21	-6.166	5.973	48.483	51.517	46.348	53.652	Fragile
PRT.27	-6.180	15.542	11.442	88.558	22.986	77.014	Fragile

PRT.03: Level of complexity
PRT.06: Level of traffic disturbance
PRT.10: Shortage of materials
PRT.11: Shortage of equipment
PRT.12: Inflation of labor wage
PRT.15: Shortage of supplier
PRT.20: Frequency of on-site inspection
PRT.21: Information management
PRT.27: Environmental/Safety issues prior starting execution of the project

Table 21 indicates that six predictors for reconstruction schedule performance are considered robust: (1) level of complexity (PRT.03), (2) level of traffic disturbance

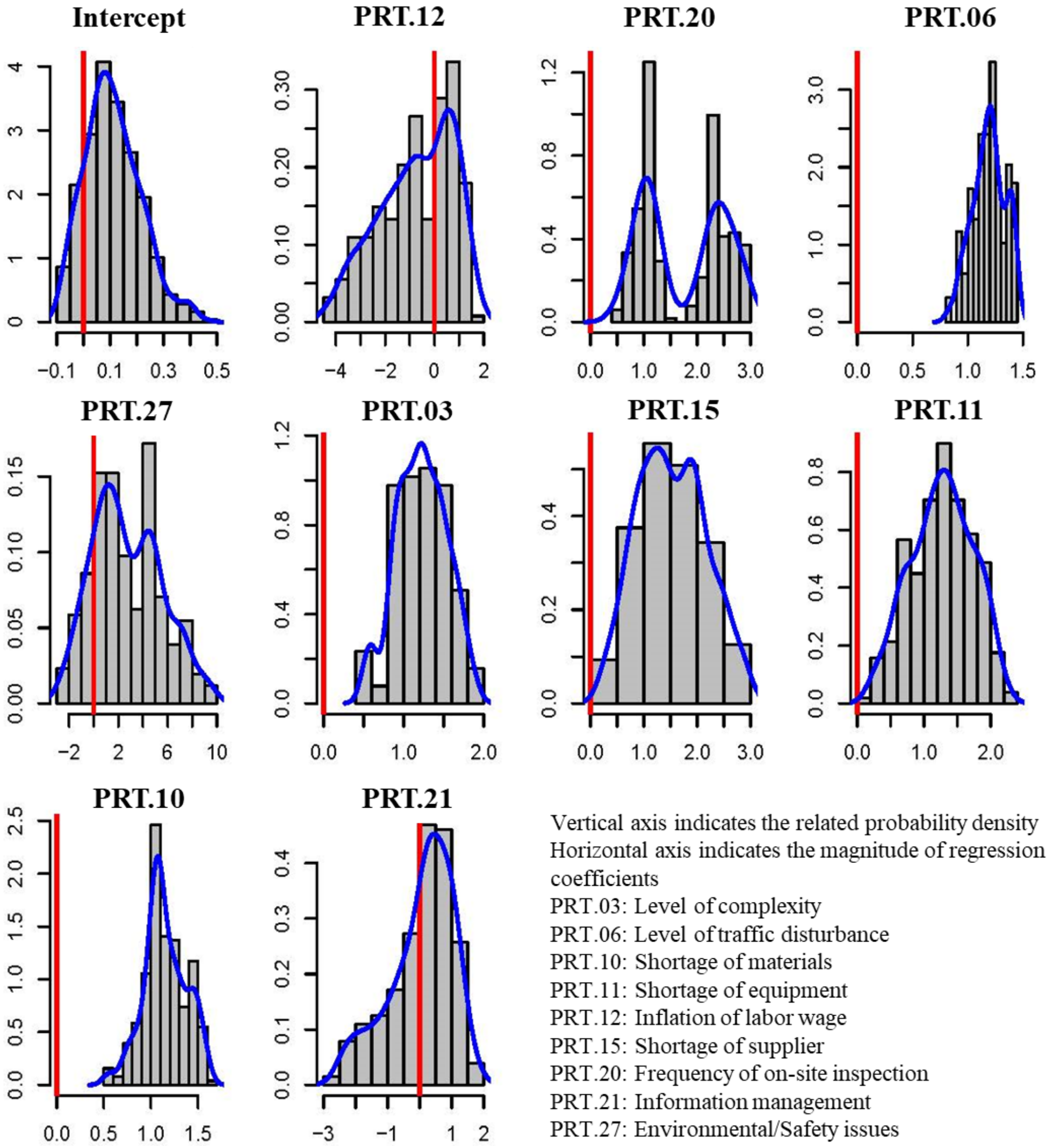
(PRT.06), (3) shortage of materials (PRT.10), (4) shortage of equipment (PRT.11), (5) shortage of suppliers (PRT.15), and (6) frequency of on-site inspections (PRT.20).

Post-disaster reconstruction projects are inherently complex, and increasing the complexity (PRT.03) increases the number of challenges and issues for the project parties. Project managers need time to resolve the problems; consequently, it takes longer to complete the reconstruction project.

Table 21 shows that traffic disturbances and congestion (PRT.06) are considered robust predictors for the schedule performance of post-hurricane reconstruction projects. They lead to wasting time in delivering materials and machinery and increase the probability of schedule delays.

Table 21 indicates that shortages of materials (PRT.10) and shortages of equipment (PRT.11) are robust predictors for schedule performance in post-hurricane reconstruction of transport infrastructures. An adequate supply of materials and machinery plays a critical role in a timely recovery; therefore, a lack of these resources seriously affects the schedule performance.

After a disaster, there is often a shortage of suppliers (PRT.15) which requires that different strategies be implemented. Since a shortage of suppliers causes shortages of material and machinery resources, reconstruction projects cannot be executed according to plan, and the strategy for resolving each shortage takes time and causes delays in the completion schedule.



Vertical axis indicates the related probability density
Horizontal axis indicates the magnitude of regression coefficients
PRT.03: Level of complexity
PRT.06: Level of traffic disturbance
PRT.10: Shortage of materials
PRT.11: Shortage of equipment
PRT.12: Inflation of labor wage
PRT.15: Shortage of supplier
PRT.20: Frequency of on-site inspection
PRT.21: Information management
PRT.27: Environmental/Safety issues

Figure 19. Schematic Results of the EBA Proposed by Sala-i-Martin for Reconstruction Schedule Performance Predictors

As indicated in Table 21, the frequency of on-site inspections (PRT.20) was recorded as a robust predictor. Multiple risks are usually part of mega-scale reconstruction projects after a disaster, and frequent on-site inspections can prevent serious issues by facilitating the adoption of effective strategies in a timely manner. Therefore, it can be concluded that this PRT is beneficial for improving the schedule performance of the mentioned reconstruction projects.

The graphical results of the EBA analysis proposed by Sala-i-Martin are indicated in Figure 19 and show that six PRTs (PRTs 03, 06, 10, 11, 15 and 20) were obtained as robust predictors and the rest of the predictors were recorded as fragile ones. Figure 19 illustrates that in the robust predictors, a considerable portion (at least 95%) of corresponding coefficient estimates were on the same side of zero.

8.5. EBA Analysis of Reconstruction Rework Predictors

A sensitivity analysis was conducted to determine the robustness and fragility of reconstruction rework predictors, and the results are presented in Table 22 and Figure 20. The EBA analysis methods proposed by Sala-i-Martin (1997) and Leamer (1985) were adopted, and the results are shown in Table 22.

Table 22 illustrates that the following predictors were recorded as robust: (1) distance from a highly populated area (PRT.04), (2) information management (PRT.21), (3) work suspension throughout execution of the project (PRT.28), (4) regulatory requirements (PRT.29), and (5) availability of required temporary pathways (PRT.30).

As indicated in Table 22, when a post-hurricane reconstruction project is located in a highly populated area (PRT.04), the probability of reworks might increase. Highly populated areas have multiple restrictions and limitations that are applicable to the execution of reconstruction projects, such as: (1) traffic congestion, (2) extensive network of utilities, and (3) reduction in the time of execution. The mentioned restrictions might affect the workers' performance and increase the possibility of their making more mistakes, leading to the conclusion that PRT.04 might increase the number and cost of reworks.

Table 22. Results of EBA Analysis for Rework Predictors

Predictor	Leamer's EBA Result		Sala-i-Martin's EBA Result				Type of Predictor
	Lower Extreme Bound	Upper Extreme Bound	Normal CDF ($\beta \leq 0$)	Normal CDF ($\beta > 0$)	Non-Normal CDF ($\beta \leq 0$)	Non-Normal CDF ($\beta > 0$)	
Intercept	0.855	2.422	0.000	100.000	0.000	100.000	Robust
PRT.04	-0.922	5.671	3.942	96.058	3.800	96.200	Robust
PRT.08	-4.871	3.142	64.020	35.980	51.779	48.221	Fragile
PRT.18	-5.784	6.048	55.799	44.201	57.765	42.235	Fragile
PRT.20	-2.032	1.378	51.407	48.593	44.900	55.100	Fragile
PRT.21	-0.181	0.975	0.162	99.838	4.972	95.028	Robust
PRT.24	-2.354	1.743	43.364	56.636	41.037	58.963	Fragile
PRT.27	-3.573	2.573	54.689	45.311	49.283	50.717	Fragile
PRT.28	0.197	0.947	0.000	100.000	0.001	99.999	Robust
PRT.29	-1.809	8.788	4.175	95.825	3.768	96.232	Robust
PRT.30	-1.829	5.935	1.330	98.670	4.528	95.472	Robust

PRT.04: Distance from highly-populated area
PRT.08: Shortage of field labors
PRT.18: Frequency level of logistic management issues
PRT.20: Frequency of on-site inspection
PRT.21: Information management
PRT.24: Coordination
PRT.27: Environmental/Safety issues prior starting execution of the project
PRT.28: Work suspension through execution of the project
PRT.29: Regulatory requirement
PRT.30: Availability of required temporary pathways

As indicated in Table 22, information management (PRT.21) was recorded as a robust predictor for post-hurricane reconstruction reworks in transport infrastructures. Transferring knowledge and information among the project parties at the right time prevents duplications of work and mitigates the number of mistakes and errors that are made because of inaccurate information and data. As a result, the stated PRT is a critical predictor for post-hurricane reconstruction reworks.

Work suspension throughout the execution of a reconstruction project (PRT.28) might happen due to many reasons, such as environmental and/or safety issues. The work suspension usually causes considerable delays, and the project managers and staff experience additional pressure to mitigate substantial time overruns that can lead to an increase in the number and cost of errors.

The results of the EBA analysis proposed by Sala-i-Martin are graphically shown in Figure 20, which illustrates that five PRTs (PRTs 04, 21, 28, 29, and 30) were recorded as robust predictors, and the remaining ones were recorded as fragile predictors. This figure indicates that in the robust predictors, a considerable portion (at least 95%) of corresponding coefficient estimates are on the same side of zero.

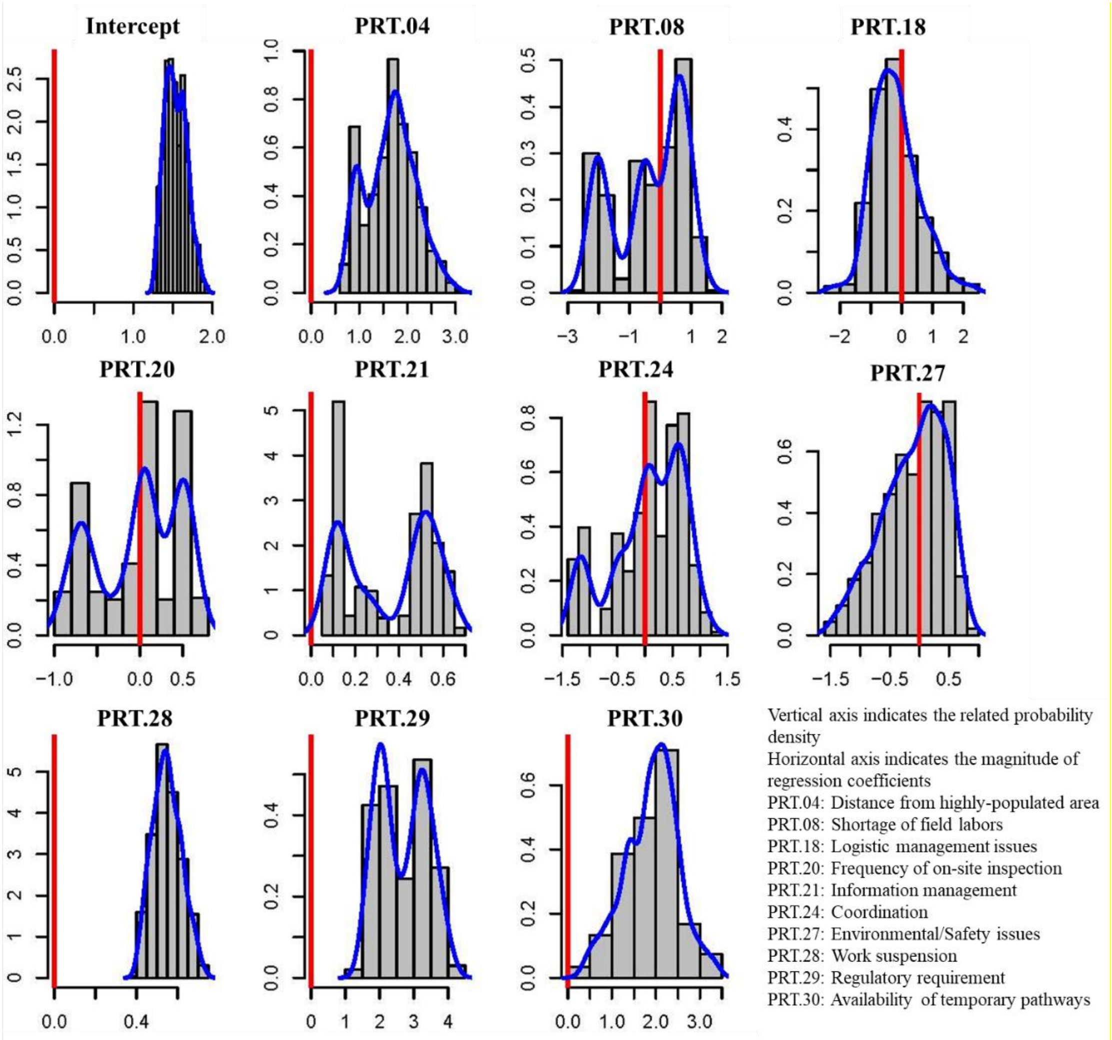


Figure 20. Schematic Results of EBA Proposed by Sala-i-Martin for Reconstruction Rework Predictors

8.6. Comparative Analysis of Robust Predictors

In this section, comparative analysis of robust predictors for reconstruction cost and schedule performance as well as rework in transportation infrastructures after hurricanes was conducted and the results are presented in Figure 21. This figure shows that information management (PRT.21) is a shared robust predictor between reconstruction cost performance and rework. Additionally, frequency of on-site inspection (PRT.20) is a shared robust predictor between reconstruction cost performance and schedule performance.

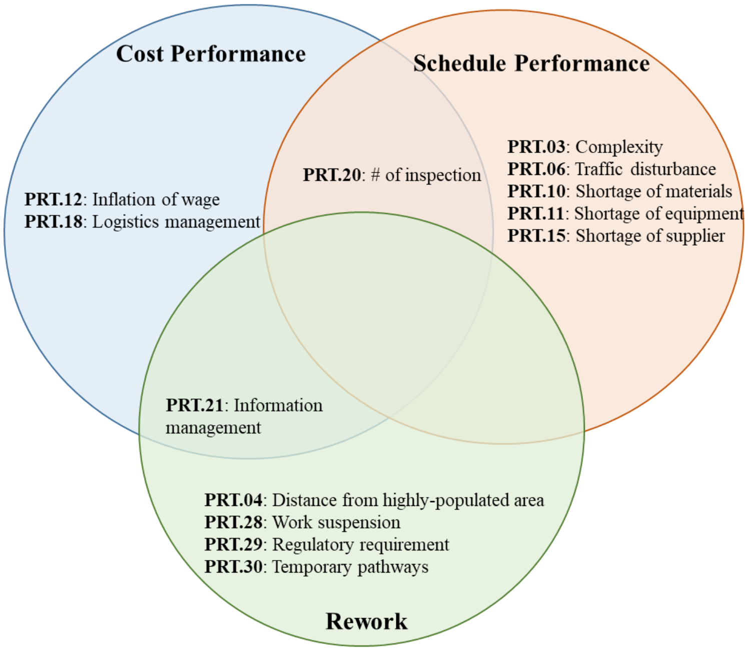


Figure 21. Schematic Results of Comparative Analysis of Robust Predictors

As presented in Figure 21, information management (PRT.21) is a robust predictor shared between reconstruction cost performance and rework. Lack of transferring knowledge, data, and information at the right time between stakeholders and team members causes different errors and mistakes in the project. These errors and mistakes derive multiple reworks and consequently increase cost of project.

Figure 21 shows that frequency of on-site inspection (PRT.20) is the shared robust predictor between reconstruction cost and schedule performance in post-hurricane reconstruction of transportation infrastructures. With frequent on-site inspection, quality of work, particularly project's safety, could be monitored and serious issues might be preventable. Therefore, it would be possible to prevent extra budget and time to accomplish the project.

8.7. Summary

Extreme bound analysis was conducted for three predictive models of cost performance, schedule performance, and cost of reworks associated with post-hurricane reconstruction of transport infrastructures. Two versions/forms of EBA method proposed by Sala-i-Martin (1997) and Leamer (1985) were adopted to examine how robustly each influential predictor is related to the corresponding predictive model. The final decisions regarding the robustness/fragility of influential predictors were made based on the EBA method proposed by Sala-i-Martin. The outcomes were presented in both graphical and numerical formats. Then, comparative analysis was performed to identify the shared robust predictors which contribute to cost escalations, time delays, and rework in the mentioned projects.

9. IMPLICATION OF RESULTS IN PRACTICE

9.1. Implication of Results

Since the present research was conducted to improve success of post-hurricane reconstruction of transportation infrastructures, the procedure of implication of the results is schematically presented in Figure 22. Decision-makers and project managers could utilize the outcomes of this research in order to implement effective strategies at the right time to mitigate cost escalations, time delays, and reworks in the mentioned projects.

As shown in Figure 22, project managers can consider each of the significant PRTs that contribute to cost overruns (26 significant PRTs), schedule delays (23 significant PRTs), and reworks (25 significant PRTs) in order to assure their availability in post-hurricane reconstruction of transportation infrastructures. Next, project managers can consider which of the available and existed significant PRTs influentially predict cost performance, schedule performance, and cost of reworks in the stated projects. As presented in Figure 22, there were recorded seven, nine, and ten influential predictors for cost performance, schedule performance, and reworks in these projects. The project managers can use the developed prediction models and corresponding equations to predict cost performance, schedule performance, and cost of reworks in post-hurricane reconstruction of transport infrastructures.

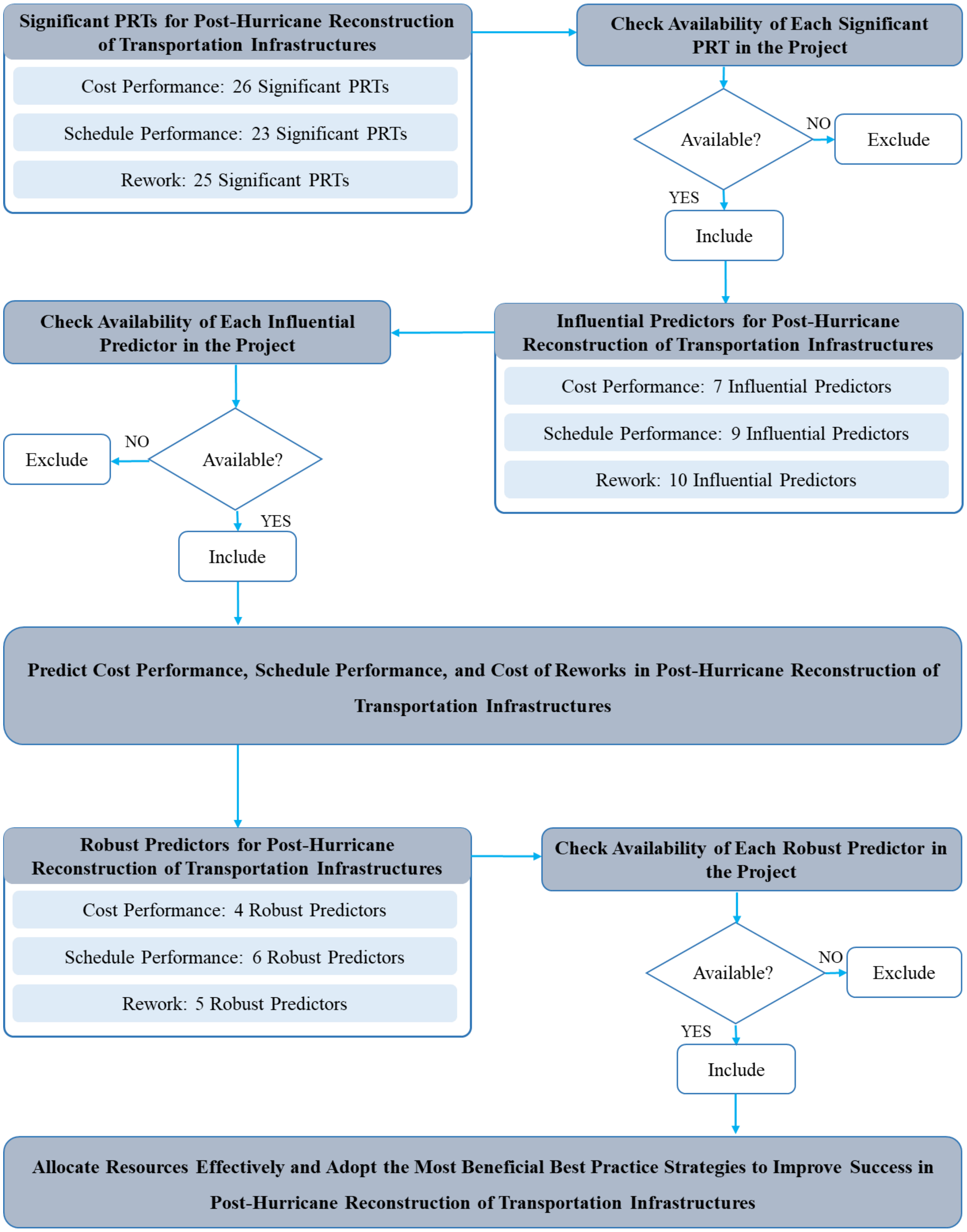


Figure 22. Schematic Process of Implication of Results in Practice

Since shortly after hurricanes, there are commonly serious limitations in terms of resources such as funds; therefore, there is needed a decision support system to help project managers and decision makers allocate resources effectively. To this end, the EBA method was adopted to determine which of the influential predictors robustly connected to the developed models. Accordingly, as shown in Figure 22, the determined robust predictors would assist project managers in allocating resources effectively. For this purpose, project managers could select the most beneficial strategies to significantly mitigate cost escalations, delays, frequency and cost of reworks in post-hurricane reconstruction of transportation infrastructures.

9.2. Summary

The process of implication of outcomes obtained in this research that can be adopted by authorities, decision makers, and project managers working in post-hurricane reconstruction of transport infrastructures was explained in detail. The process of implication of results was schematically presented in order to make this process understandable and readable for practitioners and researchers. The following chapter presents the conclusions drawn from this research and suggestions for future studies.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1. Conclusions

Various challenges, risks, and uncertainties are endemic to the reconstruction of transport infrastructures after hurricanes because of the complex, chaotic, and dynamic nature of the disaster environment. The existing literature lacks sufficient studies that propose solutions to these issues and challenges; therefore, the goal of this research was to fill that knowledge gap and improve the success of post-hurricane reconstruction of transport infrastructures.

In this research, the factors were determined that contribute to cost overruns, schedule delays, and reworks in the post-hurricane reconstruction of transport infrastructures. For cost performance and schedule performance of reconstruction projects, 26 and 23 influential factors, respectively, were determined as statistically significant. Additionally, 25 factors were statistically determined to significantly contribute to reworks. It is believed that this information will assist decision makers and project managers in timely identification of factors that reduce the success of a project so that they can make a proactive plan to deliver post-hurricane reconstruction of transport infrastructures on time and within budget.

Three models were developed to predict cost performance, schedule performance, and cost of reworks in reconstruction projects of transport infrastructures after hurricanes. A stepwise multiple regression method was adopted, and the predictive model for reconstruction cost performance showed that seven influential factors contribute to the regression model ($R^2 = 0.924$). In case of schedule performance, nine influential factors were recorded as significant predictors ($R^2 = 0.996$), and ten factors contribute to the predictive model for the cost of reworks ($R^2 = 0.998$). The predictive models facilitate a better understanding of their impacts on cost overruns, schedule delays, and cost of reworks and can serve as a support system for decision makers and project managers who are performing quantitative risk assessments and want to adopt effective strategies prior to the reconstruction of transport infrastructures damaged by hurricanes.

The results revealed that frequency of on-site inspection, information management, and safety/environment issues were recorded as influential predictors in all three developed models to predict cost performance, schedule performance, and reworks in post-hurricane reconstruction of transport infrastructures. Information management in a reconstruction project leads to transferring knowledge, data, and information at the right time among the project's parties and team members. Thus, decision makers could effectively implement the most beneficial strategy in order to prevent and/or mitigate any major issues and/or mistakes so that considerable schedule delays, cost overruns, and reworks would be avoidable.

The EBA method was used in this research to determine which predictors in the three models are robustly connected to the corresponding regression model. To achieve this aim, the form of EBA method proposed by Sala-i-Marin was adopted. The results revealed that four cost performance predictors and six schedule performance predictors were robustly connected to corresponding regression models, and five significant rework predictors were recorded as robust predictors for the cost of reworks. These findings will provide accurate data and information to stakeholders and project managers who make decisions about how to effectively allocate limited resources after hurricanes and mitigate schedule delays and cost overruns in the reconstruction of transport infrastructures.

The results demonstrated that information management was a robust predictor shared between reconstruction cost performance and rework. Moreover, frequency of on-site inspection was the shared robust predictor between reconstruction cost and schedule performance in post-hurricane reconstruction of transportation infrastructures. With frequent on-site inspection, quality of work, particularly project's safety, could be monitored and major challenges would be mitigated by adopting the most effective best practices. As a result, it would be possible to prevent extra budget and time to accomplish the project.

10.2. Recommendations for Future Studies

This research can be expanded in several ways. The most important is to improve the predictive models by incorporating the dynamic and chaotic environments that are present after hurricanes. The development of a dynamic model could help investigate the interactions between influential factors throughout the execution of transport infrastructures reconstruction by considering the dynamic and chaotic post-hurricane conditions. Since the reconstruction of transport infrastructures during post-hurricane conditions consists of multiple uncertainties and risks, a dynamic model might also substantially assist decision-makers and project managers in performing quantitative risk assessments more accurately.

Another area of research could involve conducting experimental studies to improve the predictive models in order to estimate the cost and schedule performance, as well as the cost of reworks, more precisely. Other techniques, methods, and tools could be adopted to predict the cost and schedule performance, as well as the cost of reworks, in post-hurricane reconstruction of transport infrastructures. The success predictors could be investigated and predictive models could be developed for the reconstruction of transport infrastructures after other types of natural disasters, such as floods and earthquakes, as each type of natural disaster is unique. It is also recommended that predictive models be developed and the success factors be studied for post-disaster reconstruction of the other types of transportation infrastructures, such as bridges.

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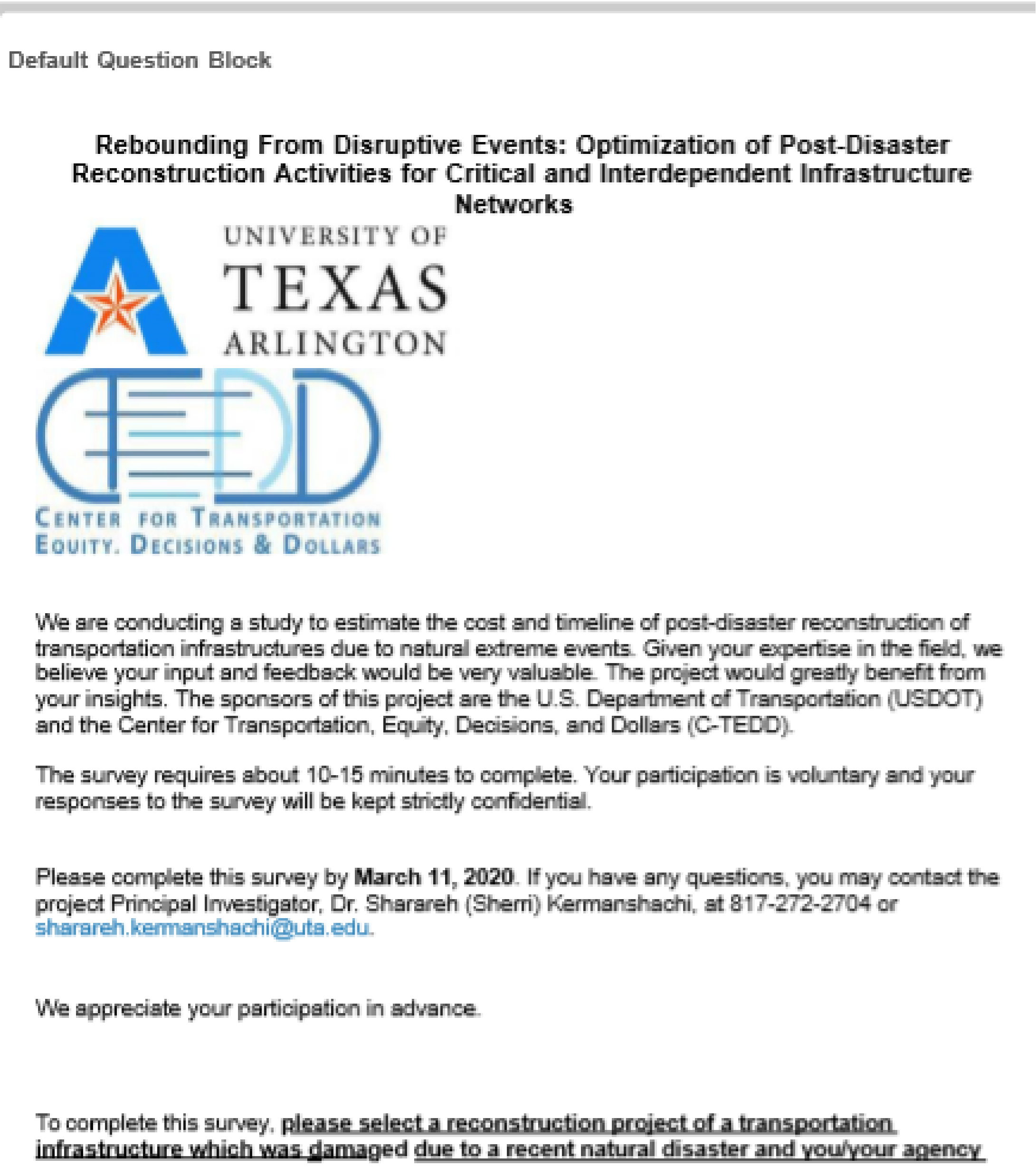
Appendix A: Survey



Default Question Block

Rebounding From Disruptive Events: Optimization of Post-Disaster Reconstruction Activities for Critical and Interdependent Infrastructure Networks

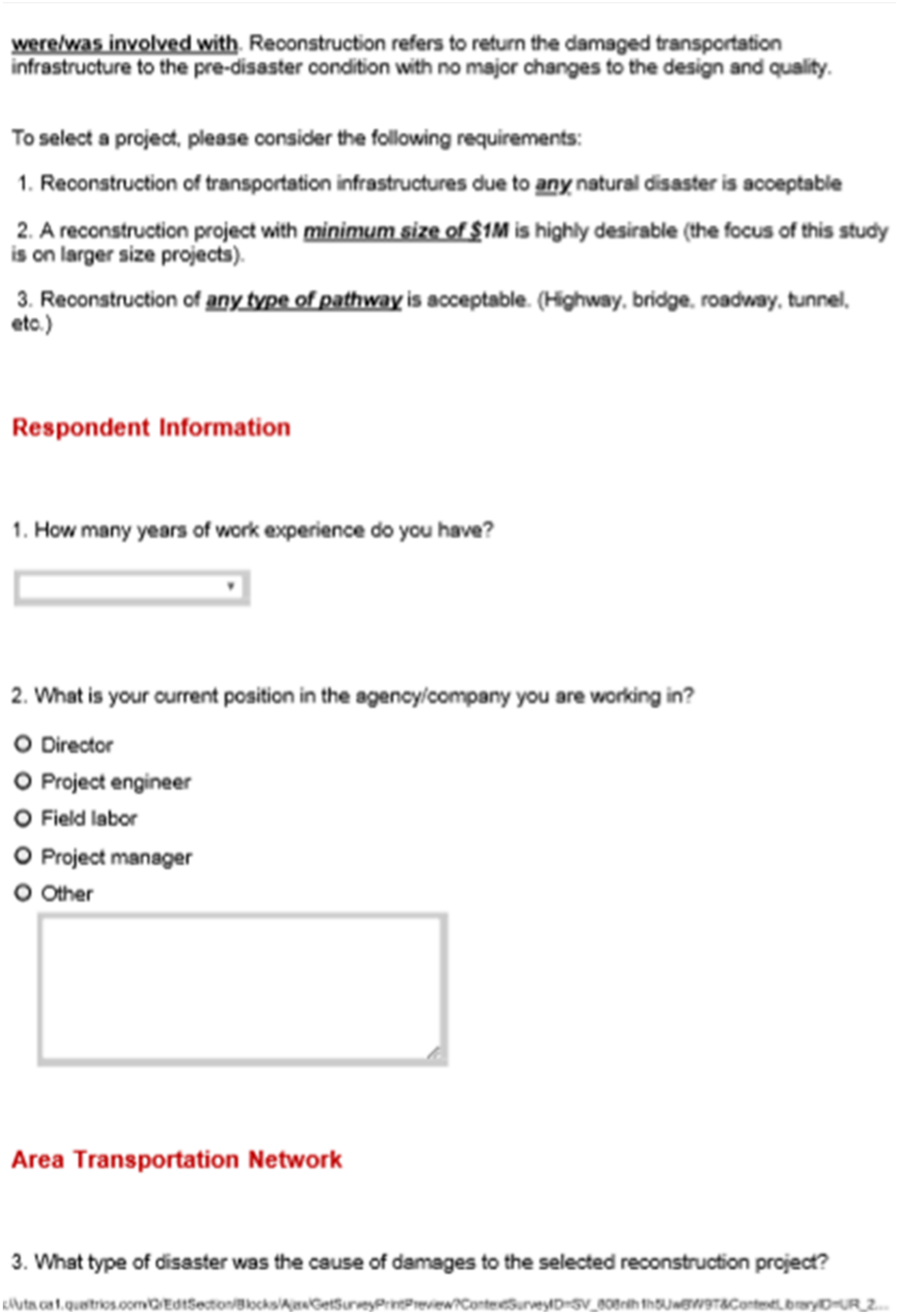
We are conducting a study to estimate the cost and timeline of post-disaster reconstruction of transportation infrastructures due to natural extreme events. Given your expertise in the field, we believe your input and feedback would be very valuable. The project would greatly benefit from your insights. The sponsors of this project are the U.S. Department of Transportation (USDOT) and the Center for Transportation, Equity, Decisions, and Dollars (C-TEDD).

The survey requires about 10-15 minutes to complete. Your participation is voluntary and your responses to the survey will be kept strictly confidential.

Please complete this survey by **March 11, 2020**. If you have any questions, you may contact the project Principal Investigator, Dr. Sharareh (Sherri) Kermanshachi, at 817-272-2704 or sharareh.kermanshachi@uta.edu.

We appreciate your participation in advance.

To complete this survey, **please select a reconstruction project of a transportation infrastructure which was damaged due to a recent natural disaster and you/your agency**



were/was involved with. Reconstruction refers to return the damaged transportation infrastructure to the pre-disaster condition with no major changes to the design and quality.

To select a project, please consider the following requirements:

1. Reconstruction of transportation infrastructures due to ***any*** natural disaster is acceptable

2. A reconstruction project with ***minimum size of $1M*** is highly desirable (the focus of this study is on larger size projects).

3. Reconstruction of ***any type of pathway*** is acceptable. (Highway, bridge, roadway, tunnel, etc.)

Respondent Information

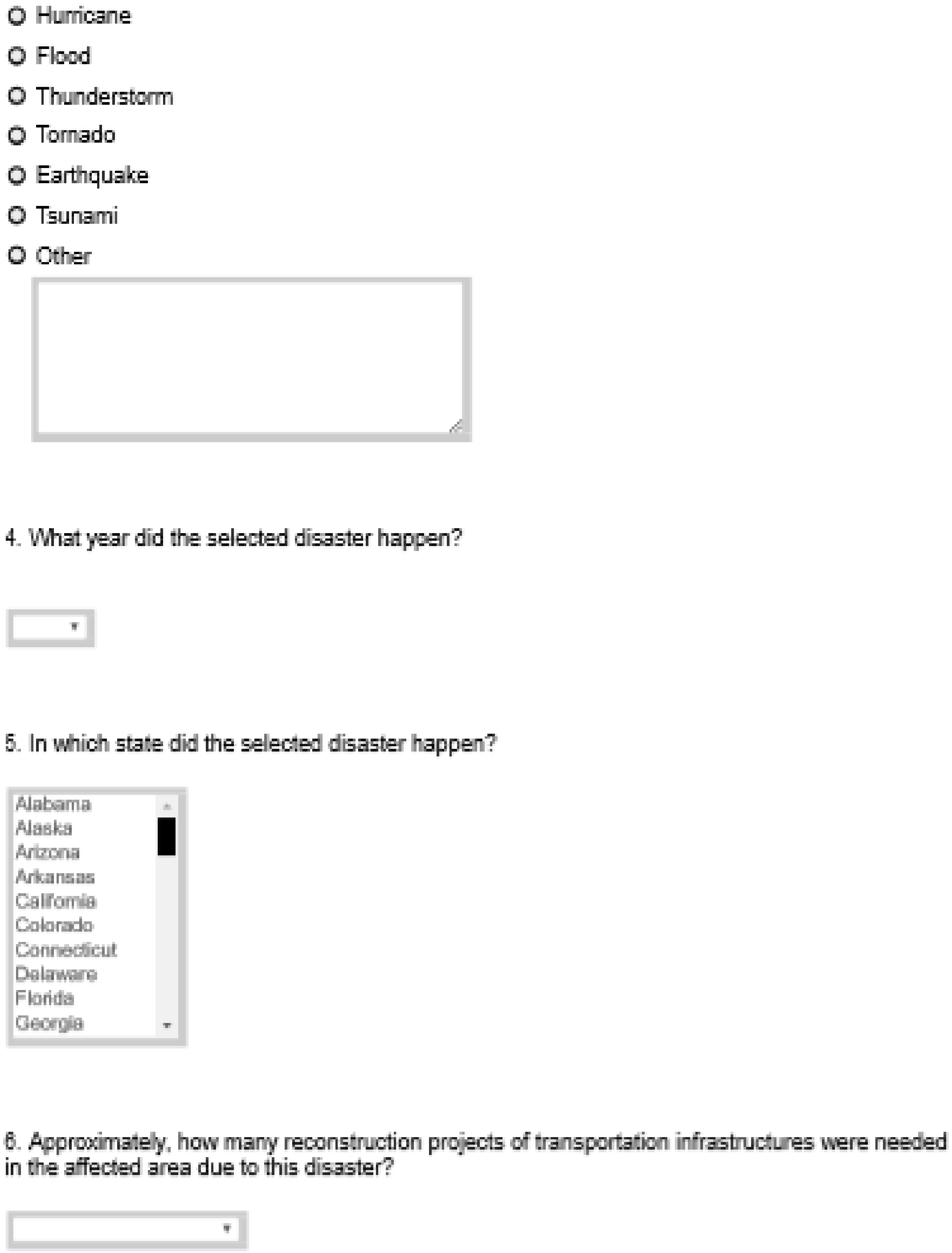
1. How many years of work experience do you have?

2. What is your current position in the agency/company you are working in?

○ Director
○ Project engineer
○ Field labor
○ Project manager
○ Other

Area Transportation Network

3. What type of disaster was the cause of damages to the selected reconstruction project?



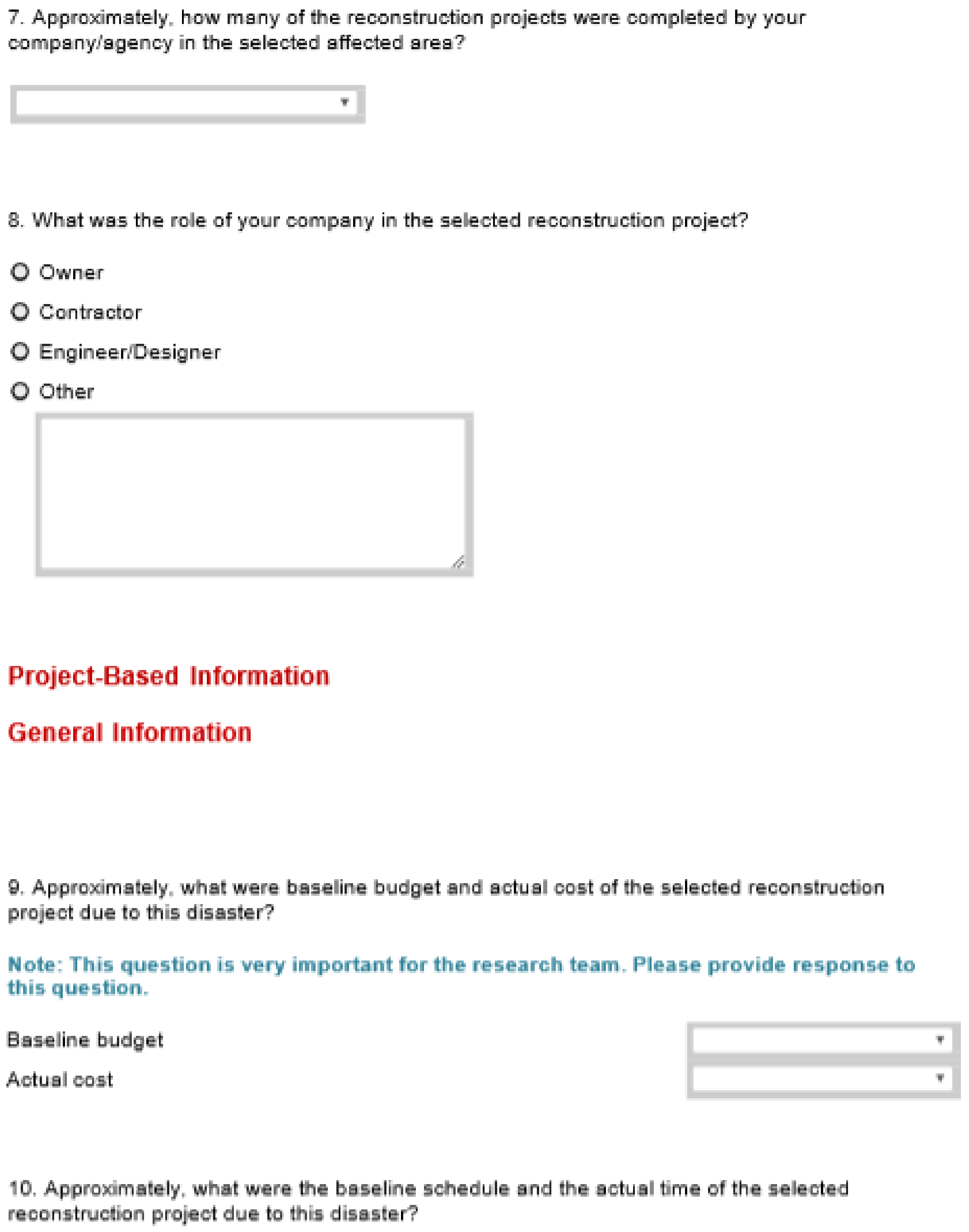
○ Hurricane
○ Flood
○ Thunderstorm
○ Tornado
○ Earthquake
○ Tsunami
○ Other

4. What year did the selected disaster happen?

5. In which state did the selected disaster happen?

Alabama
Alaska
Arizona
Arkansas
California
Colorado
Connecticut
Delaware
Florida
Georgia

6. Approximately, how many reconstruction projects of transportation infrastructures were needed in the affected area due to this disaster?



7. Approximately, how many of the reconstruction projects were completed by your company/agency in the selected affected area?

8. What was the role of your company in the selected reconstruction project?

○ Owner
○ Contractor
○ Engineer/Designer
○ Other

Project-Based Information

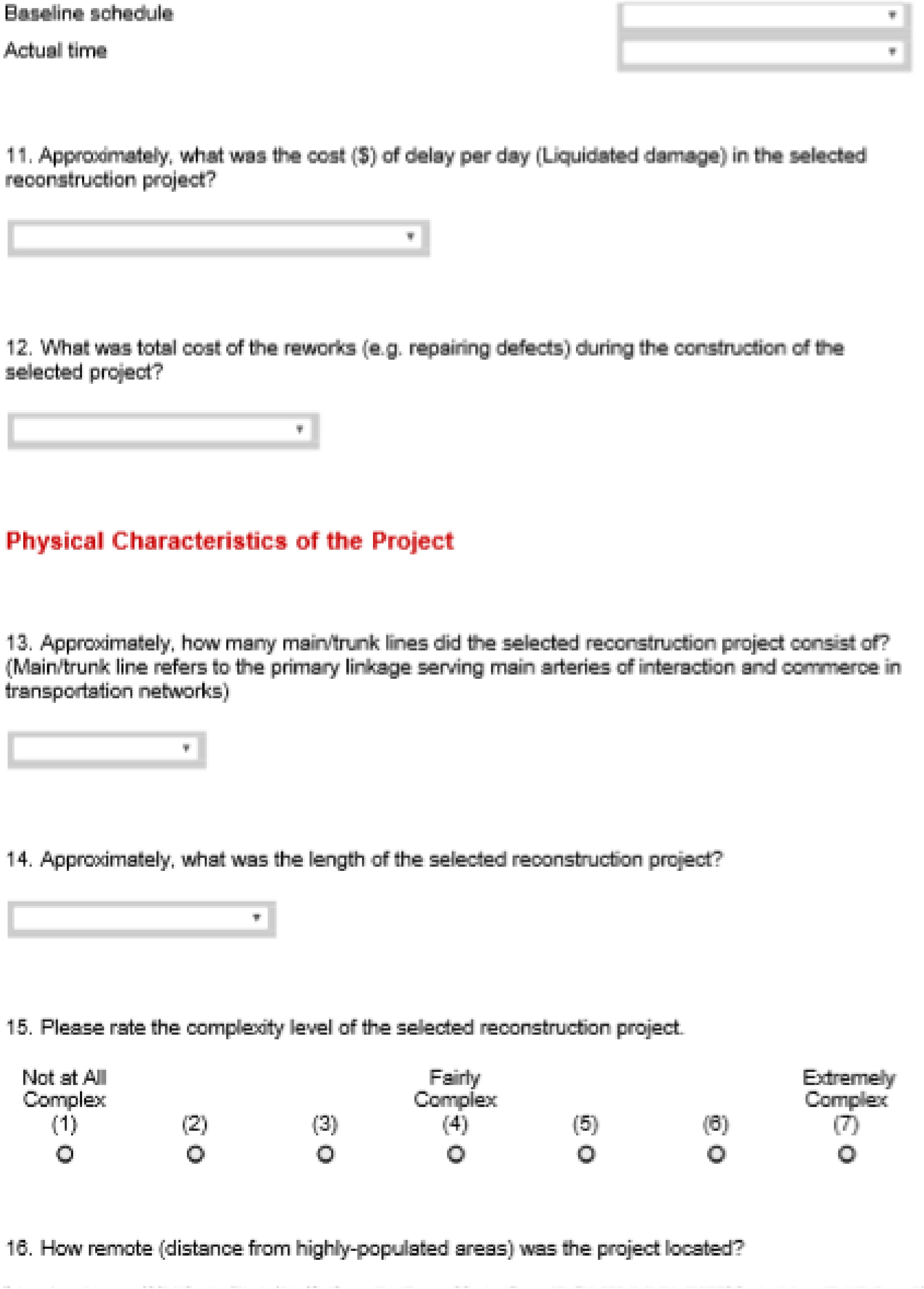
General Information

9. Approximately, what were baseline budget and actual cost of the selected reconstruction project due to this disaster?

Note: This question is very important for the research team. Please provide response to this question.

Baseline budget
Actual cost

10. Approximately, what were the baseline schedule and the actual time of the selected reconstruction project due to this disaster?



Baseline schedule

Actual time

11. Approximately, what was the cost ($) of delay per day (Liquidated damage) in the selected reconstruction project?

12. What was total cost of the reworks (e.g. repairing defects) during the construction of the selected project?

Physical Characteristics of the Project

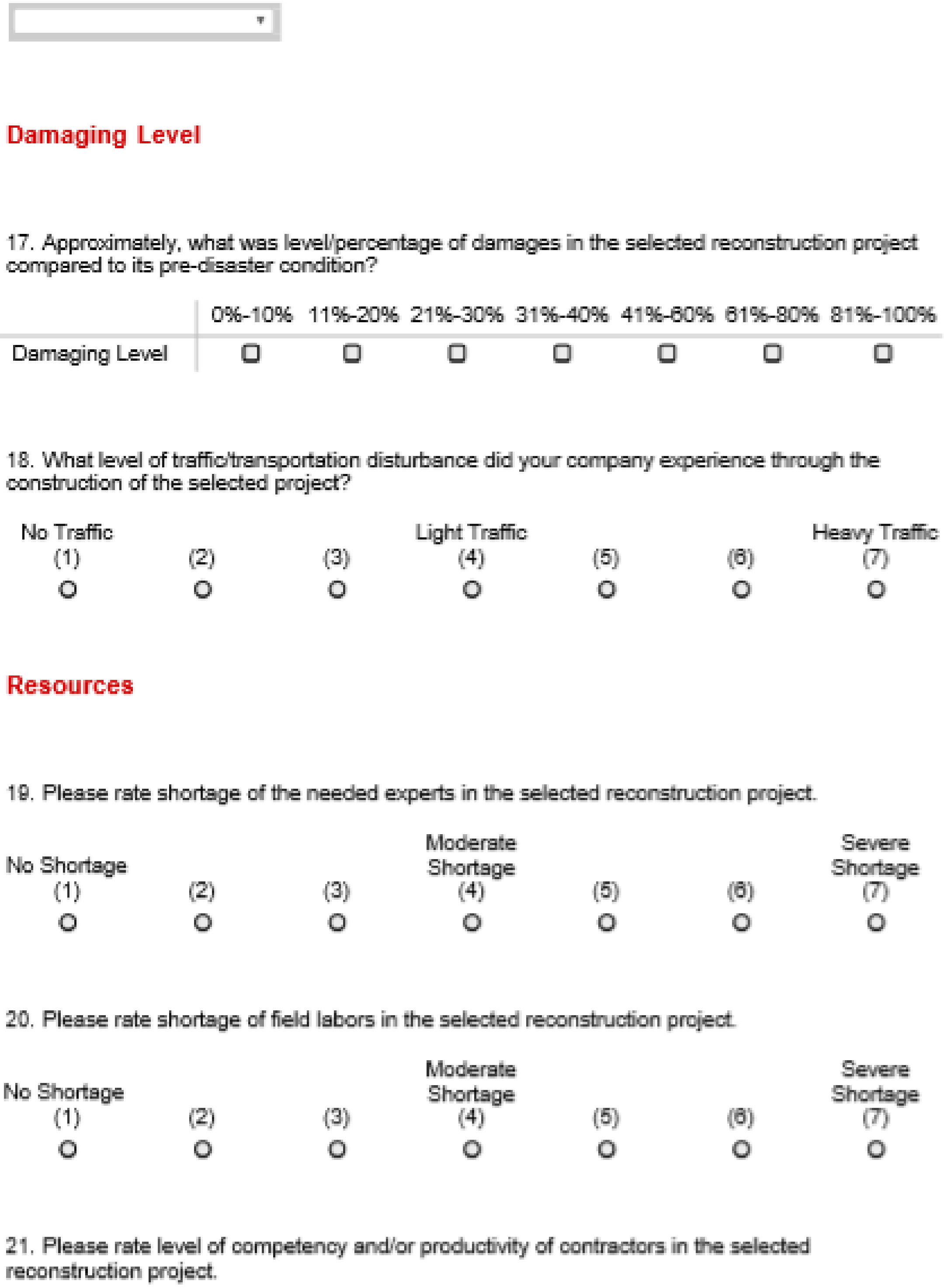
13. Approximately, how many main/trunk lines did the selected reconstruction project consist of? (Main/trunk line refers to the primary linkage serving main arteries of interaction and commerce in transportation networks)

14. Approximately, what was the length of the selected reconstruction project?

15. Please rate the complexity level of the selected reconstruction project.

Not at All Complex (1)	(2)	(3)	Fairly Complex (4)	(5)	(6)	Extremely Complex (7)
○	○	○	○	○	○	○

16. How remote (distance from highly-populated areas) was the project located?



Damaging Level

17. Approximately, what was level/percentage of damages in the selected reconstruction project compared to its pre-disaster condition?

	0%-10%	11%-20%	21%-30%	31%-40%	41%-60%	61%-80%	81%-100%
Damaging Level	☐	☐	☐	☐	☐	☐	☐

18. What level of traffic/transportation disturbance did your company experience through the construction of the selected project?

No Traffic (1)	(2)	(3)	Light Traffic (4)	(5)	(6)	Heavy Traffic (7)
○	○	○	○	○	○	○

Resources

19. Please rate shortage of the needed experts in the selected reconstruction project.

No Shortage (1)	(2)	(3)	Moderate Shortage (4)	(5)	(6)	Severe Shortage (7)
○	○	○	○	○	○	○

20. Please rate shortage of field labors in the selected reconstruction project.

No Shortage (1)	(2)	(3)	Moderate Shortage (4)	(5)	(6)	Severe Shortage (7)
○	○	○	○	○	○	○

21. Please rate level of competency and/or productivity of contractors in the selected reconstruction project.

Not at All Competent (1)	(2)	(3)	Moderately Competent (4)	(5)	(6)	Highly Competent (7)
○	○	○	○	○	○	○

22. Please rate frequency level of logistics management issues in the selected reconstruction project. (Logistics management is the process of planning, implementing and controlling supply chain resources from the point of origin, such as raw material accumulation, to the correct location on the construction site.*)*

Limited No. of Issues (1)	(2)	(3)	Reasonable No. of Issues (4)	(5)	(6)	Substantial No. of Issues (7)
○	○	○	○	○	○	○

23. Please rate shortage of competent suppliers in the selected reconstruction project.

No Shortage (1)	(2)	(3)	Moderate Shortage (4)	(5)	(6)	Severe Shortage (7)
○	○	○	○	○	○	○

24. Please rate shortage of materials in the selected reconstruction project.

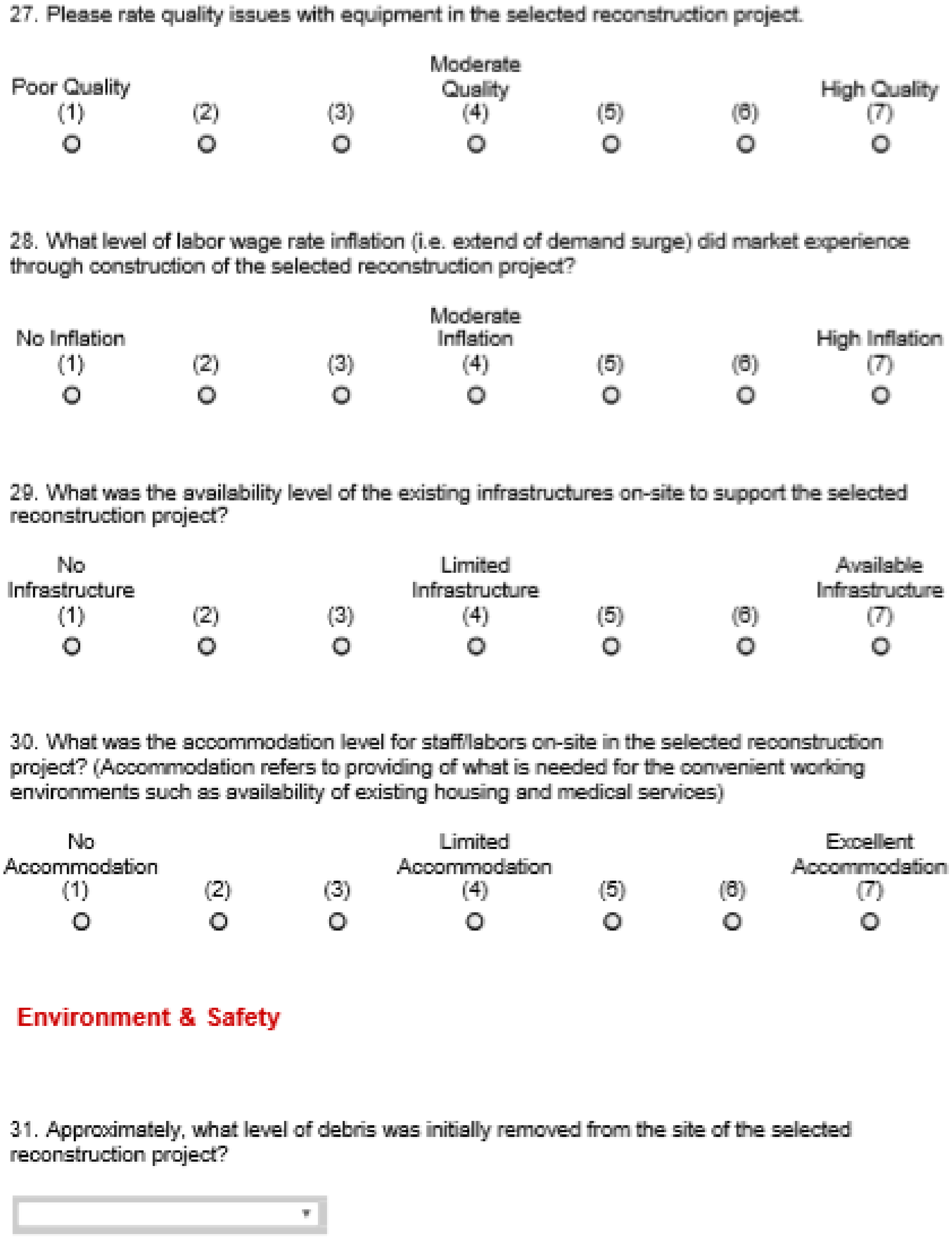
No Shortage (1)	(2)	(3)	Moderate Shortage (4)	(5)	(6)	Severe Shortage (7)
○	○	○	○	○	○	○

25. Please rate shortage of equipment in the selected reconstruction project.

No Shortage (1)	(2)	(3)	Moderate Shortage (4)	(5)	(6)	Severe Shortage (7)
○	○	○	○	○	○	○

26. Please rate quality issues with materials in the selected reconstruction project.

Poor Quality (1)	(2)	(3)	Moderate Quality (4)	(5)	(6)	High Quality (7)
○	○	○	○	○	○	○



27. Please rate quality issues with equipment in the selected reconstruction project.

Poor Quality			Moderate Quality			High Quality
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

28. What level of labor wage rate inflation (i.e. extend of demand surge) did market experience through construction of the selected reconstruction project?

No Inflation			Moderate Inflation			High Inflation
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

29. What was the availability level of the existing infrastructures on-site to support the selected reconstruction project?

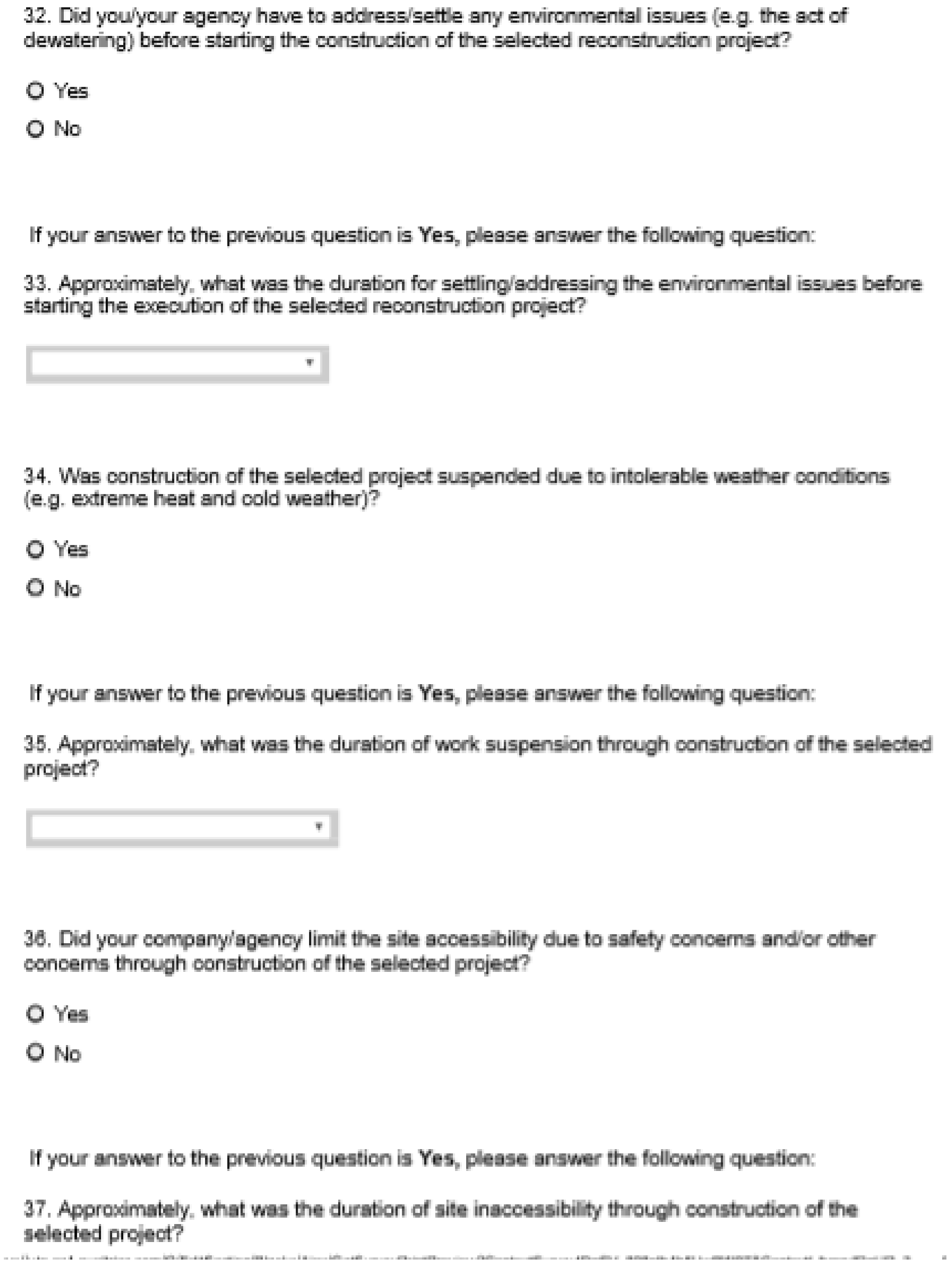
No Infrastructure			Limited Infrastructure			Available Infrastructure
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

30. What was the accommodation level for staff/labors on-site in the selected reconstruction project? (Accommodation refers to providing of what is needed for the convenient working environments such as availability of existing housing and medical services)

No Accommodation			Limited Accommodation			Excellent Accommodation
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

Environment & Safety

31. Approximately, what level of debris was initially removed from the site of the selected reconstruction project?



32. Did you/your agency have to address/settle any environmental issues (e.g. the act of dewatering) before starting the construction of the selected reconstruction project?

○ Yes

○ No

If your answer to the previous question is **Yes,** please answer the following question:

33. Approximately, what was the duration for settling/addressing the environmental issues before starting the execution of the selected reconstruction project?

34. Was construction of the selected project suspended due to intolerable weather conditions (e.g. extreme heat and cold weather)?

○ Yes

○ No

If your answer to the previous question is **Yes,** please answer the following question:

35. Approximately, what was the duration of work suspension through construction of the selected project?

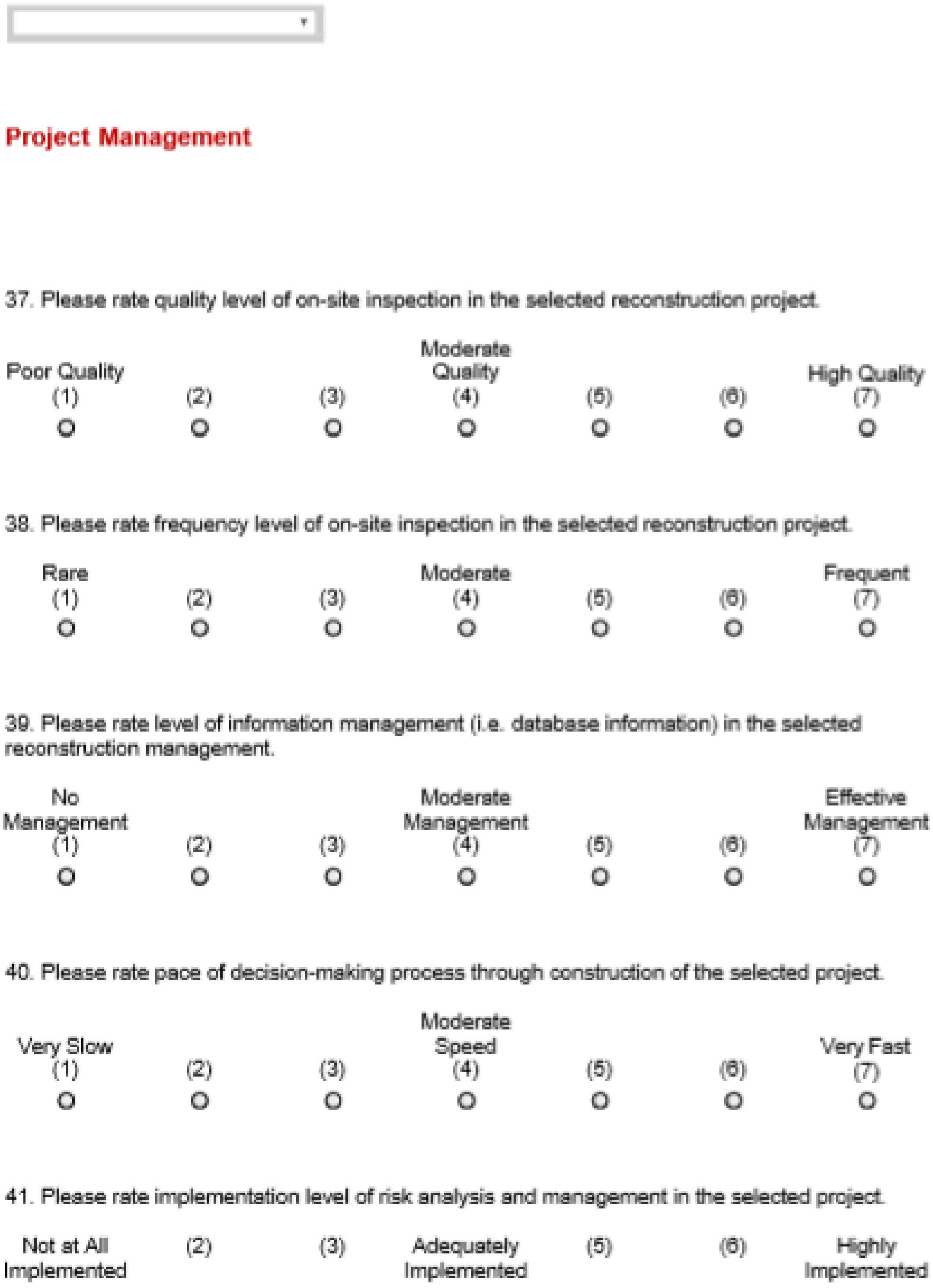
36. Did your company/agency limit the site accessibility due to safety concerns and/or other concerns through construction of the selected project?

○ Yes

○ No

If your answer to the previous question is **Yes,** please answer the following question:

37. Approximately, what was the duration of site inaccessibility through construction of the selected project?



Project Management

37. Please rate quality level of on-site inspection in the selected reconstruction project.

Poor Quality			Moderate Quality			High Quality
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

38. Please rate frequency level of on-site inspection in the selected reconstruction project.

Rare			Moderate			Frequent
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

39. Please rate level of information management (i.e. database information) in the selected reconstruction management.

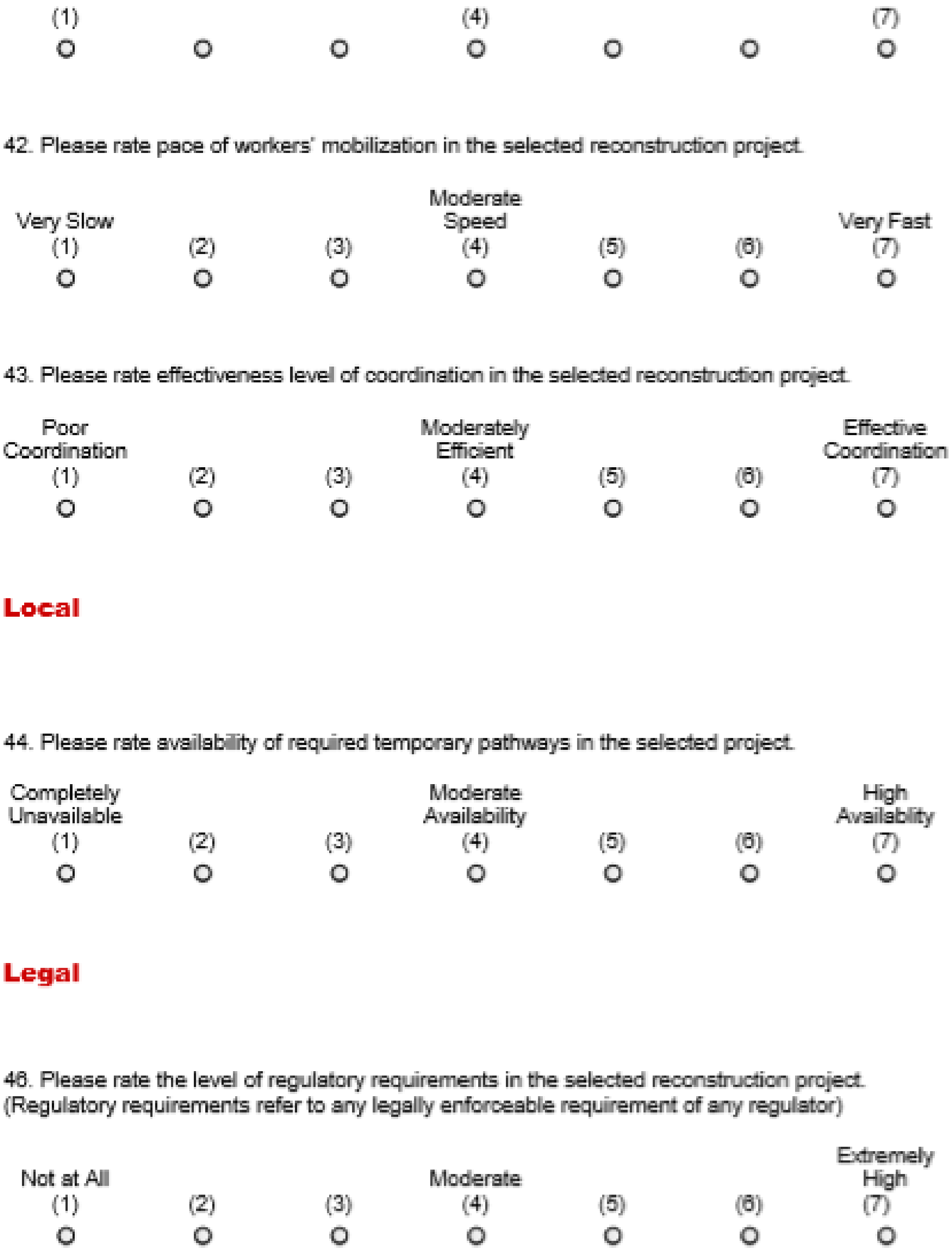
No Management			Moderate Management			Effective Management
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

40. Please rate pace of decision-making process through construction of the selected project.

Very Slow			Moderate Speed			Very Fast
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

41. Please rate implementation level of risk analysis and management in the selected project.

Not at All Implemented	(2)	(3)	Adequately Implemented	(5)	(6)	Highly Implemented



(1)			(4)			(7)
○	○	○	○	○	○	○

42. Please rate pace of workers' mobilization in the selected reconstruction project.

Very Slow			Moderate Speed			Very Fast
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

43. Please rate effectiveness level of coordination in the selected reconstruction project.

Poor Coordination			Moderately Efficient			Effective Coordination
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

Local

44. Please rate availability of required temporary pathways in the selected project.

Completely Unavailable			Moderate Availability			High Availablity
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○

Legal

46. Please rate the level of regulatory requirements in the selected reconstruction project.
(Regulatory requirements refer to any legally enforceable requirement of any regulator)

Not at All			Moderate			Extremely High
(1)	(2)	(3)	(4)	(5)	(6)	(7)
○	○	○	○	○	○	○