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RESILIENT AND STRUCTURALLY CONTROLLABLE DESIGN OF MULTI-LEVEL INFRASTRUCTURE NETWORKS UNDER DISRUPTIONS

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RESILIENT AND STRUCTURALLY CONTROLLABLE DESIGN OF MULTI-LEVEL INFRASTRUCTURE NETWORKS UNDER DISRUPTIONS

A DISSERTATION APPROVED FOR THE
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BY

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Glossary

An ***infrastructure network*** comprises of different entities that are connected by the flow of materials, products, information or electricity.

A ***disruption*** is an event which is not planned or anticipated and may affect the structure or dynamics of infrastructure networks.

A ***stable infrastructure network*** is one that is able to cope with disruptions and to continue a planned execution after being disrupted.

A ***robust infrastructure network*** is one that is made relatively insensitive to disruptions, thereby making it possible to continue delivering service as before in the face of disruptions.

A ***flexible infrastructure network*** is one that is able to avoid the impact of disruptions by quickly changing the structure and dynamics of the network.

A ***resilient infrastructure network*** is one that is capable of effectively absorbing, adapting to or rapidly recovering from disruptive events, and returning to its original state or moving to a new state after being disrupted.

A ***controllable infrastructure network*** is one that, with a suitable choice of inputs, can be driven from any initial state to any desired final state within finite time.

A ***structurally controllable infrastructure network*** is one that is capable of having access to its entire nodes via controllers (i.e., driver nodes).

Verification in this dissertation refers to internal consistency.

Validation in this dissertation refers to justification of knowledge claims.

Abstract

An infrastructure network comprises of different entities that are connected by the flow of materials, products, information or electricity. Disruptions could occur at any section of the network for a wide variety of reasons. Some examples include: company mergers (e.g., Halliburton's impending purchase of Baker Hughes), labor union strikes (e.g., labor strike on the west coast of the United States in 2002), sanctions imposed or lifted (e.g., economic sanctions against Iran being lifted by the UN in July 2015), plantations being destroyed (banana plantations were destroyed by Hurricane Mitch in 1998), air traffic being suspended due to weather or terrorism, main suppliers put out of commission by natural disasters (e.g., the 1999 earthquake in Taiwan disrupted semiconductor fabrication facilities), etc. A resilient infrastructure network is one that has the ability to recover quickly from disruptions and ensure customers are minimally affected, while the simultaneous design of operational and strategic decisions in all levels of the network structure are considered. It becomes very important to design a resilient multi-level infrastructure network in order to manage disruptions using appropriate pre-disruption and post-disruption restoration strategies. The capability of structural controllability can help in recovering a disrupted infrastructure network and increasing its resilience before, during and after the occurrence of disruptions.

In this dissertation, the problem of applying structural controllability in order to design a resilient multi-level infrastructure network under disruptions with the selection of appropriate restoration strategies and consideration of the trade-off between effectiveness and redundancy in the resilience analysis is considered. The

aforementioned problem has four aspects worth of consideration: *a*) multi-level network structures, *b*) restorations strategies, *c*) resilience analysis, and *d*) structural controllability. In this regard, the primary research question is defined as: *What methods are required for designing a resilient infrastructure network under disruptions through selecting appropriate restoration strategies in a manner of applying structural controllability*? The primary research question is broken into four secondary questions in respect to each four aspects of the considered problem as follows.

- What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?
- What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?
- What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?
- What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?

In response to the primary research question, two methods are proposed in this dissertation. The first method is the multi-level infrastructure network (MLIN) method which refers to the first aspect of the problem. The second method is the resilient and structurally controllable infrastructure network (RCIN) method which refers to the second, third and last aspects of the problem. Based on these two proposed methods, the main created new knowledge in this dissertation is in tailoring and incorporating the structural controllability theory in the resilience analysis of disrupted infrastructure networks.

The proposed MLIN and RCIN methods are verified and validated using two examples from the energy industry in the context of the validation square. An example of a network of electric charging stations for plug-in hybrid electric vehicles using renewable energy and power grid as sources of energy is used to demonstrate and validate the MLIN method. An example of a network of a multi-product European petroleum industry is used to demonstrate and validate the RCIN method. Although the proposed methods are solved for the two examples, both of them are generalizable to be applicable to any network-based complex engineered systems under disruptions.

CHAPTER 1 RESILIENT AND STRUCTURALLY CONTROLLABLE DESIGN OF MULTI-LEVEL INFRASTRUCTURE NETWORKS UNDER DISRUPTIONS

In this chapter, the importance, characteristics, challenges and requirements regarding the problem of designing resilient and structurally controllable multi-level infrastructure networks are addressed. Then, the research gap is highlighted, followed by defined research questions and expected contributions. Then, the two proposed methods, the multi-level infrastructure network (MLIN) method, and resilient and structurally controllable infrastructure network (RCIN) method, as contributions in this dissertation, are introduced. Finally, the verification and validation in this dissertation is planned based on the validation square explained. The organization of Chapter 1 is shown in Figure 1-1. The importance of the disruption management in infrastructure networks is addressed in Section 1.1. This section is followed by the operational and strategic decisions in multi-level networks in Section 1.1.1, and resilient and structurally controllable infrastructure networks under disruptions in Section 1.1.2. From the perspective of systems based design, characteristics of designing resilient and structurally controllable multi-level infrastructure networks are addressed in Section 1.2, and the challenges and requirements associated with each aspect of design are discussed in Section 1.3.

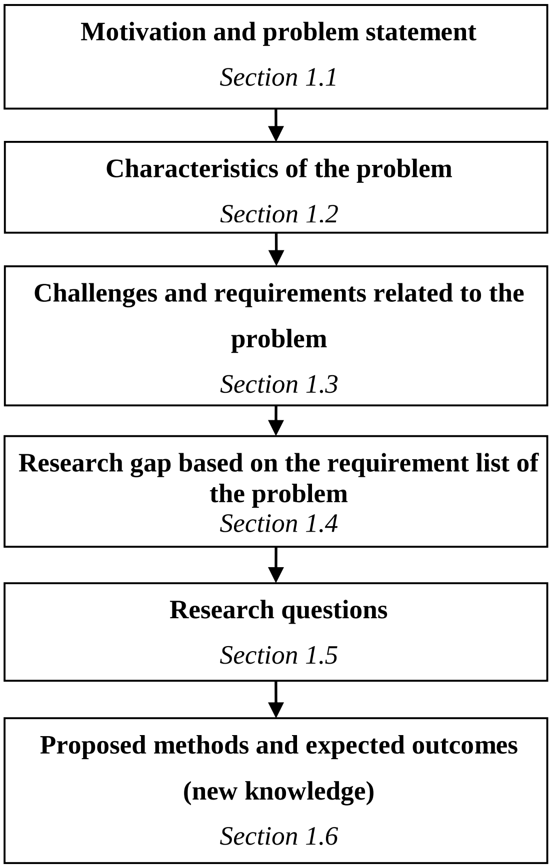


Figure 1-1 Structure and connectivity between different sections in Chapter 1

The gap analysis is discussed after a brief critical evaluation of the literature in Section 1.4, and research questions and corresponding hypotheses are established in Section 1.5. The two proposed methods are briefly explained in Section 1.6. The validation square roadmap, explained in Section 1.7, is used as a guideline for validating the methods in this dissertation. Finally, the structure of this dissertation is discussed in Section 1.7 and illustrated in Figure 1-7.

1.1 MANAGING DISRUPTIONS IN INFRASTRUCTURE NETWORKS COSNIDERING OPERATIONAL AND STRATEGIC DECISIONS

An infrastructure network is comprised of different entities that are connected by the flow of materials, products, information or electricity. Disruptions can occur at any facility or transportation arcs of networks for a wide variety of reasons such as transportation delays, power outages, natural or man-made disasters. A resilient infrastructure network has the ability to recover quickly from disruptions and ensure customers are minimally affected. Hence, it is very important to design resilient infrastructure networks in order to manage disruptions. Network disruptions are events which are not planned or anticipated and may disrupt the normal flow of materials within infrastructure networks (Hendricks and Singhal, 2003; Kleindorfer and Saad, 2009; Svensson, 2000). In consequence, firms may be exposed to operational and financial risks within infrastructure networks (Stauffer, 2003).

In addition, the nature of long-term (strategic decisions) and short-term (operational decisions) decisions are highly convoluted in infrastructure networks. Strategic decisions determine the topology of infrastructure available for infrastructure networks, and operational decisions determine the dynamics and performance of infrastructure networks. Considering the interactions between these two types of decisions (strategic and operational decisions) are necessary in designing infrastructure networks. Different aspects of strategic and operational decisions, and managing disruptions in infrastructure networks are explained in Sections 1.1.1 and 1.1.2, respectively.

1.1.1 Operational and Strategic Decisions in Multi-Level Network Design

Infrastructure network design involves determining the network structure and the flow of products or information over the structure. Two types of decisions (i.e., strategic decisions and operational decisions) are involved in the network design problems: first, decisions on location and capacity of facilities (strategic decisions); second, decisions on supplying the demand of markets (production and inventory considerations) through available routes (transportation considerations) (Gong and co-authors, 2014).

Some examples of the strategic decisions regarding the topology of infrastructure networks are as follows.

- Determine number and location of facilities (nodes) in the network structure;
- Determine capacity of facilities (nodes);
- Determine feasible connections between facilities (nodes) in the network structure.

Some examples of the strategic decisions regarding the dynamics of infrastructure networks are as follows.

- Determine facility layout and production planning in facilities (nodes);
- Determine storage quantities and inventory planning in facilities (nodes);
- Determine transportation planning among facilities (nodes).

The simultaneous design for operational/short-term decisions and strategic/long-term decisions results in a more efficient design process. Add to this, the importance of modeling multi-level networks (e.g., node-level and network-level decisions in large scale multi-level networks).

In designing a multi-level network both the strategic and operational decisions in the hierarchical structure of networks should be considered. There are various hierarchical decisions related to the network structure. For example, in a bi-level structure of an electronic company (e.g., Dell Inc.), there are both node-level and network-level decisions: a) strategic decisions are mainly considered as the network-level decisions or decisions related to the structure of infrastructure networks such as the network configuration, resource allocation, location and capacity of manufacturing plants, distribution centers, and suppliers, b) operational decisions are mainly considered as the node-level decisions such as decisions regarding the handling of the incoming customer orders. At the node-level decisions, while the network configuration is considered fixed, the planning policies can be defined.

1.1.2 Resilient and Structurally Controllable Networks under Disruption

Capability of infrastructure networks in reducing cost and being agile with respect to customers' expectations improves the level of service in the market. However, the distributed nature of infrastructure networks make them more vulnerable against disruptions in the business and working environments. An important feature of business and working environments is unpredictability due to the huge number of unexpected events since the occurrence of disruptions is an undeniable part of today's environments.

Numerous disruption sources are involved in infrastructure networks that make networks vulnerable to handle disruptions. Network disruptions are events that are not planned or anticipated and may affect the structure or dynamics of networks (Hendricks and Singhal, 2003; Kleindorfer and Saad, 2009; Svensson, 2000). In consequence, firms may be exposed to operational and financial disruptions within infrastructure networks (Stauffer, 2003). According to Sarkar and co-authors (2002), during the labor strike in 2002, 29 ports in the West coast of United States were shut down that led to the closure of New United Motor Manufacturing production factory. Because of the destructive earthquake of Japan in 2011, Toyota Motor Company stopped operations in its twelve assembly plants. Ceasing operations in these assembly plants, mainly because of disruptions in its chain's manufacturing subsystems, led to production loss of 140,000 automobiles. The lightning bolt that, in March 2000, struck a Philips semiconductor plant in Albuquerque, New Mexico, created a 10-minute blaze that contaminated millions of radio-frequency chips (RFCs) and subsequently delayed deliveries to its two largest customers, Finland's Nokia and Sweden's Ericsson. Although facing the same situation, two companies responded differently and thus ended up with two endings: one survived from the disruption while the other ultimately exited from the business (Gong and co-authors, 2014).

A tornado hits, a bomb explodes, a supplier goes out of business or the union begins a wildcat strike. Disruptions can be classified as random events (including natural disasters), accidents or intentional disruptions (such as job actions or acts of terrorism or sabotage) in which estimating the likelihood of each class differs (Sheffi, 2005). Mulani and Lee (2002) show that disruption managers spend about 40–60% of their working time handling disruptions in infrastructure networks (Ivanov and Sokolov, 2013).

Therefore, a system is considered not just with disruptive events and their attendant likelihoods, but also the system's resistance to and recovery from these events; managing disruptions through restoration scenarios is critical.

Infrastructure network design requires resilience as the capability of effectively absorbing, adapting to or recovering from disruptive events, and returning to its original state or moving to a new state (i.e., less or better than the original state) after being disrupted. The importance of resilience is in the face of disruptions when the ability to restore the planned execution along with the achievement of the planned or acceptable performance is the objective.

In addition, the importance of structurally controlling networks over the disruption period is important. According Liu and co-authors (2011), “a network is structurally controllable if, with a suitable choice of inputs, it can be driven from any initial state to any desired final state within finite time”. This definition agrees with the intuitive notion of structural controllability that is the capability to guide a network’s behavior toward a desired state through the appropriate manipulation of a few driver nodes. An infrastructure network can be controlled with suitable manipulation through driver nodes (i.e., control nodes or controllers), and all other nodes in the network are accessible through these driver nodes. This accessibility facilitates transferring extra inventory to disrupted nodes and results in a higher resilience. Therefore, applying structural controllability is a way to increase the resilience of disrupted infrastructure networks.

According to the topics addressed in Section 1.1, the problem that is considered in this dissertation is as follows.

The problem that is considered in this dissertation is on applying structural controllability in designing a resilient multi-level infrastructure network in the face of disruptions. In addition, selection of appropriate post-disruption and pre-disruption restoration strategies is part of the problem while considering the trade-off between effectiveness and redundancy in resilience analysis of disrupted infrastructure networks.

In order to understand all aspects of the considered problem, the characteristics of this problem are explained in Section 1.2. In addition, in Chapters 3 and 4, the problem statement is explained in more detail.

1.2 CHARACTERISTICS OF DESIGNING MULTI-LEVEL INFRASTRUCTURE NETWORKS UNDER DISRUPTIONS

In this section, the main characteristics of resilient and structural controllability of multi-level infrastructure networks are discussed. Different methods for the multi-level network design are developed in the literature, mainly based on the facility location problems addressed in Section 1.2.1. In Section 1.2.2, the main characteristics of resilient and controllable networks from the viewpoint of different types of disruptions and measures for resilience analysis are addressed.

1.2.1 Multi-Level Infrastructure network Design

The simultaneous design for operational/short-term decisions and strategic/long-term decisions that support it will result in a more efficient design for multi-level structure of networks. In addition, the importance of modeling multi-level decisions (e.g., node-level and network-level decisions) in large-scale, multi-level networks should be considered. Although the potential economic benefits of design for multi-level infrastructure networks, the barriers are both the computational and mathematical complexity of the problem.

Mainly all models in this area are built upon the facility location problem. Facility location problems have proven to be a fertile ground for modeling infrastructure networks. There are four main categories for the facility location problems, such as analytical models, network models, continuous models and discrete models (Daskin, 2008). Among all these models, the main characteristic is the importance of considering the interactions between different levels of the hierarchical structure. In addition, considering conflicts among system goals (i.e., sustainability goals such as economic, social and environment goals) in designing multi-level networks, while the focus of each goal may be on different levels, is essential.

1.2.2 Managing Disruptions in Resilient and Structurally controllable Infrastructure networks

Disruptions in infrastructure networks are classified in different ways. For example, Waters (2007) divides infrastructure network risk sources into internal risks or uncertainties (i.e., can be controlled) and external risks or disruptions (i.e., cannot be controlled). Internal risks appear in normal operations, such as late deliveries, excess stock, poor forecast, human error, faults in IT systems, etc. External risks come from outside of a network, such as earthquakes, hurricanes, industrial action, wars, terrorist attacks, price rise, problems with trading partners, shortage of raw materials and crime. Although understanding risks and their occurrence possibility in a system is necessary, resilience analysis is different from risk analysis in several ways. Principally, conventional risk assessment methods are used to determine the negative consequences of potential undesired events, and to mitigate the organization's exposure to those undesirable outcomes. In resilience analysis, it is emphasized that an assessment of the system's ability to (a) anticipate and absorb potential disruptions, b) develop adaptive means to accommodate changes within or around the system, and c) establish restoration strategies aimed at either building capacity to withstand disruptions or recover as quickly as possible after an impact.

Accessibility to all nodes in a disrupted network is critical in order to achieve high resiliency. Structural controllability is a way toward accessibility to all nodes from driver nodes (i.e., controllers) and having high resiliency.

According to the characteristics addressed in this section, multi-level network design (see Section 1.2.1), restoration strategies, resilience analysis, and structural controllability (see Section 1.2.2) are four aspects of the considered problem (see Section 1.1) in this dissertation. These four aspects of the resilient and structural controllability of multi-level infrastructure networks are shown in Figure 1-2.

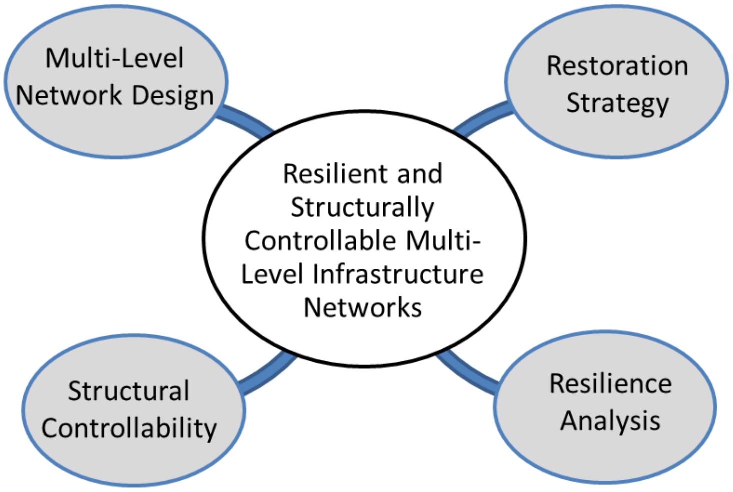


Figure 1-2 Four aspects of resilient and controllable infrastructure networks under disruptions

In next section, the challenges and requirements associated with each of these four aspects are explained.

1.3 CHALLENGES AND REQUIREMENTS IN DESIGNING RESILIENT AND CONTROLLABLE MULTI-LEVEL NETWORK DESIGN

In this section, the challenges in designing resilient and structurally controllable multi-level infrastructure networks are discussed. Through analyzing the challenges, the requirements in addressing each of these challenges are defined and shown in Table 1-1.

From the multi-level aspect of the problem, the simultaneous design of **the node-level (focus on the operational/short-term decisions) and the network-level (focus on the strategic/long-term decisions) decisions provides an efficient design process for infrastructure networks with hierarchical structures**. Although the potential economic benefits of designing networks with multi-level structures can be substantial, relatively little has been done in this field. The barriers are both the computational and mathematical complexity of the problem. Add to this the importance of modeling multi-level networks with conflicting system goals, and the fact that behavior can be highly non-linear and it is easy to understand the limited study that design of large scale multi-level systems have received. In other words, **considering the conflicts among system goals, such as sustainability drivers (i.e., economic, social and environment drivers) in designing multi-level networks is essential.**

From restoration strategies and resilience analysis aspects, the continuity of normal network functions is the goal in designing resilient networks, while disruptions occur. As is shown in Table 1-1, **the challenge in designing resilient infrastructure networks is to select appropriate pre-disruption (e.g., fortifying facilities, back-up inventory, etc.) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity, etc.) restoration strategies providing adequate protection from disruptions without reducing effectiveness**. **The cost of recovering a disrupted network should also be considered along with the cost of redundancy**. Therefore, **considering the trade-off among effectiveness and redundancy is a challenge in the resilience analysis aspect.**

From the structural controllability aspect, in the face of disruptions, the capability of controlling a disrupted network through driver nodes (i.e., controllers) is critical for increasing the resilience of the network. As is shown in Table 1-1, a **critical issue in applying restoration strategies to recover disrupted infrastructure networks is determining the location and number of driver nodes in order to operate selected restoration strategies and access to all disrupted nodes**.

As is shown in Table 1-1, four aspects of designing resilient and structurally controllable multi-level infrastructure networks are addressed in the first column, and each aspects is followed by several challenges discussed in this section. Finally, four requirements are defined, one requirement for each aspect, in order to overcome the challenges in each aspect.

Table 1-1 Mapping four aspects of the problem, challenges and requirements

Aspects of the considered problem	**Challenges in resilient and structurally controllable multi-level infrastructure networks**	**Requirements in resilient and structurally controllable multi-level infrastructure networks**
Multi-level network	• Interactions between different hierarchical levels of a network; • Conflicts among goals (e.g., sustainability drivers: economic, social and environment) in designing networks.	Integrated formulation for designing a multi-level network considering operational (short term) and strategic (long term) decisions with conflicting goals.
Restoration strategies	• Computationally heavy analysis to select appropriate restoration strategy.	Selecting the appropriate pre-disruption and post-disruption restoration strategies for recovering a disrupted infrastructure network.
Resilience analysis	• Trade-off between redundancy and efficiency; • Incorporating the dynamic behavior of networks (time-based variables); • Conflicting system goals.	Quantitative measures which can represent the resilience of a recovered network after a disruptive event while considering the trade-off between redundancy and effectiveness.
Structural controllability	• Fragility and dis-connectivity in disrupted infrastructure networks; • Inaccessible nodes in a disrupted network.	Determining the location and minimum number of driver nodes to make networks structurally controllable

Considering the requirements for addressing the challenges related to each aspect of resilient and controllable multi-level infrastructure networks, different methods are presented in the literature. The research gap is addressed in next section.

1.4 RESEARCH GAPS IN DESIGNING RESILIENT AND STRUCTURALLY CONTROLLABLE MULTI-LEVEL NETWORK DESIGN

A comprehensive critical literature review with focus on all four aspects of designing resilient networks, such as multi-level network design, restoration strategies, resilience analysis, and structural controllability, is performed and explained in Chapter 2. In this section, the main findings of the critical evaluation of the literature and issues in the related literature are explained, the research gap is derived, and it is summarized in Table 1-2.

1.4.1 Research Gap in the Multi-Level Network Design's Literature

Considering strategic and operational decisions simultaneously in hierarchical network structures with conflicting system goals is critical. Facility location problem models are a fertile ground for modeling infrastructure networks. There are four main categories for the facility location problems such as analytical models, network models, continuous models and discrete models (Daskin, 2008). In both network models and discrete models, demands generally arise on the nodes and nodes are expected to be a finite set of candidate locations. For some applications, a hybrid model of facility location problems can be used. However, in these models usually one level of decisions with only one time scale is considered in the literature. For instance, in a supply network of products, two levels of decisions can be considered: 1) in the first level (network-level decisions), location, allocation, and capacity decisions can be considered with a longer time scale (e.g., one year), and 2) in the second level (node-level decisions), production planning and maintenance scheduling at plants, and inventory planning at warehouses can be considered with a shorter time scale (e.g., day or hour).

In the first level, the strategic decisions and in the second level, operational decisions are considered.

In dynamic facility location problems, although the multi-period modeling is considered, operational and strategic decisions with different time scales are not considered. In these models, only the strategic level decisions, such as location, allocation and capacity decisions, are considered (Shulman (1990), Dias and co-authors (2007), and Jena and co-authors (2013)). However, considering operational decisions in the lower levels of a network, which can be formulated using simulation models, and the strategic decisions are addressed very sparse in the literature.

In addition, considering the interaction among goals in the presence of conflicting system goals is critical. For example, when sustainability drivers are considered in designing a network, the conflicts among economic, social, and environment drivers should also be considered. In Section 2.1, more methods related to the multi-level network design are critically evaluated, and some of these methods are compared with each other in Tables 2-1and 2-2.

As discussed in Table 1-2, considering the current methods in the literature of multi-level network design, one research gap in the current literature is that an integrated method for designing a multi-level network with focus on operational and strategic decisions, and conflicting system goals is required.

1.4.2 Research Gap in the Restoration Strategy's and Resilience Analysis's Literature

The continuity of operations in a disrupted infrastructure network is required since the functioning of a society depends heavily on energy, transportation, telecommunication, and financial networks which play an important role in human's life. In the face of disruptive events, the question of efficient restoration strategies raised by a resilient infrastructure network is approached. Chopra and Sodhi (2004) categorize potential infrastructure network risks into nine categories: a) disruptions (e.g., natural disaster, terrorism, war, etc.), b) delays (e.g., inflexibility of supply source), c) systems (e.g., information infrastructure breakdown), d) forecast (e.g., inaccurate forecast, bullwhip effect, etc.), d) intellectual property (e.g., vertical integration), e) procurement (e.g., exchange rate risk), f) receivables (e.g., number of customers), g) inventory (e.g., inventory holding cost, demand and supply uncertainty, etc.), h) capacity (e.g., cost of capacity).

Waters (2007) divides infrastructure network risk sources to internal risks (can be controlled) and external risks (cannot be controlled). Internal risks appear in normal operations, such as late deliveries, excess stock, poor forecast, human error, faults in IT systems, etc. External risks come from outside of a network, such as earthquakes, hurricanes, industrial action, wars, terrorist attacks, price rise, problems with trading partners, shortage of raw materials and crime. In addition, Waters (2007) introduces another three categories of risk sources: a) environmental risk sources which comprise any uncertainties arising from the interactions in the infrastructure network environment. These may be the result of accidents (e.g., fire), socio-political actions (e.g., fuel protests or terrorist attacks) or acts of God (e.g., extreme weather or earthquakes), b) Organizational risk sources which lay within the boundaries of networks and range from labor (e.g., strikes) or production uncertainties (e.g., machine failure) to IT-system uncertainties, and c) Network-related risk sources which arise from interactions between organizations within an infrastructure network.

Kar (2010) categorizes risks in infrastructure networks into two groups: a) Systematic risks related to environmental factors which are unavoidable. Companies do not have any control on these factors such as demand-side uncertainty, supply-side disruption, regulatory, legal, and bureaucratic changes, and infrastructure disruption. b) Non-systematic risks dealing with factors that can be controlled to a large extent by a company such as facility disruption of manufacturing subsystem.

Although understanding risks and their occurrence possibility in a system is necessary, resilience analysis is different from risk analysis in several ways. Principally, conventional risk assessment methods are used to determine the negative consequences of potential undesired events, and to mitigate the organization's exposure to those undesirable outcomes. In the resilience analysis, it is emphasized that an assessment of the system's ability to (a) anticipate and absorb potential disruptions; (ii) develop adaptive means to accommodate changes within or around the system; and (iii) establish response behaviors aimed at either building the capacity to withstand the disruption or recover as quickly as possible after an impact.

Several authors of recent papers have indicated the importance of explicitly incorporating a time dimension into the definition of resilience, especially Haimes (2009). A comprehensive critical evaluation of the literature is presented in Section 2.2, and several papers are compared with each other using various characteristics in Table 2-3.

As discussed in Table 1-2, in the current literature, one research gap is related to the selection of appropriate combination of time-based, pre-disruption and post-disruption restoration strategies for recovering a disrupted infrastructure network. Even in the few number of papers that consider both pre-disruption and post-disruption restoration strategies (see table 2-3), the trade-off among redundancy and effectiveness is not considered in the resilience analysis. In this research gap, measures for resilience analysis, such as service level, delivery time, and cost, often do not include the time dimension. Therefore, the dynamic aspect of resilience analysis is not considered in any comprehensive method when making decisions about restorations strategies.

1.4.3 Research Gap in the Structural Controllability's Literature

One efficient approach in order to mitigate the risk of disruptions in disrupted networks is applying structural controllability. Structural controllability can bring accessibility to all nodes using driver nodes (i.e., controllers) that can be vital while disruptions happen in a network. Liu and co-authors (2011) apply the structural controllability based on Lin' Theorem on self-organized complex networks. Since this work is multi-disciplinary, in Section 2.3.1 structural controllability and its related concepts are introduced. In Section 2.3.2, a critical evaluation of the literature is presented, and in Table 2-3, several papers in this area are compared with each other.

As discussed in Table 1-2, in the current literature, one research gap is related to the application of structural controllability for controlling infrastructure networks, especially after the occurrence of disruptions. In this research gap, determining the location of driver nodes and operating the selected appropriate restoration strategies to recover a disrupted network are required.

More than 75 papers in the literature are critically evaluated (see Tables 2-1, 2-2, and 2-3) in the context of the four aspects of the problem (see Figure 1-2), such as multi-level network design, restoration strategies, resilience analysis, and structural controllability. A summary of the critical evaluation of the main studies in the literature is addressed and analyzed in Table 1-2.

Table 1-2 Summary of critical evaluation of existing methods

Aspects	**Methods**	**Evaluation of Literature**	**Research Gap**
Multi-level network design	Dynamic facility location problems by Shulman (1990), Dias and co-authors (2007), Daskin (2008), and Jena and co-authors (2013)	• Since the time scale for operational and strategic decisions are different, it is difficult to use the current models for integrated design while there are different decision levels. • The focus of models in this area is mainly on the network-level design; not on bringing out decisions regarding the node level.	The research gap is that an integrated method (consists of simulation modeling and mathematical modeling) for designing a multi-level network with focus on operational and strategic decisions, and conflicting system goals is required.
Restoration strategies	Considering cost as redundancy and recovery time as efficiency by Kristianto and co-authors, Gong and co-authors (2014)	Focus of these models is on selecting the appropriate restoration strategies without respect to the recovery time or considering the trade-off between redundancy and effectiveness.	The research gap is that the selection of appropriate pre-disruption and post-disruption restoration strategies while considering the trade-off between redundancy and effectiveness is required.
Resilience analysis	Considering service level and lost sales while disruptions happen by Das (2011), Schmit (2011), Ramirez and Marquez (2012)	Focus of this part of the literature is on one aspect of the resilience analysis, either cost/profit or service level/lost sales. Even in papers that consider both of them, considering the recovery time is neglected.	The research gap is that a comprehensive set of time-based measures, such as service level, cost, recovery or delivery time, is required for the resilience analysis while considering the trade-off between redundancy and effectiveness.
Structural controllability	Structural controllability for complex networks by Liu and co-authors (2011)	Focus here is on applying structural controllability for self-organized networks and it is not applied for infrastructure networks or recovering disrupted networks.	The research gap is in applicability of structural controllability in controlling disrupted infrastructure networks and consequently increasing its resilience, and using driver nodes to operate restoration strategies in recovering a disrupted network.

In next section, research questions and hypotheses, defined based on the performed gap analysis, are explained in detail.

1.5 RESEARCH QUESTIONS IN DESIGNING RESILIENT AND STRUCTURAL CONTROLLABLE MULTI-LEVEL INFRASTRUCTURE NETWORK

The main objective in this dissertation is the development of methods for the resilient and structurally controllable design of multi-level infrastructure networks with consideration of occurrence of disruptions. This research on resilient multi-level infrastructure networks is unique in two aspects: one is that the structural controllability is considered in order to determine the location and minimum number of driver nodes and their functions in recovering a disrupted network; and, the second one is considering operational and strategic decisions in node-level and network-level decisions in multi-level networks. Therefore, based on the derived research gaps (see Section 1.4) and requirements of the problem (see Section 1.2), the primary research question is defined as follows.

Primary Research Question: What methods are required for designing a resilient infrastructure network under disruptions through selecting appropriate restoration strategies in a manner of applying structural controllability?

In order to partition the primary research question into detailed research questions, secondary research questions are defined. The connectivity between the requirements, research questions and research hypotheses for each of the four aspects of the problem are addressed in Table 1-3.

As is shown in Table 1-3, the research questions and their associated hypotheses are defined based on requirements for each aspect of the problem. In order to make the connection between requirements and research questions clear, Table 1-3 is expanded for each aspect as follows.

Table 1-3 Mapping the four aspects of research, requirements, research questions and hypotheses

Aspects	Requirements	Research Questions	Research Hypotheses
Multi-level network design	Integrated formulation for designing a multi-level network considering operational (short term) and strategic (long term) decisions with conflicting goals.	RQ1: What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?	Implement an integrated simulation model (for operational decisions in the node-level) and mathematical model (using the compromise Decision Support Problem) to design a multi-level network with conflicting goals.
Restoration strategies	Selecting the appropriate pre-disruption and post-disruption restoration strategies for recovering a disrupted infrastructure network.	RQ2: What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?	Implement a method to select appropriate restoration strategies for possible occurrence of disruptions considering is dependent on anticipation, preparedness, adaptability, and recovery phases.
Resilience analysis	Quantitative measures which can represent the resilience of a recovered network after a disruptive event while considering the trade-off between redundancy and effectiveness.	RQ3: What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?	Implement a method that includes measures for analyzing resilience of disrupted networks while addressing redundancy and effectiveness.
Structural controllability	Determining the location and minimum number of driver nodes to make networks structurally controllable	RQ4: What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?	Implement a method occupied with maximum matching and minimum input theorem to find the minimum number of driver nodes to control a disrupted network in order to increase the resilience.

Multi-level network design: the simultaneous design of the node-level (focus on the operational/short-term decisions) and the network-level (focus on the strategic/long-term decisions) decisions that supports it will result in enhanced structural controllability and provide a more efficient design process for multi-level networks. Add to this the importance of modeling conflicting system goals, and the fact that behavior can be highly non-linear and it is easy to understand the limited study that design of multi-level networks have received.

Research Question 1: What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?

In order to decrease the computational complexity, an integrated method (i.e., instead of iterative methods) for all decisions levels in the hierarchy and for both operational and strategic decisions are considered. The Research Hypothesis 1 is defined as follows.

Research Hypothesis 1: Implement an integrated simulation model (for operational decisions in the node-level) and mathematical model (using the compromise Decision Support Problem) to design a multi-level network with conflicting goals.

Restoration strategies: As the recovery capacity increases within an infrastructure network, the network returns to the normal performance quicker and the disruption will likely be less severe. An unplanned event that disrupts an infrastructure network with the capability to respond quickly and effectively is less likely to be severe than the same infrastructure network disruption affecting a network with little or no capability to recover (Gong and co-authors, 2014). Therefore, a method is required to select the best set of pre-disruption and post-disruption recovery strategies among many strategies (e.g., back-up inventory, fortified facilities, product family and alternative BOM. etc.) in face of disruptions.

Research Question 2: What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?

Responding to this research question is possible through developing some possible restoration strategies and a mathematical model to design for resilient infrastructure networks. The hypothesis for answering to the Research Question 3 is addressed as follows.

Research Hypothesis 2: Implement a method to select appropriate restoration strategies for possible occurrence of disruptions considering is dependent on anticipation, preparedness, adaptability, and recovery phases.

Resilience analysis: Resilience is a property of a network that is capable of absorbing, adapting to or rapidly recovering from disruptions. In the resilience analysis it is emphasized that the network has the ability to (i) anticipate and absorb potential disruptions; (ii) develop adaptive means to accommodate changes within or around the system; and (iii) establish response behaviors aimed at either building the capacity to withstand the disruption or recover as quickly as possible after an impact (Francis and Bekera, 2014).

Measures for resilience analysis often do not include the time dimension. Since the concern is not just with disruptions, but also the network's resistance to and recovery from these events, the resilience analysis must explicitly incorporate time into the calculation. Considering the trade-off between redundancy and efficiency, and conflicts between measures is important in designing infrastructure networks under disruptions. In order to develop an appropriate method for this, quantitative measures should be defined to consider the trade-off. The second research question is addressed as follows.

Research Question 3: What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?

Resilience analysis is dependent on time, and the trade-off between redundancy and effectiveness can be considered by having conflicting objective functions. The research hypothesis is formulated as follows.

Research Hypothesis 3: Implement a method that includes measures for analyzing resilience of disrupted networks while addressing redundancy and effectiveness.

Structural controllability with driver nodes: It is accepted in the literature and practice that various sources of uncertainty should be considered during planning for the performance of infrastructure networks. At the same time, the performance of infrastructure networks will be achieved subject to real-time execution dynamics (Ivanov and Sokolov, 2012; Sarimveis and co-authors, 2008; Vahdani and co-authors, 2011). Decisions in infrastructure network planning and control are therefore interconnected.

A critical issue in applying control strategies to infrastructure network adaptation-based resilience analysis is the location, number and function of controllers (i.e., driver nodes in infrastructure networks). In technical systems, the controller is a device (e.g., a sensor) that adapts system behavior within milliseconds, based on error identification. A controller in an infrastructure network can be a fortified node(s) with accessibility to all other nodes. This property of driver nodes can help in managing disruptions and mitigating risk of disruptions. Identifying locations, numbers and functions of these controllers (i.e., driver nodes) is important; the research question in this regard is addressed as follows.

Research Question 4: What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?

In order to answer to this research question, the following research hypothesis is presented.

Research Hypothesis 4: Implement a method occupied with maximum matching and minimum input theorem to find the minimum number of driver nodes to control a disrupted network in order to increase the resilience.

In next section, the considered problem in this dissertation, the main contributions and the proposed methods are presented.

1.6 PROPOSED METHODS IN DESIGNING RESILIENT AND STRUCTURALLY CONTROLLABLE MULTI-LEVEL NETWORKS

In this dissertation, designing the resilient and structurally controllable multi-level infrastructure networks under disruptions is considered. The considered problem has four aspects which can be categorized in two parts: (1) multi-level infrastructure network design which refers to the multi-level network design aspect, and (2) disruption management which refers to restoration strategy, resilience analysis, and structural controllability aspects. In Figure 1-3, these two parts are shown. As is shown in the left side of Figure 1-3, all levels of decisions (i.e., Level 1... Level n), includes operational and strategic decisions, are considered in designing multi-level infrastructure networks. As is shown in the right side of Figure 1-3, restoration strategies, resilience analysis, and structural controllability are applied to manage and mitigate the risk of disruptions.

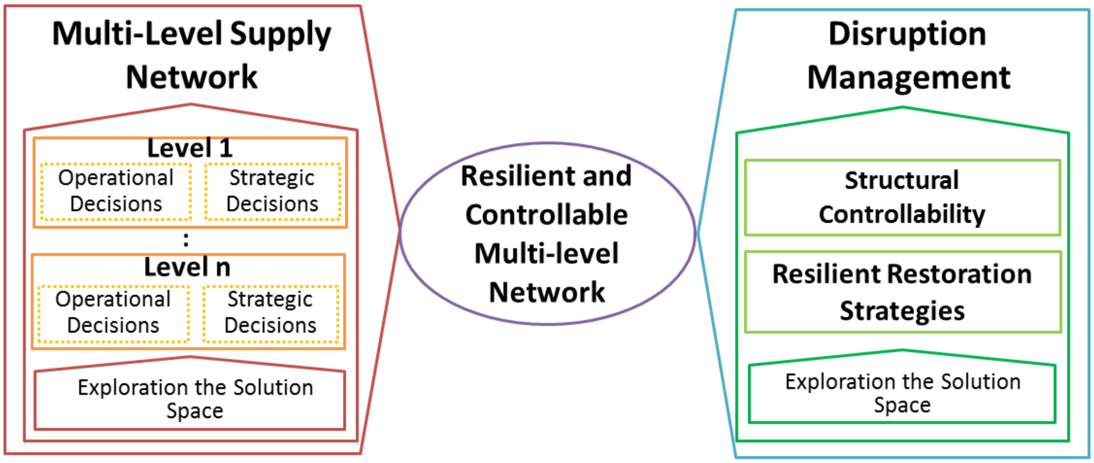


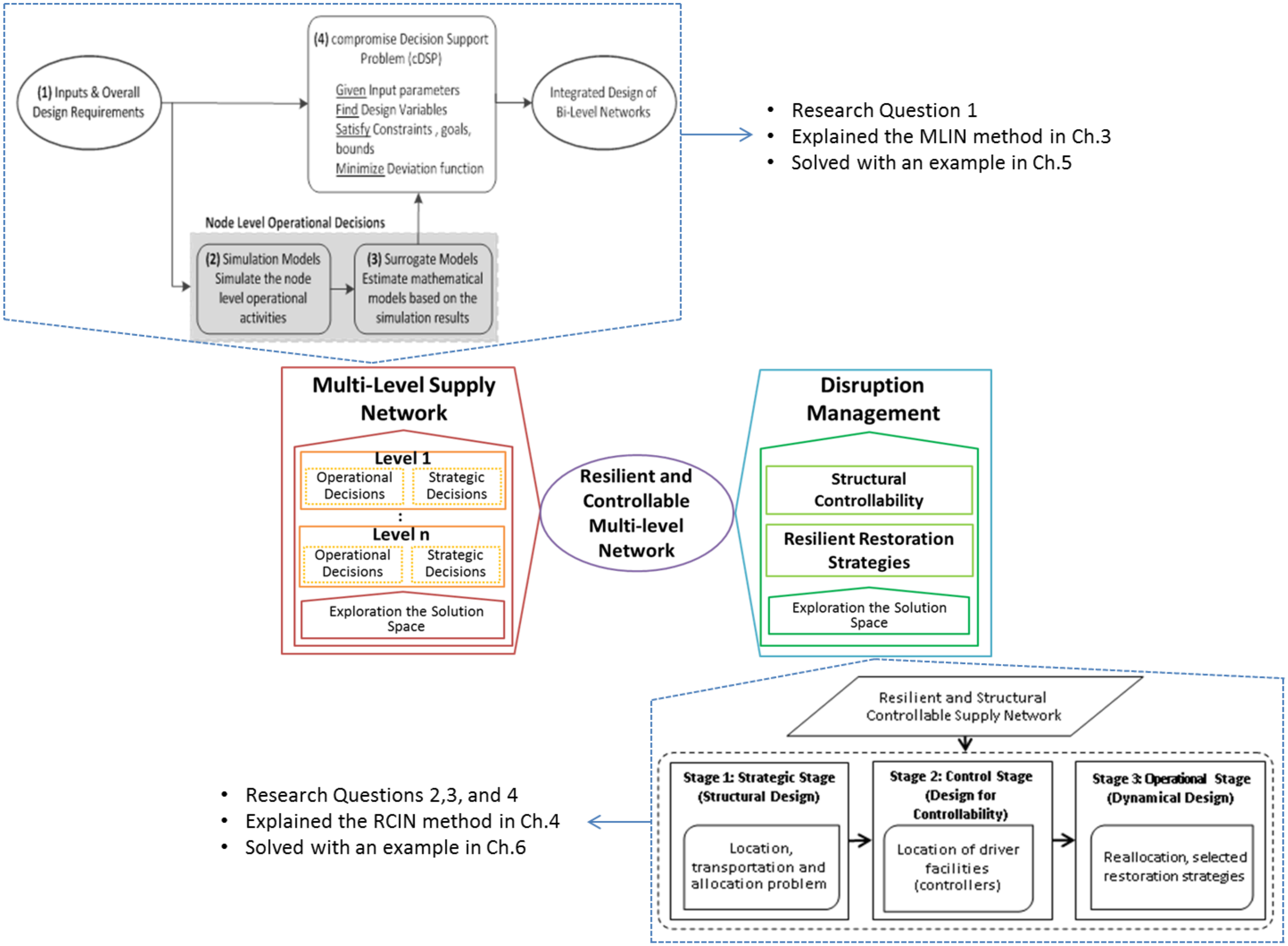
Figure 1-3 Resilient and structural controllability of a multi-level network

In order to achieve the resilient and controllable design of multi-level infrastructure networks (see Figure 1-3), two methods are developed, named the Multi-Level Infrastructure network (MLIN) method, and the Resilient and structurally controllable Infrastructure network (RCIN) method, as the contributions in this dissertation. As is shown in Figure 1-3, since methods for complex infrastructure networks are incomplete and inaccurate, especially when disruptions happen, exploration of the solution space is required.

The multi-level infrastructure network (MLIN) method: designing multi-level infrastructure networks while operational (short-term) and strategic (long-term) decisions are considered in the hierarchical structure are addressed in the MLIN method. The focus in the lower level of decisions (e.g., node-level decisions) is more on the operational decisions, and the focus in the higher level (e.g., network-level decisions) is more on the strategic decisions. The conflicts among the system goals are also considered in the MLIN method through applying the compromise Decision Support Problem (cDSP). Some of the operational decisions with a shorter time scale are simulated using a discrete-event simulation modeling, and both operational and strategic decisions are integrated using the cDSP. The proposed MLIN method is explained in detail in Chapter 3 and is solved for an example of the plug-in hybrid electric vehicle charging stations in Chapter 5 (see Figures 1-4 and 3-3).

The resilient and structurally controllable infrastructure network (RCIN) method: the main purpose in this method is to determine the location, number and function of driver nodes (i.e., controllers) in order to mitigate the risk of disruptions via having accessibility to all node (i.e., disrupted or safe nodes). The structural controllability is considered as the key technical and theoretical concept in the RCIN method. Back-up inventory and fortification are considered as pre-disruption restoration strategies, and reconfiguration, flexible inventory and production capacity are considered as post-disruption restoration strategies in the proposed RCIN method. The proposed RCIN method includes three stages and is explained in detail in Chapter 4 (see Figures 1-4 and 4-5).

In both Figure 1-4 and Table 1-4, the connection between different aspects of the problem, research questions, and structure of this dissertation is shown and explained. As is shown in Figure 1-4, the multi-level infrastructure network aspect (the left side of Figure 1-4) is related to Research Question 1. The multi-level infrastructure network (MLIN) method is proposed as the first contribution in this dissertation and in response to Research Question 1. The MLIN method is explained in Chapter 3, and it is validated using an example in Chapter 5. The disruption management (the right side of Figure 1-4) is related to Research Questions 2, 3, and 4. The resilient and structurally controllable infrastructure network (RCIN) method is proposed as the second contribution in this dissertation in response to Research Questions 2, 3, and 4. The RCIN method is explained in Chapter 4, and it is evaluated using an example in Chapter 6.



- Research Question 1
- Explained the MLIN method in Ch.3
- Solved with an example in Ch.5

- Research Questions 2,3, and 4
- Explained the RCIN method in Ch.4
- Solved with an example in Ch.6

Figure 1-4 Connectivity between methods and research questions

Table 1-4 Mapping between aspects, research questions, contributions, and proposed methods

Aspect	Research Question	Research Hypothesis	Contribution	Detail of Contribution	Chapter
Multi-level network design	RQ1: What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?	Implement an integrated simulation model (for operational decisions in the node-level) and mathematical model (using the compromise Decision Support Problem) to design a multi-level network with conflicting goals.	Multi-level infrastructure network (MLIN) method	Integrated node-level and network-level decisions considering both operational and strategic decisions with conflicting design goals	Explained the MLIN method in Chapter 3, evaluated it in Chapter 5
Restoration strategies	RQ2: What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?	Implement a method to select appropriate restoration strategies for possible occurrence of disruptions considering is dependent on anticipation, preparedness, adaptability, and recovery phases.	Resilient and structural controllability infrastructure network (RCIN) method	Selection of appropriate pre-disruption and post-disruption restoration strategies of a disrupted infrastructure network considering redundancy and effectiveness	Explained the RCIN method in Chapter 4, evaluated it in Chapter 6
Resilience analysis	RQ3: What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?	Implement a method that includes measures for analyzing resilience of disrupted networks while addressing redundancy and effectiveness.	Resilient and structural controllability infrastructure network (RCIN) method	Resilience analysis using time-based measures such as service level, recovery time and control cost considering redundancy and effectiveness	Explained the RCIN method in Chapter 4, evaluated it in Chapter 6
Structural controllability	RQ4: What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?	Implement a method occupied with maximum matching and minimum input theorem to find the minimum number of driver nodes to control a disrupted network in order to increase the resilience.	Resilient and structural controllability infrastructure network (RCIN) method	Location and minimum number of driver nodes in a disrupted network in order to restore the network by applying restoration strategies	Explained the RCIN method in Chapter 4, evaluated it in Chapter 6

In next section, the validation strategy based on the validation square, an overview of the dissertation, and connection between chapters, are presented.

1.7 OVERVIEW AND VALIDATION STRATEGY OF THE PROPOSED METHODS

Engineering design is primarily concerned with open problems that involve objective and subjective elements and no single right answer. As Seepersad and co-authors (2006) indicate that there is no single right answer in designing complex systems they propose a method called ‘Validation Square’ with which a researcher can build confidence in the utility of methods and examples with respect to a purpose. Their method is associated with whether a method provides design solutions correctly (structural validity) and whether it provides correct design solutions (performance validity). This process of validation is represented in the Validation Square as is shown in Figure 1-5.

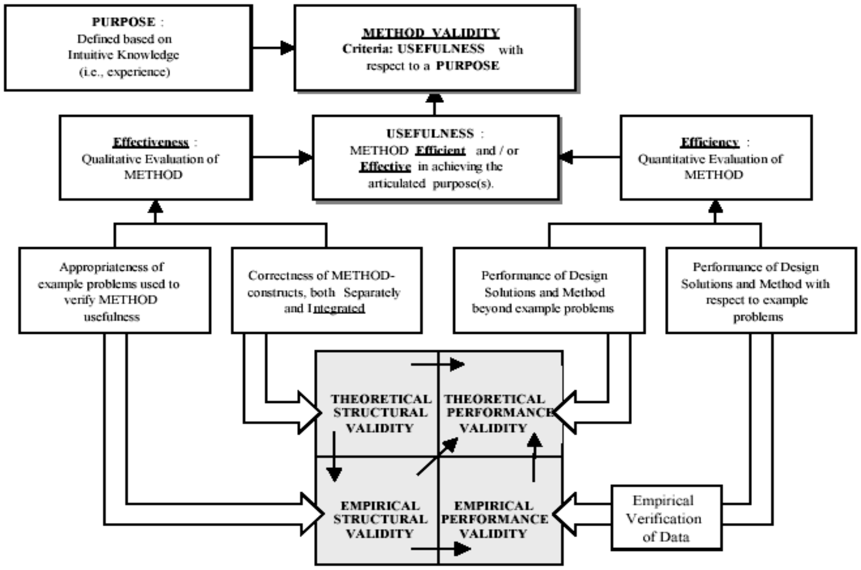


Figure 1-5 Validation square (Seepersad and co-authors, 2006)

Accepting theoretical structural validation means accepting the individual structural/ logical validity as well as accepting overall consistency of the assembly of constructs. Empirical structural validation includes building confidence in the soundness of the example problems to illustrate and verify a suggested design method. Empirical performance validation is used to build confidence in the utility of a method for the example problems and case studies. Theoretical performance validation includes building confidence in the generality of the method and accepting that the method can be useful for others beyond the example problems. In this dissertation, the validation square is adopted as a guideline for validating the methods for designing a resilient and controllable multi-level infrastructure network, MLIN and RCIN methods. The following tasks are planned for the validation and summarized in Figure 1-6.

Theoretical Structural Validation

- Critical evaluation of the relevant literature and identification of the research gap (Section 1.4 and Chapter 2)
- Justify that the four hypotheses are logically formulated to appropriately cover the research questions (Section 1.5 and Chapters 2)
- Discuss the development of the multi-level infrastructure network design (MLIN) method (Chapter 3), and the resilient and structurally controllable infrastructure network design (RCIN) method (Chapters 4)
- Identify merits, limitations, requirements, and application domains for the proposed methods (Section 3.11 for the MLIN method and Section 4.7 for the RCIN method)

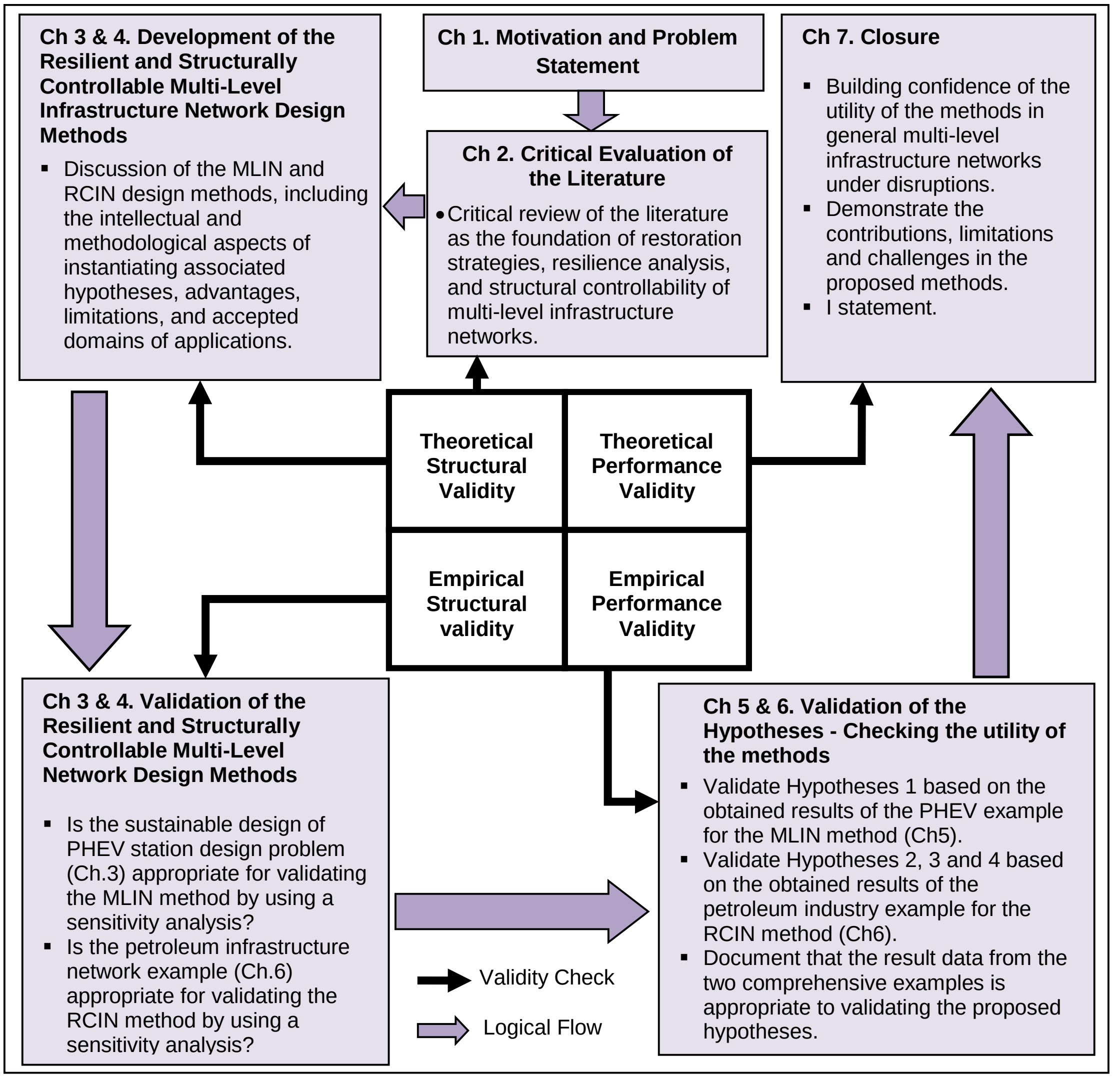


Figure 1-6 Validation strategy in this dissertation

Empirical Structural Validation

- Discuss the challenging aspects and evaluate the elements of the multi-level infrastructure network (MLIN) method with considering the example of designing a network of electric charging stations for plug-in hybrid electric vehicles, and finally argue that the example is appropriate to test Hypothesis 1 (Chapter 3)

- Discuss the challenging aspects and evaluate the elements of the resilient and structurally controllable infrastructure network (RCIN) method with considering the example of the petroleum industry under disruptions, and finally argue that the example is appropriate to validate Hypotheses 2, 3, and 4 (Chapter 4)

Empirical Performances Validation

- Test the MLIN method and validate Hypothesis 1 based on the comprehensive example of the network of electric charging stations for plug-in hybrid electric vehicles (PHEVs) (Chapter 5)
- Test the RCIN method and validate Hypotheses 2, 3 and 4 based on the comprehensive example of the petroleum industry (Chapter 6)

Theoretical Performances Validation

- Discuss that the hypotheses in this dissertation are also valid for general resilient and structurally controllable multi-level infrastructure networks under disruptions (Chapter 7)
- Argue that the comprehensive examples represent the challenges of the general resilient and structurally controllable multi-level infrastructure networks under disruptions (Chapter 7)

The structure of the dissertation is shown in Figure 1-7.

In Chapter 1, motivations, problem statement, characteristics of the problem, challenges and requirements are discussed for (a) the multi-level networks with operational and strategic decisions, (b) the resilient and structurally controllable networks under disruptions. The research questions, corresponding hypotheses, and contributions (proposed MLIN and RCIN methods) are addressed, and the validation strategy is established for the dissertation.

In Chapter 2, the theoretical foundations for designing resilient and structurally controllable multi-level networks under disruptions are introduced and discussed. Foundations include facility location problems, resilience in disrupted networks and structural controllability of networks. For theoretical structural validation, relevant literature in each of these research areas is referenced, discussed, and critically evaluated. The purpose is to discuss the availability, strengths, and limitations of methods that are foundational for the resilient and structurally controllable multi-level network design methods and to identify research gaps addressed in this dissertation.

In Chapter 3, the multi-level infrastructure network (MLIN) method is explained considering both conflicting system goals, and operational and strategic decision levels. The method is clearly defined based on the problem statement and its requirement list, and the problem scope that the multi-level network design method can cover is also defined. The approach of considering conflicting system goals, which is based on the compromise Decision Support Problem (cDSP), is discussed. Each step of the MLIN method is discussed in detail. The Theoretical Structural Validation of the MLIN method is checked providing advantages, limitations, and applications of the method based on Hypothesis 1 proposed in Chapter 1. The Empirical Structural Validation of the MLIN method is checked using a sensitivity analysis of the cDSP of the PHEV example.

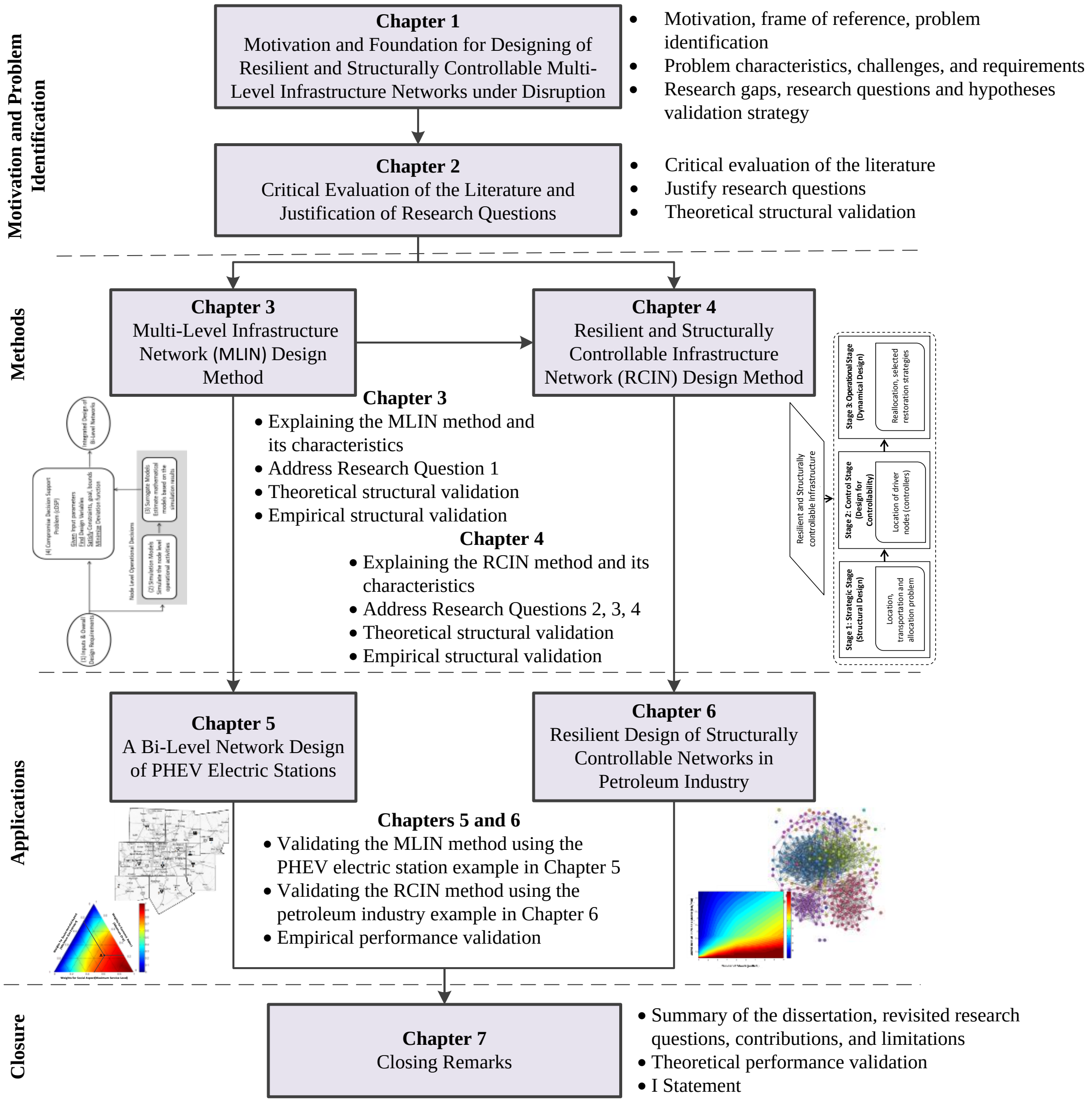


Figure 1-7 Dissertation structure

In Chapter 4, the resilient and structurally controllable infrastructure network (RCIN) method is explained. Similar to the structure of Chapter 3, the RCIN method is clearly defined based on the problem statement and its requirement list, and the problem scope that the method can cover is also defined. Each step of the RCIN method is discussed in detail. The Theoretical Structural Validation of the method is checked providing advantages, limitations, and applications of the method based on Hypotheses 2, 3 and 4 proposed in Chapter 1. The Empirical Structural Validation of the RCIN method is checked using a sensitivity analysis of the cDSP of the petroleum example.

In Chapter 5, designing a network of plug-in hybrid electric vehicle charging stations is presented as an example for demonstrating the effectiveness of the multi-level infrastructure network (MLIN) method. Each step of the method is followed in solving the example. The input data for the example is discussed. The simulation model is performed and results are discussed. The surrogate modeling approach (MARS) is employed to construct a mathematical model based on the results of the simulation model. The compromise Decision Support Problem (cDSP) is formulated to find the best solution considering the bi-level network structure of the example. Hypothesis 1 is validated based on the results of this design problem for the Empirical Performance Validation.

In Chapter 6, designing a petroleum industry infrastructure network under disruptions is considered as an example to demonstrate the effectiveness of the resilient and structurally controllable infrastructure networks (RCIN) method under disruptions. Each step of the method is followed in solving the example. Hypotheses 2, 3, and 4 are validated based on the results of this design problem for the Empirical Performance Validation.

In Chapter 7, the research questions proposed in this dissertation are answered by summarizing the validation results of the hypotheses. The contributions (i.e., new knowledge) and achievements out of the dissertation are discussed. The critical evaluation of the dissertation research and necessary future work are provided. A leap of faith is taken in the accomplishments, arguing the generalizable applications for the proposed MLIN and RCIN methods for the Theoretical Performance Validity. In addition, the *I Statement* is presented in this chapter in which several future directions of the work is presented, and one of the directions is expanded with more detail.

1.8 CHAPTER SYNOPSIS

In Chapter 1, the motivation and introduction regarding the multi-level infrastructure networks, and the resilient and structural controllability of infrastructure networks are addressed. The considered problem in this dissertation is presented as follows.

The problem that is considered in this dissertation is on applying structural controllability in designing a resilient multi-level infrastructure network in the face of disruptions. In addition, selection of appropriate post-disruption and pre-disruption restoration strategies is part of the problem while considering the trade-off between effectiveness and redundancy in resilience analysis of disrupted infrastructure networks.

The addressed problem has four aspects such as multi-level networks, resilience analysis, restoration strategies, and structural controllability. The characteristics of the problem are addressed, and then followed by challenges associated with it. After a critical evaluation of the literature, four research questions are defined. Two methods, named RCIN and MLIN methods, are presented as the main contributions in this dissertation to answer to the research questions. As it is shown and explained in Figure 1-4 and Table 1-4, research question 1 is addressed using the MLIN method in Chapter

3, and Research Questions 2, 3, and 4 are addressed using the RCIN method in Chapter 4. In addition, the validation square, discussed in Section 1.7, is used as a guideline for validating the methods in this dissertation.

In the next chapter, in order to validate the contributions of the proposed methods, the existing literature related to the four research questions identified in this chapter is critically evaluated.

CHAPTER 2 CRITICAL EVALUATION OF THE LITERATURE AND JUSTIFICATION OF RESEARCH QUESTIONS

In this chapter, a critical evaluation of the literature, and expansion of the research gap, presented in Section 1.4, is presented. This chapter is organized based on the four aspects of the considered problem (see Section 1.2): *i*) the literature related to the first aspect of the problem, the multi-level infrastructure network, is presented in Section 2.1, *ii*) the literature related to the second and third aspects of the problem, restoration strategies and resilience analysis, is addressed in Section 2.2, and *iii*) in Section 2.3, the literature of the fourth aspect of the problem, structural controllability, is presented.

In each section (Sections 2.1, 2.2, and 2.3), first, the fundamental concept and definitions related to each aspect is presented, then it is followed by the critical evaluation of the literature, and finally the related research question is presented. In Section 2.4, the Validation Square is revisited, and the Theoretical Structural Validation in this dissertation is explained.

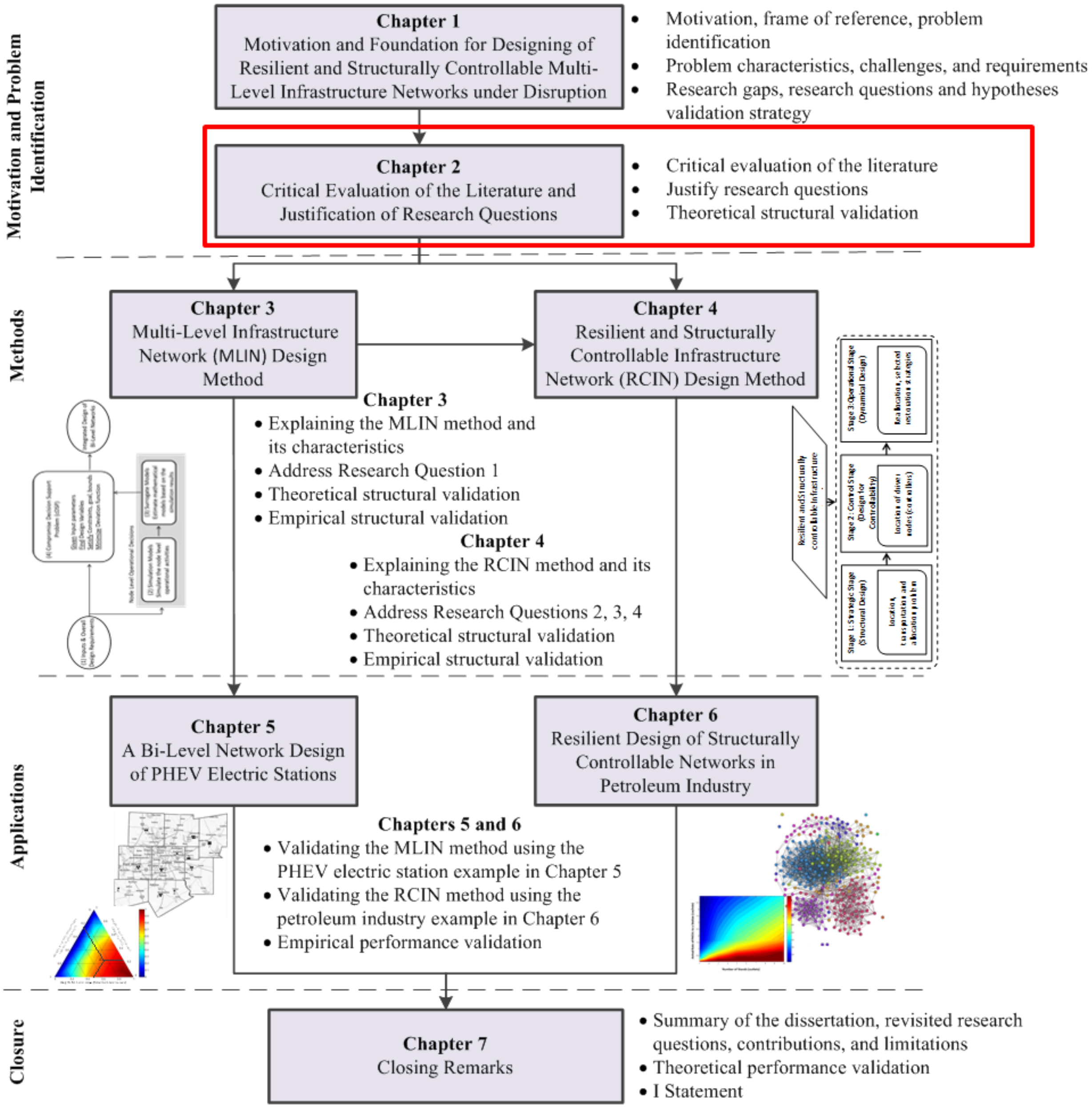


Figure 2-1 Dissertation structure

2.1 DYNAMIC FACILITY LOCATION PROBLEMS FOR MULTI-LEVEL NETWORKS

The simultaneous design of the control systems (operational/short term decisions) and the infrastructure (strategic/long term decisions) that supports it will result in both enhanced controllability and provide a more efficient design process. **Although the potential economic benefits of design for controllability of multi-level complex, large scale systems can be substantial, relatively little has been done in this field. The barriers are both the computational and mathematical complexity of the problem**. Mainly most approaches in this area are built upon the facility location problem approach.

The simultaneous consideration of both the strategic and operational decisions is the goal in designing multi-level infrastructure networks with hierarchical structure. There are various multi-level decisions related to the network structure; for example, in a bi-level structure there are node-level decisions and network-level decisions. Operational decisions are mainly related to the node-level decisions and strategic decisions are mainly related to the network-level decisions. Decisions regarding the location and capacity of manufacturing facilities, warehouses, and supply sources are categorized as the network-level design or strategic decisions. The structure of an infrastructure network for its next several years is determined in the network-level decisions. Decisions regarding the individual customer orders are categorized as the node-level design or operational decisions. At the operational level, while the network configuration and planning policies are considered fixed (i.e., given from the strategic level or network-level decisions), handling the incoming customers' orders in the best possible manner, reducing uncertainty, and maximizing performance are considered.

Facility location problems have proven to be a fertile ground for operations researchers interested in modeling, algorithm development, and complexity theory. There are numerous ways of subdividing the broad spectrum of location models (Daskin, 2008). Daskin (2008) divides the facility location problems into four categories: analytical location models, continuous location models, network location models and discrete location models. An illustration of different discrete location models is presented in Figure 2-2.

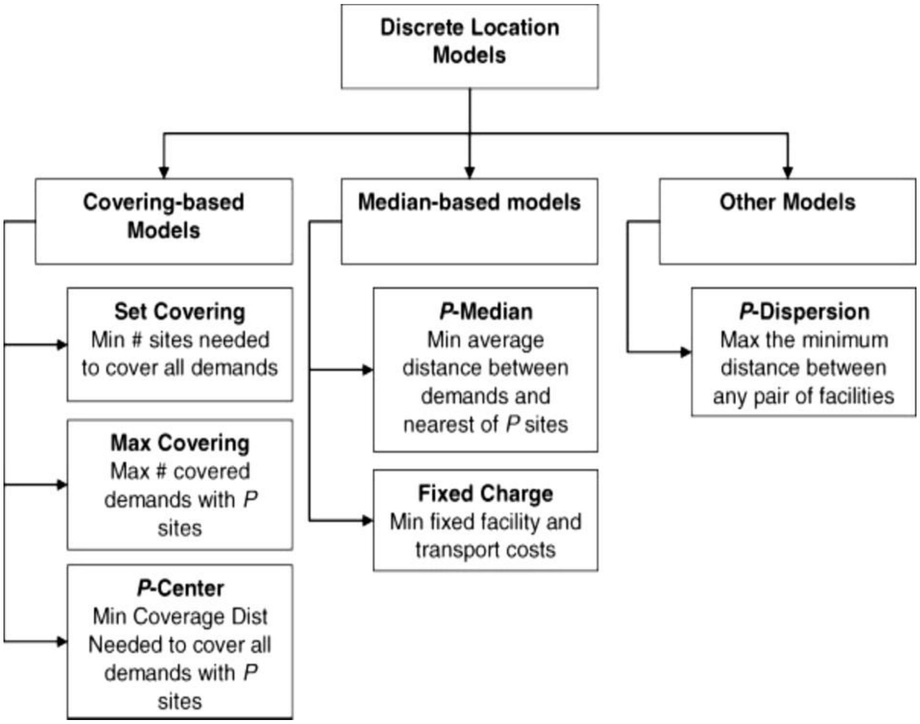


Figure 2-2 Classification for the discrete location models (Daskin, 2008)

Analytic models are the simplest of location models. In such models typically it is assumed that demand is distributed in some way (e.g., uniformly) over a service area and that facilities can be located anywhere within the area. Analytic models are typically solved using algebra, calculus or other simple techniques. While analytical models assume that demands are distributed continuously across a service region and that facilities can be located anywhere within the region, continuous models typically assume that demands arise only at discrete points (Daskin, 2008).

In network models, it is assumed that demands arise, and facilities can be located, only on a network composed of nodes and links. Often demands occur only on the nodes, while facilities can be located anywhere on the network. The focus of much of the network location literature is on finding polynomial time algorithms, often for problems on specially structured networks such as trees (Daskin, 2008).

In discrete location models, there may or may not be an underlying distance metric. Distances or costs between any pair of nodes may be arbitrary, although they generally follow some rule (e.g., Euclidean, Manhattan, network, or great circle distances). Demands generally arise on the nodes and the facilities are restricted to a finite set of candidate locations.

Within this structure (i.e., facility location problem), some other approaches may be applied to consider both different time scales for strategic and operational decisions in a hierarchical structure such as adaptive dynamic programming, design and analysis of computer experiments perspective (DACE), Bender's decomposition and the inductive design exploration method (IDEM).

Considering conflicts among system goals is essential. In designing multi-level infrastructure networks, the focus of some system goals are more on the node-level or short-term decisions, and the focus of some other system goals are more on the network-level or long-term decisions. One important example in this area is considering the conflicts among sustainability drivers (i.e., economic, social and environment drivers) in designing the multi-level network of electric charging stations. In this example, the charging pattern of electric cars is considered in the node-level, and the location of charging stations is considered in the network-level. In the same manner, the social driver of sustainability is related to the node-level decisions, and the economic driver of sustainability (e.g., the cost of locating electric charging stations) is related to the network-level. Because of the importance of the sustainability issues, the future of the green energy and electric vehicles, and similarities between this example and the proposed MLIN method (e.g., both node-level and network-level decisions and conflicting goals), the area of sustainability and electric charging stations as the main part of the literature for performing the gap analysis are considered. Therefore, in Sections 2.1.1 and 2.1.2, two areas of the related literature are critically reviewed.

2.1.1 Facility Location Problems in Designing Electric Charging Stations

Alternative energy sources are critically important for curbing greenhouse gas emissions and creating a more independent energy economy. The U.S. government has pledged to reduce greenhouse gas emissions by approximately 17% of 2005 levels by 2020. With the existing technologies, plug-in hybrid electric vehicles (PHEVs) are the most feasible approach to significantly lower the consumption of oil and improve fuel economy and are critically important for a fundamental transformation to shift the transportation sector from traditional oil based fleets to electrical power vehicles (MirHassani and Ebrazi, 2013).

Plug-in hybrid electric vehicles (PHEVs) face a chicken-and-egg infrastructure dilemma. PHEV manufacturing companies will not produce vehicles that citizens will not buy, while citizens are reluctant to buy PHEVs until a sufficient number of electric charging stations have been installed (Kuby and Lim, 2005; Melaina, 2003, 2007). Therefore, the need for designing a system of electric charging stations by considering location, allocation and capacity decision problems can be demonstrated. Different approaches to modeling systems of electric vehicle charging stations have been taken in the literature (see Table 2-1).

As it is shown in Table 2-1, in the literature of electric vehicles, the stochastic behavior of parameters is not considered and models are mainly deterministic models. In addition, the focus is mainly on deterministic models, and the literature of models with multiple-periods is very sparse. There are few papers in the literature that consider both the node-level and network-level decisions. It demonstrates the gap in the literature, and it shows how the MLIN method with considering the multiple-period assumption with node-level and network-level decisions can fill the research gap.

Table 2-1 Literature and the stochastic behavior of PHEV drivers

Author	**Parameters**		**System goals**		**Time horizon decisions**			**Level of decision**		**Charging station and vehicle technology**		
	Stochastic	**Deterministic**	**Single-goal**	**Multi-goal**	**Static (single-period)**	**Dynamic (multi-period)**	**Adaptive (incremental design)**	**Node level**	**Network level**	**Level I and II**	**DC fast charging (Level III)**	**Battery Swap**
(Bapna and co-authors, 2002)		✓		✓	✓				✓	✓	✓	
(Lim and Kuby, 2010)		✓	✓		✓				✓	✓	✓	
(Wang and Wang, 2010)		✓	✓		✓				✓	✓	✓	
(Frade and co-authors, 2011)		✓	✓		✓			✓	✓	✓		
(He and co-authors, 2013)		✓		✓	✓				✓	✓	✓	
(Xi and co-authors, 2013)		✓	✓		✓			✓	✓	✓		
(Nurre and co-authors, 2014)		✓	✓			✓			✓	✓	✓	✓
MLIN model	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	

Some studies are based on the location-routing and vehicle-routing models. Worley and co-authors (2012) develop a discrete integer-programming model to locate charging stations and to find electric vehicle routings based on the vehicle routing problem. Li and co-authors (2011) propose a model to locate charging stations based on regional traffic flow of electric vehicles, while minimizing the cost. Kameda and Mukai (2011) develop a location-routing model for electric charging stations based on taxi data for Japan. Ge and co-authors (2011) develop a grid partition method to choose locations of charging stations within each partition. In this method, the traffic density in each partition is taken into account, while cost of accessing charging stations is minimized.

Set covering (minimize the number of located facilities), maximum covering (maximize the covered demand for a maximum of *k* facilities), and *p*-median (minimize cost for locating exactly *p* facilities) models are three major proposed categories of ways of selecting charging station locations. Wang and Lin (2009) recommend a refueling-station-location model based on set covering. They demonstrate the applicability of their mixed-integer mathematical model by achieving multiple origin-destination intercity travel via electric vehicles on Taiwan. Wang and Lin (2009) show that greater vehicle ranges will require fewer refueling stations based on sensitivity analysis. As is shown in Table 2-1, Frade and co-authors (2011) present a model on the location of electric vehicle charging stations for an area in Lisbon. The model is a maximum covering model to determine the number and capacity of charging stations, while maximizing the met demand within an acceptable distance of the stations. Lin and co-authors (2008) develop a *p*-median based model in which nodes are weighted by the travel time between charging station candidates and demand nodes. In this model, vehicle-mile traveled data is used to minimize the total travel time from demand nodes to the charging stations.

In some studies, a hybrid modeling approach for locating charging stations is presented. As is Shown in Table 2-1, Wang and Wang (2010) formulate a mixed-integer mathematical model to locate charging stations to serve both inter-city and intra-city travel. Their proposed model is a hybrid *p*-median and maximum covering model to minimize the cost of locating stations and maximize population coverage. The applicability of this model is analyzed with an example from an island in Taiwan and He and co-authors (2013) develop a hierarchical modeling structure for the interplay between transportation and power systems. They propose an equilibrium-modeling framework to optimize the locations and capacities of charging stations in a metropolitan area.

Kuby and co-authors (2009) develop a model for locating refueling stations to maximize the volume of the vehicle flow that passes fueling stations. These flows are measured either by the number of vehicle-trips or vehicle-miles traveled. They use this model to investigate strategies for rolling out an initial refueling infrastructure in Florida at two different scales of analysis: metropolitan Orlando and statewide. The output of this analysis is to identify a set of stations that perform well under a variety of assumptions and therefore they assume that the solution is robust. Nicholas and co-authors (2004) apply the geographic information system (GIS) as a tool for evaluating station siting decisions as part of a greater refueling network. A GIS model is developed for locating hydrogen stations in Sacramento County, California. Average one-way driving time from home or work to a station is used as a metric to evaluate scenarios. Dias and co-authors (2007) propose a dynamic location problem to reduce the available capacity at facility locations over the planning horizon. Opening and closing assumption of facilities and different discrete capacities for facilities are considered in their proposed model.

In this section, the focus is on the importance of the node-level and network-level decisions in multi-level infrastructure networks. As discussed in this section and in Section 1.4, the interactions among the node-level and network-level decisions are not well considered. In the reviewed papers, the focus is mainly on the network-level decisions. Little attention has been paid to integration of the network-level and node-level problems. Also, as is shown in Table 2-1, considering the stochastic behavior of PHEV drivers (stochastic behaviors in the node-level) and their uncertain demands in the literature is sparse. In next section, the focus is on the design of multi-level networks with conflicting system goals.

2.1.2 Facility Location Problems from Sustainability and Renewable Energy for Electric Charging Stations Perspective

Plug-in hybrid electric vehicles (PHEVs) is an approach to significantly lowering the consumption of oil and improving fuel economy and are critically important for a fundamental transformation that shifts the transportation sector from traditional oil based fleets to electrical power vehicular technologies. The federal government is encouraging purchases of PHEVs through the Energy Independence and Security Act (EISA), the American Reinvestment and Recovery Act (ARRA), and other bills aimed at stimulating the U.S. economy. Congress has approved tax credits amounting to $758 million to subsidize the purchase of up to 250,000 PHEVs to 2020. This amounts to about $3,000 per vehicle, although the precise amount may range from $2,500 to $7,500 depending on vehicle attributes (Skerlos and Winebrake, 2010).

The EV Everywhere Grand Challenge, announced by President Obama in March 2012, targets using PHEVs to be as affordable and convenient for American families as gasoline-powered vehicles by 2022 (US DOE, 2014). However, the environmental benefits of PHEVs depend on the availability of fuel for electricity generation and the emissions by its supporting infrastructure. With electricity generation principally based on coal, PHEVs may lead to even higher emissions (the environmental driver). In addition, PHEVs face a chicken-egg infrastructure dilemma. PHEV charging station investors will not develop new charging infrastructure that citizens will not use (the economic driver), at the same time, citizens will be reluctant to buy PHEVs until a sufficient number of electric charging stations with high levels of service have been installed (the social driver). This highlights the need for an appropriate sustainable design (the integrated environmental, economic and social driver) for electric charging stations to reach the maximum climate benefits, economic profits, and social welfare from PHEVs. Several papers are reviewed based on these aforementioned characteristics in Table 2-2.

Egbue and Long (2012) determine the influences of sustainability issues on consumer decisions to purchase an electric vehicle. The results of their internet-based survey show that eighty-three percent of respondents indicated some familiarity with the concept of sustainability. In addition, seventy-nine percent of the sample indicated that sustainability influenced their decision when purchasing a vehicle.

The economic goal of sustainability is usually addressed as minimizing cost or maximizing profits (Khosrojerdi and co-authors, 2013; Khosrojerdi and co-authors, 2012). Wang and Lin (2009) use a set-covering model to minimize cost of locating fast refueling stations for alternative fuel vehicles (AFVs) along major arterial roads in Taiwan. Mak and co-authors (2012) address the economic driver of sustainability by minimizing the cost of battery swapping stations and maximizing return-on-investment. However, these economic models are apart from other driver of sustainability and mostly focus on facility location decisions and number of charging spots per location.

The environmental driver of sustainability is usually addressed with lowering gas emissions and carbon footprint by considering the life cycle analysis (LCA) of sources of electricity or charging infrastructure used to charge the vehicle. According to the life cycle assessment studies electric vehicles have the potential to reduce gas emission.

However, potential benefits depend on the source of electricity used to charge the vehicle. In 2009, the U.S. grid mix consisted of 45% coal, 23% natural gas, 20% nuclear, 7% hydroelectric, 4% other renewable, 1% petroleum, and 0.6% other (EIA, 2009).

Table 2-2 Literature and life cycle analysis of energy sources and the integration of renewable sources of energy into charging PHEVs

Reference	**Sustainability**			**Source of Energy**		**Emission (Life Cycle Analysis)**			**Energy Interactions***			**Approach/ Method**
	Economic	**Environ mental**	**Social**	**Renewable Energy**	**Power Grid**	**Electric Vehicle**	**Charging Infrastructures**	**Energy Sources**	**V2 G**	**B2 G**	**G2V or G2B**	
Weiss and co-authors (2009)		✓				✓		✓	✓			Life cycle analysis
Nansai and co-authors (2001)		✓			✓	✓	✓					Life cycle analysis
Wang and Wang (2010)	✓		✓		✓				✓			Multi-objective mixed-integer programming
Frade and co-authors (2011)	✓		✓		✓							Multi-objective maximum covering model
Wang and co-authors (2011)	✓			✓	✓						✓	Unit commitment model
Liu (2012)			✓		✓						✓	Facility location assignment model
Lucas and co-authors (2012)		✓			✓	✓	✓				✓	Life cycle analysis, Global Warming Potential for 100 years (GWP$_{100}$) and Cumulative Energy Demand (CED)
Karabasoglu and Michalek (2013)	✓	✓			✓	✓					✓	Powertrain Systems Analysis Toolkit (PSAT)
Marshall and co-authors (2013)		✓			✓	✓					✓	Naturalistic drive cycle and vehicle travel patterns
He and co-authors (2013)	✓		✓		✓						✓	Equilibrium modeling framework
Nurre and co-authors (2014)	✓				✓				✓		✓	Deterministic optimization model
MLIN model	✓	✓	✓	✓	✓		✓	✓		✓	✓	

Lipman and Delucchi (2010) provide a comprehensive review of studies in this area. Elgowainy and co-authors (2009) express that PHEVs charging from the US grid-mix generate 20% to 25% lower gas emission than conventional cars. As is shown in Table 2-2, They suggest that to receive significant reduction in emissions, PHEVs must recharge from a grid-mix which consists of largely non-fossil sources (Karabasoglu and Michalek, 2013).

Hadley and Tsvetkova (2008) analyze the potential impacts of PHEVs on regional power generation, concluding that the introduction of PHEVs will result in an increase in demand, generation, electricity prices, and gas emissions. Elgowainy and co-authors (2010) conduct a well-to-wheels analysis of energy use and greenhouse gas emissions of PHEVs for several US regions.

Wang and co-authors (2011) develop a new unit commitment model which can simulate the interactions among PHEVS, wind power and demand response. As it is shown in Table 2-2, it appears that considering the focus on the integration of renewable sources of energy (wind, solar, etc.) in generating electricity at charging stations and their impact on gas emissions and carbon footprint is very sparse in the literature.

Several studies use the life cycle analysis to assess energy use and CO_2 emissions by charging infrastructures, addressing fuels well-to-wheel life cycle (Baptista and co-authors 2010; Lucas and co-authors 2012; Thomas, 2009). Nansai and co-authors (2001) perform LCA of charging stations for electric vehicles (EVs) categorizing the life cycle in three stages, production, transportation and installation of the charging equipment, which consists of charger, battery and stand. Edwards and co-authors (2007) concentrate on fuel production and vehicle use, which are the major contributions to the lifetime energy use and gas emission, in the Concawe study. However, it does not consider the energy or the emissions of the charging infrastructure. Lucas and co-authors (2012) present a methodology to evaluate energy use and gas emission from construction, maintenance and decommissioning of electric charging infrastructure applied in a study in Portugal.

The social benefits of PHEVs and other modes of electric transportation are significant (Khosrojerdi and co-authors, 2013; Bradley and Frank, 2009; Granovskii and co-authors, 2006; Romm, 2006; Silva and co-authors, 2009; Skerlos and Winebrake, 2010).

Bapna and co-authors (2002) address the social driver of sustainability by using a maximum covering/shortest path problem to cover the maximum demand while minimizing travel costs for the population when locating stations in India.

Frade and co-authors (2011) also address the social driver of sustainability by maximizing demand covered in Lisbon, Portugal using a maximum coverage model. They consider both daytime and nighttime demand in locating charging stations and determine number of supply points at each station.

Xu and co-authors (2013) develop a facility location model for locating charging stations in Summit County, Ohio in order to maximize the covered demand. They consider a utility function for located charging stations based on the accessibility to and availability of charging stations, the power grid capability and neighborhood safety. However, in these papers the impact of various charging behaviors of PHEV drivers and different design alternatives for charging stations (e.g., number of available charging spots per station, location of stations, etc.) on the level of service are not considered.

In this section, the focus is on evaluating the literature in considering the conflicting system goals in designing multi-level infrastructure networks. In order to critically review the literature, the context of sustainability and its three conflicting drivers (i.e., economic, social and environment drivers) are considered. In the reviewed literature, considering the conflicts among system goals and their connections to the node-level and network-level decisions are neglected.

As is shown in Table 2-2, in the current literature, a life cycle analysis of energy sources (i.e., the node-level decision) and the integration of renewable sources of energy into charging PHEVs (i.e., the network-level decision) is not considered.

2.1.3 Other Models in Designing Integrated Operational and Strategic Decisions

Different methods are considered and reviewed in this section. The simultaneous design of dynamics of the system (short term/ operational decisions – mainly related to the node-level decision) and the infrastructure (long term/ strategic decisions – mainly related to the network-level decision) that supports it will result in a more efficient design for multi-level infrastructure networks. There is an extensive literature on Design for X where a variety of X's have been proposed, e.g., manufacturability, reliability, maintainability, cost (sometimes called value engineering), assembly, logistics, usability, ergonomics, safety, serviceability, environment, recycling, etc. These methods have proven effective in both reducing design time and producing improved designs.

Although the potential economic benefits of design for controllability of complex, large-scale systems can be substantial, relatively little has been done in this field. The barriers are both the computational and mathematical complexity of the problem. System controllability is often studied with dynamic programming, which is known to be sensitive to the "curse of dimensionality". Add to this the importance of modeling uncertainty, and the fact that behavior can be highly non-linear and it is easy to understand the limited study that design for control of large scale systems has received. Several relatively small problems have been considered, for example:

- Mhaisalkar and co-authors (2003) study the design and optimization of a waste water-treatment plant however they are able to formulate the problem so only a single variable enters the dynamic program.

- Chen and co-authors (2006) describe a procedure for designing an ice storage system with the limited objective of matching chiller performance and tank size using a backward dynamic programming method.

Some work has also been done on the design for controllability of small energy systems:

- Díaz-Dorado and Pidre (2006) provide a method for the design of an unbalanced low-voltage distribution network for a small community – they focus primarily on design issues, merely insuring that proposed configurations can provide adequate service.
- Ipsakis and co-authors (2005) approach the problem of design of a stand-alone power system based on renewable energy using simulated annealing. Giannakoudis and co-authors (2004) extend this approach and deal with uncertainty in the design of power generation systems using renewable energy. They recommend stochastic annealing, a computationally intensive approach. To alleviate this problem, they propose using parallel computing for future problems. They do not include variable demand.
- Grehant and co-authors (2011) study a photovoltaic system coupled with hydrogen/oxygen storage but restrict their considerations to design by sizing pre-determined components.

As discussed in Section 2.1, several models on facility location problems in network design are suggested by researchers as discussed. There are different categories in the proposed models in the literature (see Tables 2-1 and 2-2). However, in these models only one time scale is considered, especially because considering both operational (short term decisions / short time scale) and strategic (long term decisions / long time scale) decisions are necessary. In addition, it is essential to consider both the operational processes in the node-level of networks (e.g., manufacturing processes, flow of patients in an emergency room, etc.) and the strategic decisions in the network-level of a network (e.g., the location of nodes and their capacities). However, these aspects usually do not come together in the presented models in the current literature. The research gap in the current literature is related to the integrated design of bi-level networks while both operational and strategic decisions are considered. Therefore, the following research question as discussed and justified in Section 1.5 is proposed as follows.

Research Question 1: What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?

2.2 RESILIENCE IN DISRUPTED INFRASTRUCTURE NETWORKS

Managing disruptions in infrastructure networks has become crucial in recent years due to the increase in globalization and international competition (Cagliano and co-authors, 2008). Complexity in designing infrastructure networks has increased dramatically due to the expansion of networks across borders (Nagurney and co-authors, 2010). Managing disruption and uncertainty are a major challenge in designing and controlling infrastructure networks in recent years. Recent studies indicate growth of more than 1000 percent in the average cost of a disruption from the 1960s (Tang, 2006). The Japan Tsunami in 2011, for example, disrupted several infrastructure networks, and the Japan global merchandise in term of exports to its international trading partners fell by 14.5 percent in volume terms (equivalent to 13.3 percent in value terms) in two months after the March 2011 disaster.

Although restoration strategies are required in dealing with disruptions, most of these strategies (e.g., production of semi-manufactured products and keeping inventory) are considered as wastes in some management paradigms such as lean and agile production (Christopher and Lee, 2008). Therefore, the consideration of the trade-off between *redundancy (cost)* and *efficiency (service level)* is required in developing restoration strategies for disrupted infrastructure networks. This leads to the development of more complex design methods for designing infrastructure networks to tackle these complicated problems.

In this section, the literature is reviewed in three parts: in Section 2.2.1, the literature of risk and risk analysis is reviewed; in Section 2.2.2, different terms and concepts related to the disruption management is reviewed; and finally in Section 2.2.3, the resilience analysis is reviewed. All the reviews in these three sections are based on two aspects of the problem such as the restoration strategies and resilience analysis which is addressed in Table 2-3.

2.2.1 The Concept of Risk and Risk Analysis

Capability of infrastructure networks in reducing cost and being more agile with respect to customers' rapidly changing expectations improve their competition capabilities in the market, but on the other hand their distributed natures make them more vulnerable against uncertainties in the business and working environments. Two important features of today's business and working environments are dynamism and unpredictability due to huge number of unexpected events.

Today, many experts believe that numerous risk sources are involved in infrastructure networks, and these networks are still ill-equipped to handle them. According to Sarkar and co-authors (2002), during the labor strike in 2002, 29 ports on the West coast of United States were shut down which led to the closure of New United Motor Manufacturing production factory. During the recent destructive earthquake of Japan in 2011, Toyota Motor Company had to cease operations in its twelve assembly plants, which led to production loss of 140,000 autos. The main cause of this problem was disruption of its chain's manufacturing subsystem. In addition to impairment of production facilities and factories throughout Japan, many Japanese companies had a problem with the supply of required material, fuel and power.

Dole suffered revenue declines after their banana plantations were destroyed by Hurricane Mitch in 1998; Ford was forced to close five plants for several days after terrorists' attacks on September 11 caused suspended air traffic in 2001; The 1999 earthquake in Taiwan displaced power lines to the semiconductor fabrication facilities responsible for more than 50 percent of worldwide supplies of memory chips, circuit boards, flat-panel displays and other computer components and many hardware manufacturers including HP, Dell, Apple, IBM, Gateway and Compaq suffered from it; A Motorola cell phone factory in Singapore closed after an employee came down with SARS (Martha and Subbakrishna, 2002; Monahan and co-authors, 2003). Ericsson lost 400 million Euros after their supplier's semiconductor plant caught on fire in 2000; Apple lost many customer orders during a supply shortage of DRAM chips after an earthquake hit Taiwan in 1999; 2002 longshoreman union strike at a U.S West Coast port, for example, interrupted transshipments and deliveries to many U.S.-based firms, with port operations and schedules not returning to normal until 6 months after the strike had ended. For more detail, see Cavinato (2004). Hendricks and Singhal (2003) quantify negative effects of uncertainties through empirical analysis as follows: 33% to 40% lower stock returns; 17% drop in operating income, 7% lower sales growth and 11% growth in cost. All these examples demonstrate the importance of the disruption risk management.

Risks in infrastructure networks are classified in many different ways by the researchers. Tang (2006) defines two types of risks: a) operational risks which are inherent uncertainties such as uncertain customer demand, uncertain supply, and uncertain cost, and b) disruption risks which are the major disruptions caused by natural and man-made disasters such as earthquakes, floods, hurricanes, terrorist attacks, or economic crises such as currency fluctuations or strikes. Chopra and Sodhi (2004) categorize potential supply chain risks into nine categories: a) Disruptions (e.g., Natural disaster, terrorism, war, etc.), b) Delays (e.g., inflexibility of supply source), c) Systems (e.g., information infrastructure breakdown), d) Forecast (e.g., inaccurate forecast, bullwhip effect, etc.), d) Intellectual property (e.g., vertical integration), e) Procurement (e.g., exchange rate risk), f) Receivables (e.g., number of customers), g) Inventory (e.g., inventory holding cost, demand and supply uncertainty, etc.), h) Capacity (e.g., cost of capacity). Waters (2007) divides risk sources in infrastructure networks to internal risks (can be controlled) and external risks (cannot be controlled). Internal risks appear in normal operations, such as late deliveries, excess stock, poor forecast, human error, faults in IT systems, etc. External risks come from outside of networks, such as earthquakes, hurricanes, industrial action, wars, terrorist attacks, price rise, problems with trading partners, shortage of raw materials and crime. Moreover, Waters (2007) introduces another three-category risk sources: a) Environmental risk sources which comprise any uncertainties arising from the SN environment interaction. These may be the result of accidents (e.g., fire), socio-political actions (e.g., fuel protests or terrorist attacks) or acts of God (e.g., extreme weather or earthquakes), b) Organizational risk sources which lay within the boundaries of infrastructure network parties and range from labor (e.g., strikes) or production uncertainties (e.g., machine failure) to IT-system uncertainties, and c) Network-related risk sources which arise from interactions among organizations within infrastructure networks. Kar (2010) believes risks of networks can also be categorized into two groups: a) Systematic risks which are related to environmental factors which are unavoidable. Companies do not have any control on these factors such as demand-side uncertainty; supply-side disruption; regulatory, legal, and bureaucratic changes; happening catastrophic events; and infrastructure disruption.

b) Non-systematic risks dealing with factors that can be controlled to a large extent by a company such as facility disruption of manufacturing subsystem.

A disruption is an event which is not planned or anticipated and may affect the structure or dynamics of infrastructure networks. A multitude of equivalent terms are used in the literature, including hazards, threats, shocks, perturbations, disturbances, disasters, and anomalies (Francis and Bekera, 2014).

2.2.2 Quantitative Models for Resilient Networks

An infrastructure network is a group of unique entities connected by the physical flow of materials and products (Gong and co-authors, 2014). It is an interconnected collection of suppliers, producers, distribution and retailers that collectively transform raw materials to sellable goods (Benita and Benita, 1999; Mula and co-authors, 2010). Information also flows, upstream and downstream, throughout the supply chain by varying degrees based on the level of IT integration. The strategy for product and information flows through different nodes including consumers is considered as Infrastructure network Management (Di Giacomo and co-authors, 2010). The goal of the infrastructure network is to reach a predetermined service level or output performance.

A significant challenge for infrastructure network practitioners in efficiently achieving a service level is uncertainty and the many differing sources of uncertainty. Zhang and co-authors (2011) describe two types of uncertainty; price uncertainty and demand uncertainty, wherein price uncertainty involves small fluctuations in supply price that are often predictable to a degree based on market norms. Demand uncertainty can be attributed to many sources, including; competitor strategy and product quality (Stevenson and Spring, 2007). However, uncertainty in the infrastructure network extends beyond price and demand. Klibi and co-authors (2010) define uncertainty as the inability to determine the state of a future business environment due to randomness, hazard and uncertainty.

In addition to uncertainty, disruptions cause a significant challenge for achieving a desired infrastructure network performance. A disruption can be defined as an interruption of material flow within an infrastructure network (Chopra and Sodhi, 2004). A disruptive event is then the occurrence that results in a system’s level of performance being significantly reduced; a new, less desirable, system state is often realized (Henry and Emmanuel Ramirez-Marquez, 2012).

Table 2-3 Literature review of papers for resileince analysis, restoration strategy, and structural controllability aspects

Papers	**Resilience Analysis**				**Restoration Strategy**					**Structural Controllability**	
	Service Level	Cost/ Profit	Tardiness	Transportation Time	Back up/ Fortified Facility	Back up Inventory	Reconfiguration	Alternative Products	Time-based	Self-Organized	Infrastructure Networks
Schmit (2011)	✓		-	-	✓	✓	-	-	✓	-	-
Das (2011)	✓	-	-	-	✓	✓	-	✓	✓	-	-
Liu (2011)	-	-	-	-	-	-	-	-	✓	✓	-
Ramirez (2012)	✓	-	-	-	✓	-	-	-	✓	-	-
Kristianto (2013)	-	✓	-	✓	-	-	✓	-	✓	-	-
Sawik (2013)	-	✓	-	-	✓	✓	✓	-	-	-	-
Gong (2014)	✓	✓	-	-	✓	-	✓	-	✓	-	-
Zhang (2014)	-	-	-	-	-	-	-	-	-	✓	-
Gao (2014)	-	-	-	-	-	-	-	-	-	✓	-
Levalle (2015)	✓	✓	-	-	-	-	✓	-	-	-	-
RCIN Method	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓

According to Ramirez and Marquez (see Table 2-3), the system is in the disrupted state until a recovery occurs to bring the system to a new, stable recovered system state. Distribution delays, natural and man-made disasters and infrastructure failures are among the occurrences that disrupt portions or processes within an infrastructure network (Gong and co-authors, 2013). The severity of the impact of a disruption is related to the readiness of the network (Craighead and co-authors, 2007), and researchers have developed a number of strategies, to be discussed later in this work to mitigate disruption.

Infrastructure network literature has often addressed disruption as a sub-category within risk management. Harland and co-authors (2003) discuss the prevalence of complex global, dynamic infrastructure networks and the increased risk of a disruptive event. They explain that firms cooperating in global and inter-firm collaboration should collectively evaluate risk and benefits, in order to find the most suitable strategy. Pankaj Raj and co-authors (2004) describe controllable and uncontrollable risks within an infrastructure network. Risk can be summarized as a disruptive event, the probability of that event occurring and the consequences of the occurrence (Kaplan, 1997). Disruption has also been viewed as a supply uncertainty or the result of unreliable suppliers. Tomlin (2006) describe supply-side disruptions and propose a model to discuss disruption management. Tomlin references destructive fires at Philips Semiconductor and Toyota production plants as examples of unavoidable disruptions in supply. The risk of disruption, or the probability of damage within a supply chain, is an issue that supply chains must address (Kristianto and co-authors, 2014). Global and highly efficient infrastructure networks are very susceptible to disruption. Xu and Nozick (2009) approach the issue of disruption as capacity disruptions wherein all or a sizable portion of production capacity is lost for a period of time. This loss of production capacity results in a loss of supply downstream.

Infrastructure network design requires not only robustness to cope with errors and uncertainties during execution, but also resilience as the ability of a system to return to its original state or move to a new, more desirable state after being disrupted, which demands a combination of flexible and adaptability. The importance of resilience is in the face of disruptions when the ability to maintain, execute and recover the planned execution along with the achievement of the planned (or adapted, but yet still acceptable) performance is the objective. Here the focus is mainly on cost and service level as redundancy and efficiency performance measures, respectively, in order to manage disruptions and to design resilient infrastructure networks. In this regard, the literature of flexibility and resilience of infrastructure networks will be reviewed.

An infrastructure network must be flexible and adaptable in order to respond effectively to disruption (Christopher and Peck, 2004). Adaptability refers to a response to a change in a systems environment (Dalziell and McManus 2004) wherein a system may return to an old state or reach a new equilibrium (Fiksel, 2006) where processes and capabilities may have changed. Flexibility is an infrastructure network ability to respond to changes without excessive time, cost or reduction in service level (Morlok and co-authors, 2004). In this sense, flexibility is a system attribute, and not a response (Mohamed and co-authors, 2006).

Flexibility is also described as elasticity (Das and Abdel-Malek , 2003). Gosling and co-authors (2010) summarize flexibility as either vendor or sourcing flexibility. Vendor flexibility involves the flexibility within an individual operation such as production, inventory or distribution. Sourcing flexibility describes flexibility across the infrastructure network with the selection of sourcing. An infrastructure network with sourcing flexibility can constantly adjust to changes in the market by selecting among a pool of suppliers (Tachizawa and Thomsen, 2007; Duclos and co-authors, 2003). Stevenson and Spring (2007) describe how flexibility empowers supply chains to adapt to disruption, while maintaining system equilibrium. It is critical for a successful infrastructure network to be able to maintain their fundamental characteristics and performance, as well as adapt processes when faced with disruptions (Ivanov and Sokolov, 2013). Shepherd and Gunter (2006) introduce production, capacity, volume and logistics flexibility as measurable flexibility attributes.

While flexibility allows an infrastructure network to respond to disruptions, as well as non-trending changes in demand, resilience gives the infrastructure network the ability to recover efficiently. Resilience has been generally described as the ability to "bounce back" (Sheffi and Rice, 2005), "recover quickly" (Gong and co-authors, 2013) and return to a normal operational state or better (Christopher and Peck, 2004; Ponomarov and Holcomb, 2009) when faced with disruption. The latter view accepts that flexibility and adaptability are implicit in resilience and may result in a new system configuration and performance. Francis and Bekera (2014) describe resilience as a system characteristic wherein the system is able to anticipate, absorb, adapt and respond to disruption. This characteristic is both intrinsic and strategically enhanced. Francis and Bekera also describe the widely varying definitions and strategies for resilience. Their in-depth literature review reveals that resilience is at times defined as the ability to anticipate and absorb (NIAC, 2009; Kendra and Wachtendorg, 2003; Kenzig et al, 2006), and at others the ability to adapt or circumvent (Hale and Heijer, 2006). Some find that resilience would require that a system must maintain its original identity (Cummings et al., 2005; Hollings, 1973) and others accept that a system configuration or performance may shift (Fujita, 2006; Fiksel, 2006). While approaches to resilience are varied, much of the infrastructure network literature is related to recovery from disruption.

As is shown in table 2-3, Das (2011) develops a strategic level, mixed integer supply chain, planning model to address demand and supply uncertainty. Using flexibility in capacity, distribution, product mix, customer service level and input supply, the model integrates these measures into a strategic planning model. Flexibility allows a supply chain to respond to uncertainty in the market (Bertrand, 2003). The model by (Tang and Tomlin, 2008) is based on the need to find strategies to mitigate supply chain uncertainties and improve responsiveness. The model presented by Das utilizes a scenario-based stochastic analysis to optimize profit through a flexibility strategy. Capacity flexibility is defined here to be a strategy for responding to a non-trending demand increase within a planning period. Product mix flexibility involves the product portfolio of quick selling products and extended product offerings. Customer service flexibility is the ability to exceed a base service level. Supplier flexibility involves a collection of high-quality and approved quality suppliers. The integrated flexibility-planning model is solved with a scenario-based stochastic approach for a global business unit using a commercial solver across tens of thousands of variables. Das' contribution to infrastructure network planning is in proposing a model that addresses uncertainty by integrating supplier flexibility, capacity flexibility, input and customer-service flexibility, and the novel inclusion of product-mix flexibility. However, the trade-off between redundancy (redundant back-up inventory or back-up facility) and efficiency (service level) is not considered**.** The trade-off among redundancy and efficiency is considered in this dissertation.

Gong and co-authors (2013) present (see Table 2-3) a restoration model to develop resilient infrastructure networks that are able to recover from disruptions while minimizing the downstream impact. They approach the resilient infrastructure network from the perspective of infrastructure systems. Infrastructure in this context is a group of interdependent systems that produce and distribute a dependable flow of products and services. This set of systems includes enabling technologies and facilities. They develop a mathematical representation and a restoration strategy for infrastructure network managers. In order to model the interactions and relationship among supply chains and the surrounding infrastructure networks, Gong et al. use a compact formulation of an Interdependent Layered Network (ILN). The ILN, introduced by Lee et al. (2007), represents multiple networks as layers and represent the logical relationships between the layers. No intra-network impacts for operational decisions is assumed within a supply chain. However, in the event of a disruption, the impact of the disruption is propagated throughout the structure based on the relational interdependencies. Using a supply chain layer, power system layer, telecommunications layer and transportation layer, they employ a scenario where there is a local disruption in the power supply, telecommunications and transportation layers. They then study the impact of possible restoration strategies on layered network model. The multi-objective problem is solved with Mixed Integer Linear Programming and a Branch and Bound algorithm using a commercial solver, CPLEX. Their work allows a supply chain manager to identify priorities and to find an efficient restoration strategy. However, the focus of this work is not on selecting efficient restoration strategies and practical flexibility approaches in each layer of infrastructure networks.

As is shown in Table 2-3, Kristianto and co-authors (2014) propose a two-stage programming approach to resilient infrastructure network design. They propose a reconfigurable infrastructure network design with fuzzy programming for inventory allocation and shortest-path network configuration. Using Bender's decomposition (Mercier, 2005), the authors simplified the shortest path problem with time constraints and capacity constraints (SPPTWCC) by breaking the problem into components to find inventory allocation strategies feasible for transportation routing and production schedule constraints. Resilience is built into the problem by considering stochastic variations in delivery load and time. The method allows a complex infrastructure network to respond efficiently to disruptions. However, the possibility of having disruptions on facilities is not considered in their models.

As discussed in Section 2.2, there are several studies on resilient infrastructure networks. However, the focus of these works is not on selecting efficient restoration strategies and practical flexibility approaches in disrupted networks. Therefore, the following research question as discussed and justified in Section 1.5 is proposed as follows.

Research Question 2: What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?

As discussed in Section 2.2 and specifically in Section 2.2.3, there are different models in the literature related to the quantitative models for resilience analysis. In these models usually one of the two important factors, efficiency or redundancy, is considered. However, considering both factors while disruptions happen is important. In addition, in infrastructure networks considering the met demand of customers as an efficiency factor seems to be important. These factors are not considered in the current literature as a time-dependent model for designing resilient infrastructure networks while different disruptions happen, which demonstrates a significant research gap. Therefore, the following research question as discussed and justified in Section 1.5 is proposed.

Research Question 3: What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?

2.3 STRUCTURAL CONTROLLABILITY OF NETWORKS

Infrastructure network design requires not only robustness and flexibility to cope with errors and uncertainties during execution, but also resilience as the ability of a system to return to its original state or move to a new, more desirable state after being disrupted, which demands a combination of flexible and adaptability. The importance of resilience is in the face of disruptions when the ability to maintain, execute and recover the planned execution along with the achievement of the planned (or adapted, but yet still acceptable) performance is the objective.

Add to this, the importance of controlling network over the period of disruption is important. According to control theory, a dynamical system is controllable if, with a suitable choice of inputs, it can be driven from any initial state to any desired final state within finite time. This definition agrees with the intuitive notion of control, capturing an ability to guide a system’s behavior toward a desired state through the appropriate manipulation of a few input variables, like a driver prompting a car to move with the desired speed and in the desired direction by manipulating the pedals and the steering wheel.

To review the literature in the structural controllability, some basic concepts are introduced. It starts with introducing cactus graphs and some fundamental theories in Section 2.3.1, and then it is followed with an introduction of the controllability and structural controllability in Section 2.3.2. There are very few papers in this area which are reviewed in Section 2.3.3 and addressed in Table 2-3.

2.3.1 Cactus Graphs and Maximum Matching

Graphs are mathematical structures that are used to model the pair-wise relations between objects from a certain collection. The study of graphs started in the 18th century, and graph theory is a prime area in discrete mathematics. Graph theory becomes a very useful technique for solving real-world problems. One part of graph theory is the network theory in which the networks of real systems are studied. Networks are applied in numerous disciplines. Its applications span from the Internet to biological systems. Here, the fundamental definitions and theorems for the structural controllability are introduced. However, the concepts and fundamental definitions of the graph theory are explained and discussed in detail in Thulasiraman and Swamy (1992).

Undirected cactus graph: An undirected connected simple graph is called an undirected cactus if any two simple cycles have at most one vertex in common. Equivalently, every edge of such graph belongs to at most one cycle (see Figure 2-3).

A stem is an elementary path. The initial (or terminal) vertex of a stem is called the root (or top) of the stem. A bud is an elementary cycle C plus an additional edge e that ends, but not begins, in a vertex of the cycle. This additional edge e is called a distinguished edge of the bud.

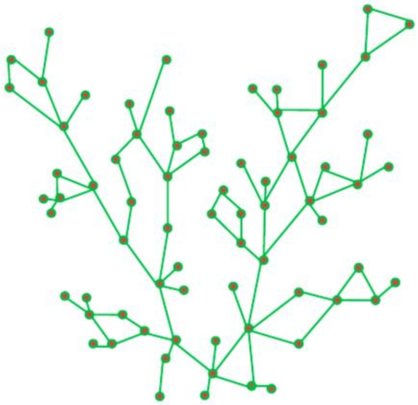


Figure 2-3 Example of an undirected cactus graph (Anh, Ngo Thi Tu (2012))

Directed cactus graph: A general directed cactus is a digraph defined recursively as follows. A stem is a cactus. Given a stem S_0 and buds B_1, B_2, …, B_l then $S_0 \cup B_1 \cup B_2 \ldots \cup B_l$ is a cactus if for every I (1<=i<=l) the initial vertex of the distinguished edge of B_i is not the top of S_0 and is the only vertex belonging at the same time to B_i and $S_0 \cup B_1 \cup B_2 \ldots \cup B_{i-1}$ (see Figure 2-4).

Maximum Matching: Matching in graph theory refers to a set of edges that do not share common vertices. The notion of matching is one of the key points to understand the Minimum Input Theorem.

Matched and unmatched in undirected graphs: For an undirected graph, a matching M is an independent edge set, i.e., a set of edges without common vertices. A vertex is matched if it is incident to an edge in the matching. Otherwise, the vertex is unmatched. Similarly, an edge of *G* is matched if it is in *M*; otherwise it is unmatched.

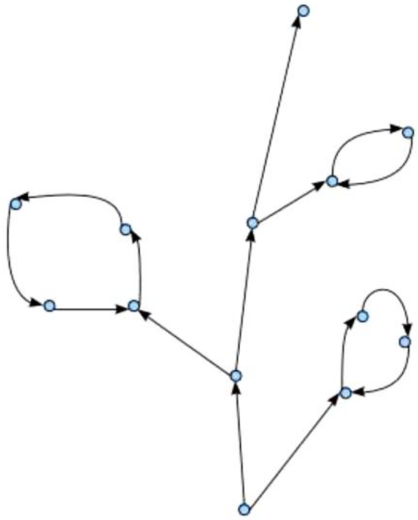


Figure 2-4 Example of a directed cactus graph (Anh, Ngo Thi Tu (2012))

Matched and unmatched in directed graphs: For a digraph G = (V,E), a matching M is a subset of E that no two edges in M share a common starting vertex or a common ending vertex. A vertex is matched if it is the ending vertex of an edge in the matching M; otherwise, it is unmatched. Similarly, an edge of G is matched if it is in M; otherwise, it is unmatched.

Alternating path: An alternating path is a path in which the edges belong alternatively to the matching and not to the matching.

Maximum Matching Theorem: A matching M in a graph G is a maximum matching if and only if there is no augmenting path in G with respect to M.

2.3.2 Controllability and Structural Controllability

Controllability is one of the fundamental concepts in modern mathematical control theory. This is a qualitative property of control systems and is of particular importance in control theory. Systematic study of controllability started at the beginning of 1960s and the theory of controllability is based on the mathematical description of the dynamical system.

The ability to move a system around its entire configuration space using only certain admissible manipulations is controllability. Specifically, a dynamic system is controllable if it can be “driven” from any initial state to any desired final state in finite time with a suitable choice of inputs.

Most natural and technological systems are organized into networks of components and these networks are governed with some underlying dynamical processes. For example, metabolism is a basic process of any living cell. In this process, cells exchange energy. They grow and build their structures and respond to the environment. Inside a living cell, metabolites are transformed by a series of reactions that are catalyzed by enzymes. These reactions form a scale-free metabolic network. A cell may “control” its metabolism by controlling the concentration of its enzymes.

The controllability of a real system is affected by two independent factors:

1) The system's architecture, represented by the weighted and directed network describing the connections of system's components with each other.

2) The dynamical rules that describe the time-dependent interactions among the components.

Consider the linear dynamic system:

where $x(t) = (x_1(t), \ldots, x_N(t))^T$ presents the state of system of N nodes at time t.

$u(t) = (u_1(t), \ldots, u_M(t))^T$ is the input vector.

A is the N*N matrix which describes the system's wiring and the interaction strength between components (for example: matrix A represents the traffic on individual communication links, or the strength of regulatory interactions in a regulatory network).

B is the input matrix describing the nodes that are controlled by the outside controllers.

In order to determine the controllability of system (1), R.E Kalman gave an algebraic criterion, which depends only on matrices A and B, called Kalman Rank Condition.

Kalman Rank Condition:

A necessary and sufficient condition for system (1) to be controllable is

Rank(c) = rank $[B, AB, A^2B, \ldots, A^{N-1}B] = N$

C is called Kalman's controllable matrix of size N*NM.

Structural Controllability: To test the controllability of a network of an arbitrary system using Kalman's rank condition, all the values of matrices A and B are required. However, for most real complex networks, the exact values of all entries of A are often unknown. In addition, checking the rank of C is computationally difficult, especially for large networks. In order to address those difficulties, Lin introduced the concept of structural controllability discussed as follows.

Structural Controllability: A system is said to be strongly structurally controllable if its controllability is independent of the system parameters, as long as they are non-zero.

Lin's Theorem on Structural Controllability: The following three statements are equivalent:

1. A linear control system (A,B) is structurally controllable.

2. i) The digraph G(A,B) contains no inaccessible nodes.

ii) The digraph G(A,B) contains no dilation.

3. The digraph G(A,B) is spanned by cacti.

Graph Dilation: Let nodes of graph G be numbered with distinct integers 1 to |G|. Then the dilation of G is the maximum (absolute) difference between integers assigned to adjacent vertices. Equivalently, it is the maximum value of |i-j| over all nonzero elements of the adjacency matrix (a_{ij}).

Driver nodes: In a controlled network, the state vertices that are directly connected to input vertices (or origins) are called controlled nodes. Those controlled nodes, which do not share input vertices, are called driver nodes.

Minimum Input Theorem: The minimum number of inputs or equivalently the minimum number of driver nodes needed to fully control a network is one if there is a perfect matching. (In this case, any single node can be chosen as the driver node.) Otherwise, it equals to the number of unmatched nodes with respect to any maximum matching (In this case, the driver nodes are just the unmatched nodes).

2.3.3 Structural Controllability in Networks

According to control theory, a dynamical system is controllable if, with a suitable choice of inputs, it can be driven from any initial state to any desired final state within a finite time. Although control theory is a mathematical highly developed branch of engineering with applications to electric circuits, manufacturing processes, communication systems, aircraft, spacecraft and robots, fundamental questions pertaining to the controllability of complex systems emerging in nature and engineering have resisted advances. The difficulty is rooted in the fact that two independent factors contribute to controllability, each with its own layer of unknown: (1) the system's architecture, represented by the network in which components interact with each other; and (2) the dynamical rules that capture the time dependent interactions between the components. Thus, progress has been possible only in systems where both layers are well mapped.

For most real complex networks with large weighted and directed networks, the exact values of all parameters and links are often unknown. Therefore, dynamical rules cannot easily be determined (Factor 2). Recent advances towards quantifying the topological characteristics of complex networks have shed light on Factor 1, prompting us to wonder whether some networks are easier to control than others and how network topology affects a system's controllability. One critical issue in applying control strategies to infrastructure network adaptation-based resilience analysis is the centralized controller and its functions. In order to manage stochastic behaviors and disruptions in different levels of the network, it is necessary to establish new methods of applying structural controllability for disruption risk mitigation in infrastructure networks.

As discussed in Section 2.3, there are some studies related to using the structural controllability in complex networks. However, the difficulty is rooted in the fact that two independent factors contribute to controllability, each with its own layer of unknown: (1) the system's architecture, represented by the network in which components interact with each other; and (2) the dynamical rules that capture the time dependent interactions between the components. Thus, progress has been possible only in systems where both layers are well mapped. For most real complex networks with large weighted and directed networks, the exact values of all parameters and links are often unknown. Therefore, dynamical rules cannot easily be determined (Factor 2). One critical issue in applying control strategies to infrastructure network adaptation-based resilience analysis is the centralized controller and its functions. In addition, there is still no achievement in applying controllability in infrastructure networks. In order to manage stochastic behaviors and disruptions in different levels of the network, it is necessary to establish new methods of applying structural controllability for disruption risk mitigation in infrastructure networks. Therefore, the following research question as discussed and justified in Section 1.5 is proposed as follows.

Research Question 4: What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?

2.4 THEORETICAL STRUCTURAL VALIDATION: RESEARCH OPPORTUNITIES AND JUSTIFICATION

In this chapter, methods and approaches in the literature related to the issues addressed by resilient and controllable multi-level infrastructure networks are discussed in the context of Table 2-4. These methods including the multi-level network design with integrated operational and strategic decisions (Section 2.1), resilience analysis for infrastructure networks (Section 2.2), and controllable design of complex systems (Section 2.3). As a process for theoretical structure validation as is shown in Figure 2-5, the capabilities of the aforementioned methods and approaches are critically evaluated with respect to the requirements of the problem of resilient and controllable multi-level infrastructure network design. In addition, in this section, the research questions are justified.

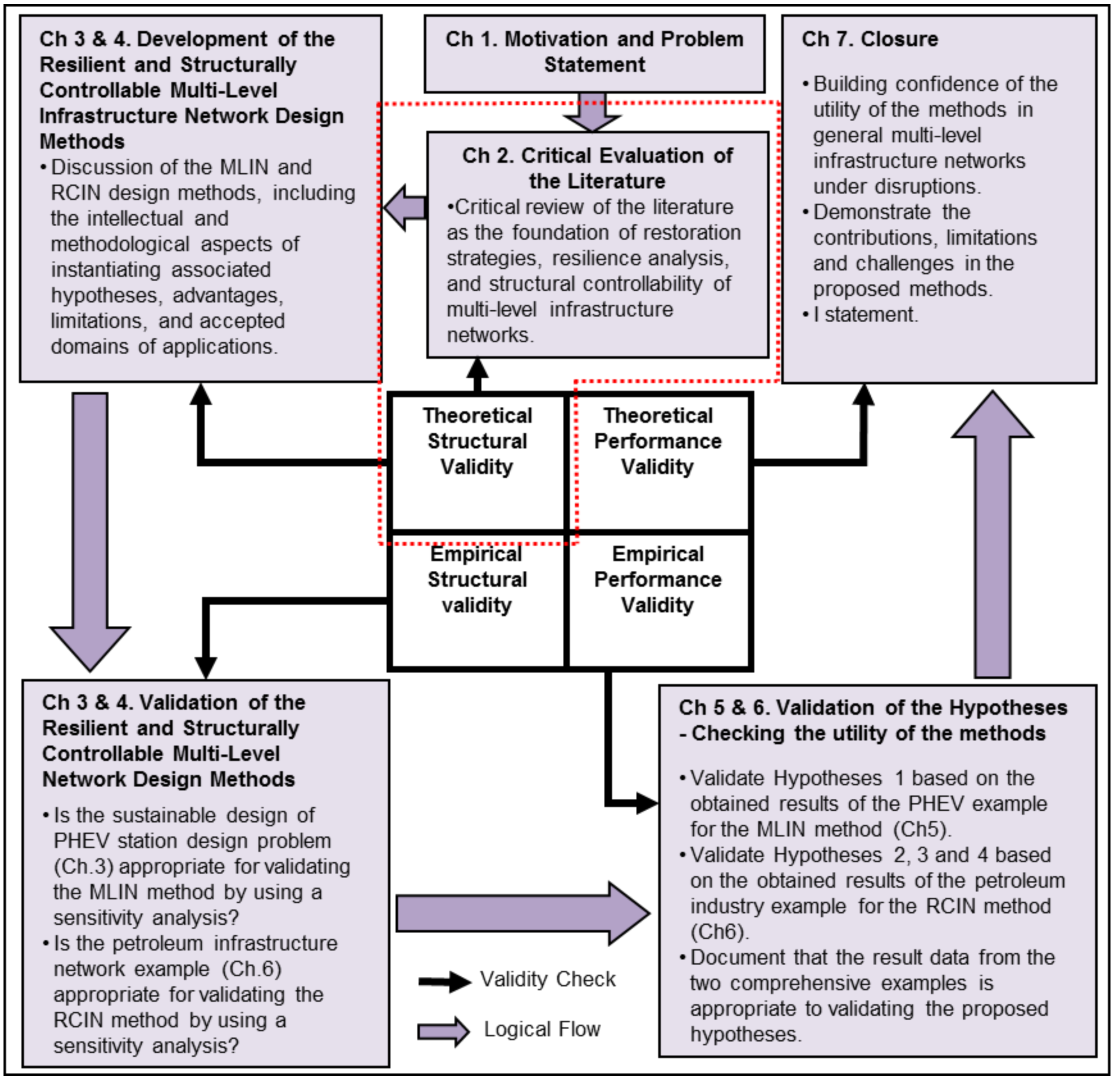


Figure 2-5 Validation strategy of the dissertation

Table 2-4 Summary of critical evaluation of existing methods

Aspects	**Methods**	**Evaluation of Literature**	**Research Gap**
Multi-level network design	Dynamic facility location problems by Shulman (1990), Dias and co-authors (2007), Daskin (2008), and Jena and co-authors (2013)	• Since the time scale for operational and strategic decisions are different, it is difficult to use the current models for integrated design while there are different decision levels. • The focus of models in this area is mainly on the network-level design; not on bringing out decisions regarding the node level.	The research gap is that an integrated method (consists of simulation modeling and mathematical modeling) for designing a multi-level network with focus on operational and strategic decisions, and conflicting system goals is required.
Restoration strategies	Considering cost as redundancy and recovery time as efficiency by Kristianto and co-authors, Gong and co-authors (2014)	Focus of these models is on selecting the appropriate restoration strategies without respect to the recovery time or considering the trade-off between redundancy and effectiveness.	The research gap is that the selection of appropriate pre-disruption and post-disruption restoration strategies while considering the trade-off between redundancy and effectiveness is required.
Resilience analysis	Considering service level and lost sales while disruptions happen by Das (2011), Schmit (2011), Ramirez and Marquez (2012)	Focus of this part of the literature is on one aspect of the resilience analysis, either cost/profit or service level/lost sales. Even in papers that consider both of them, considering the recovery time is neglected.	The research gap is that a comprehensive set of time-based measures, such as service level, cost, recovery or delivery time, is required for the resilience analysis while considering the trade-off between redundancy and effectiveness.
Structural controllability	Structural controllability for complex networks by Liu and co-authors (2011)	Focus here is on applying structural controllability for self-organized networks and it is not applied for infrastructure networks or recovering disrupted networks.	The research gap is in applicability of structural controllability in controlling disrupted infrastructure networks and consequently increasing its resilience, and using driver nodes to operate restoration strategies in recovering a disrupted network.

In Table 2-4, the evaluation results of the existing methods in the literature regarding the four aspects of resilient and controllable multi-level networks addressed in Section 1.4.2 and Table 1-1 are summarized. Based on the evaluation results, it is justified that the research questions are properly formulated.

The four proposed research questions are addressed here (see Section 1.5 for justification in defining the proposed research questions).

Research Question 1: What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?

Research Question 2: What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?

Research Question 3: What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?

Research Question 4: What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?

In this section, first the critical evaluation of the existing methods in the literature is presented. Then, the proposed research questions are addressed and justified based on the result of the literature evaluation.

2.5 CHAPTER SYNOPSIS

In this chapter, existing methods and approaches for the resilient and structurally controllable design of multi-level infrastructure networks are critically reviewed. In Section 2.1, the related works in the area of the facility location problem are reviewed. Besides the general models in this area, related works in the area of sustainability and electric charging stations for electric vehicles are also reviewed. In this review, it is found that there is less attention into having integrated models for both operational and strategic decisions in bi-level infrastructure networks. In Section 2.2, methods and approaches for resilient infrastructure networks under disruptions are classified and reviewed. In Section 2.2.1, first the concept of the risk and risk analysis is reviewed (other terms and definitions such as stability, robustness, flexibility, resilience and controllability are introduced in Appendix). In Section 2.2.2, quantitative methods for designing resilient infrastructure networks are presented. From the review, it is identified that there is a gap in the literature on considering the trade-off among redundancy and efficiency in the time-dependent resilient models. In Section 2.3, the concept and characteristics of the structural controllability is introduced, and then some approaches in this area are reviewed. In this review, it is found that there is not any work on applying the structural controllability in designing infrastructure networks.

Finally, in Section 2.4, gaps among the existing methods are identified and requirements of new resilient and controllable infrastructure network design methods are posted in order to justify the contributions of the research questions in Section 1.5.

In Chapters 3 and 4, the multi-level infrastructure network (MLIN) method and the resilient and structurally controllable infrastructure network (RCIN) method are explained in detail, respectively. The MLIN method is solved using an example of the PHEV charging stations, and the RCIN method is solved using an example of the petroleum network example in Chapters 5 and 6, respectively.

CHAPTER 3 A METHOD FOR DESIGNING A MULTI-LEVEL INFRASTRUCTURE NETWORK WITH OPERATIONAL AND STRATEGIC DECISIONS

In this chapter, details of the multi-level infrastructure network (MLIN) method is addressed. The MLIN method is tailored and explained for a bi-level infrastructure network as a specific case of a multi-level network structure. As is shown in Figure 3-1, the MLIN method, its characteristics, limitations and applicability are addressed in this chapter. The proposed MLIN method is in response to Research Question 1. In Section 3.1, the problem statement for multi-level infrastructure networks is presented and followed by the related requirement list and research question. In Section 3.2, an overview of the general structure for designing multi-level infrastructure networks is presented. In Section 3.3, the multi-level infrastructure network (MLIN) method, in the context of a bi-level network structure, is proposed, and the overall procedure of it is explained. In Sections 3.4 to 3.7, steps of the MLIN method are explained in detail for a bi-level structure. In Sections 3.8 and 3.9, an introduction of the example of the PHEV charging stations, problem statement, its word and mathematical formulations are presented. Finally, the internal consistency of the MLIN method is evaluated with identifying explicitly its favorable and unfavorable properties in Section 3.11. Not only the theoretical structural validation (Quadrant 1 of the validation square) is considered, but also using a sensitivity analysis for the demand parameter help in performing the empirical structural validation (Quadrant 2 of the validation square) in Section 3.11.

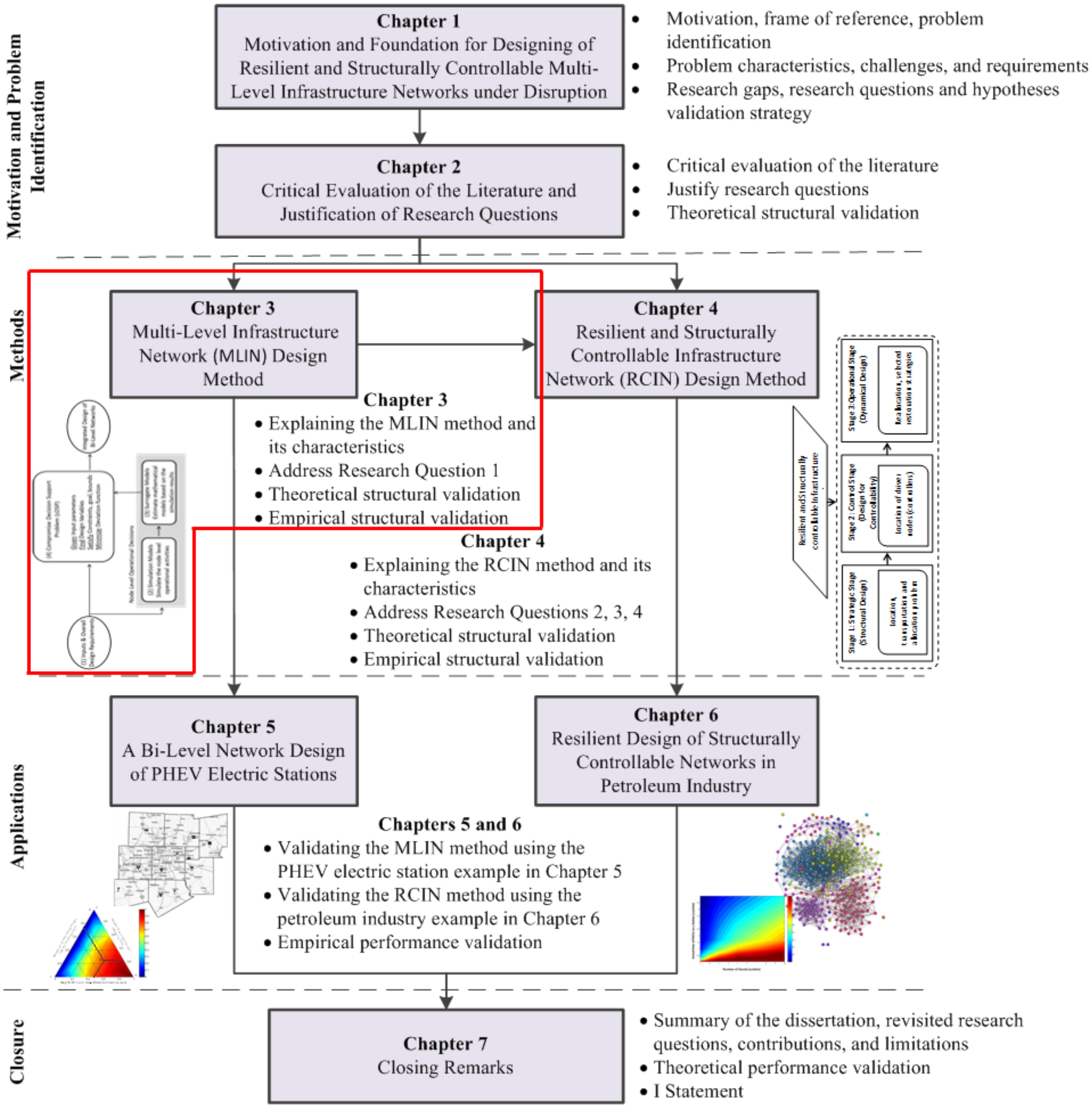


Figure 3-1 Dissertation structure

3.1 PROBLEM STATEMENT FOR DESIGNING INFRASTRUCTURE NETWORKS WITH HIERARCHICAL STRUCTURES

Infrastructure network design involves determining the network structure and the distribution of resources over the structure. In other words, both decisions on locations and capacities of facilities (strategic decisions) and supplying the demand to available facilities through available transportation routes (operational decisions) should be considered. The simultaneous design that consider the operational decisions (focus on the short-term decisions) and the strategic decisions (focus on the long-term decisions) results in both enhanced controllability and provide a more efficient design process. Add to this the importance of modeling multi-level decisions (e.g., node-level and network-level decisions) in networks with hierarchical structures.

In this chapter, *the problem of designing infrastructure networks with hierarchical structures is considered. In other words, the interactions among different levels (e.g., node-level and network-level decisions) should be considered when designing multi-level infrastructure networks with considering both the operational and strategic decisions.* As is shown in Table 3-1, which is a part of Table 1-3, the requirement for this problem is having an integrated method for designing multi-level infrastructure networks. The research question and research hypothesis defined based on the problem requirements are shown in Table 3-1. The multi-level infrastructure network (MLIN) method is developed to respond to the proposed research question (RQ1) as the first outcome of this dissertation.

Table 3-1 Connection between the problem, requirement, research question, and outcome

Aspect	Requirement	Research Questions	Research Hypotheses	Contribution
Multi-level network design	Integrated formulation for designing a multi-level network considering operational (short term) and strategic (long term) decisions with conflicting goals.	RQ1: What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?	Implement an integrated simulation model (for operational decisions in the node-level) and mathematical model (using the compromise Decision Support Problem) to design a multi-level network with conflicting goals.	The MLIN method: integrated node-level and network-level decisions considering both operational and strategic decisions with conflicting design goals

As is shown in Figure 1-4, the addressed problem in this dissertation has two aspects (i.e., multi-level infrastructure network aspect and disruption management aspect). The connection between these two aspects in designing resilient and structurally controllable of multi-level infrastructure networks and the proposed MLIN method is explained in the next section.

3.2 OVERVIEW OF THE MULTI-LEVEL INFRASTRUCTURE NETWORK METHOD

The main objective in this dissertation is the development of methods for the resilient and structurally controllable design of multi-level infrastructure networks with consideration of occurrence of disruptions. Two aspects are considered in this regard: (1) multi-level infrastructure network design aspect, and (2) disruption management aspect. In Figure 3-2, both aspects are shown. As is shown in the left side of Figure 3-2, all levels of decisions (i.e., Level 1... Level n), includes operational and strategic decisions, and should be considered in designing multi-level infrastructure networks. As is shown in the right side of Figure 3-2, resilience restoration strategies and the structural controllability can be applied to manage disruptions and mitigate the risk of disruptions.

In designing multi-level infrastructure networks, the focus in the lower level of decisions (e.g., node-level decisions) is more on the operational decisions, and the focus in the higher level of decisions (e.g., network-level decisions) is more on the strategic decisions.

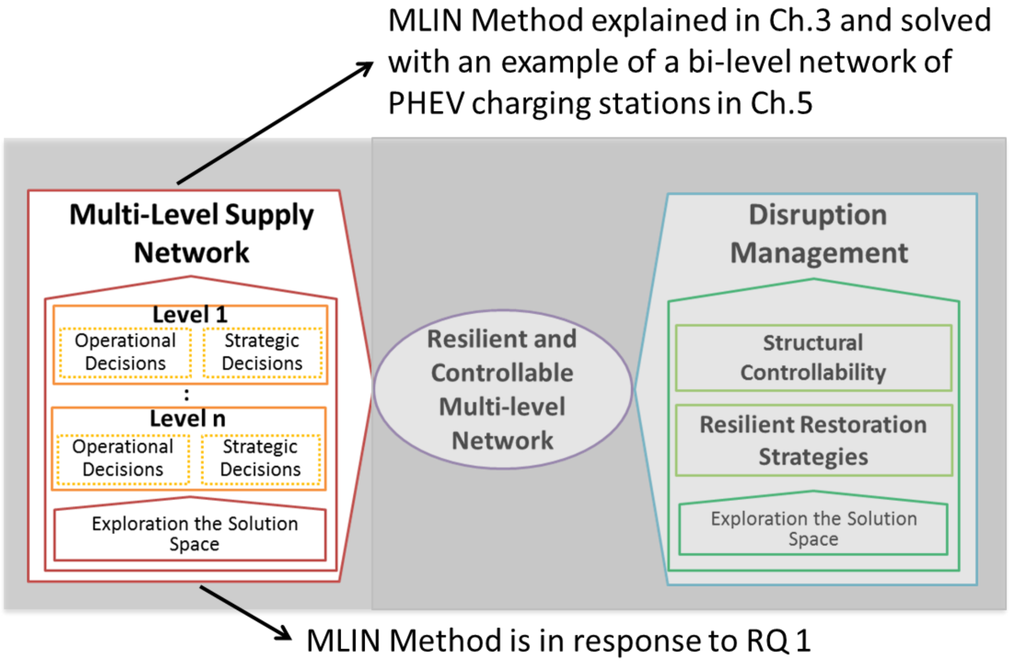


Figure 3-2 Resilient and structural controllability of a multi-level network

In this chapter, the multi-level infrastructure network aspect is considered and the MLIN Method is tailored for a bi-level infrastructure network and explained in detail (see Sections 3.3 to 3.7). Then, the problem statement and word formulation for an example of designing a bi-level network of electric charging stations is presented in

Section 3.8, and the derivation of the mathematical formulation and the mathematical formulations are presented in Sections 3.9 and 3.10.

3.3 BI-LEVEL INFRASTRUCTURE NETWORK DESIGN - MLIN METHOD

In this section, the proposed MLIN design method from the bi-level infrastructure network perspective is explained, in which node-level decisions and network-level decisions are considered. The MLIN method for designing bi-level infrastructure networks is illustrated in Figure 3-3. As is shown in Figure 3-3, the main idea is based on using simulation models (see Step 2 in Figure 3-3) for simulating operations in nodes, especially for operational decisions with the short time scales. After simulating operations in nodes, results are formulated as a mathematical model using the surrogate modeling approach (see Step 3 in Figure 3-3); the estimated mathematical model is representative of decisions in nodes. This estimated mathematical model, as the representative of node level decisions and the output of the simulation and surrogate models, can be used in the general and comprehensive mathematical model (see Step 4 in Figure 3-3) for designing both node-level and network-level decisions.

Since the models are incomplete and inaccurate, exploration of the solution space is required. Exploration of the solution space and considering the conflicts among systems goals is possible through the compromise Decision Support Problem (see Step 4 in Figure 3-3). Each of these steps is explained with more detail as follows.

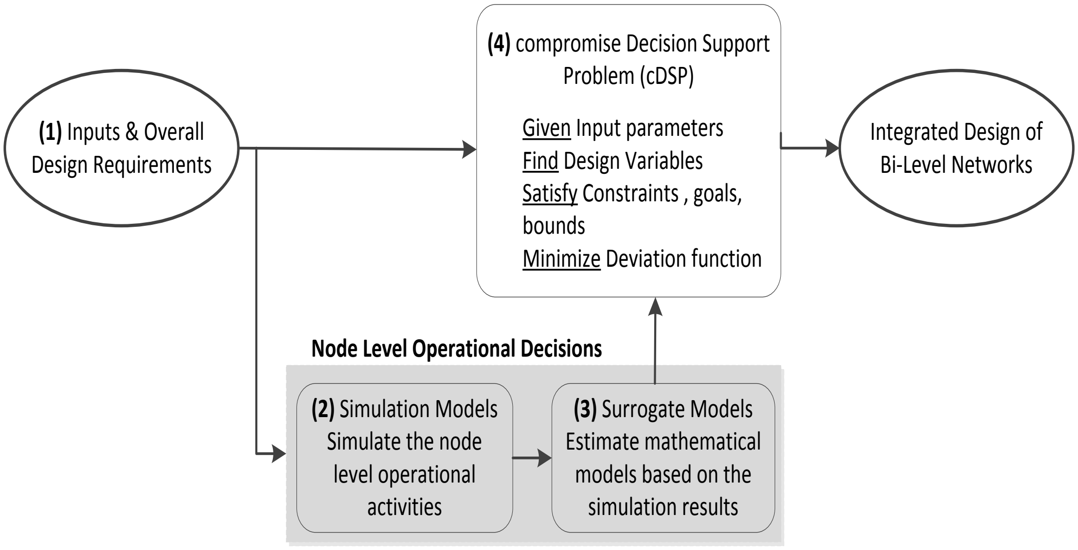


Figure 3-3 The proposed bi-level infrastructure network (MLIN) method for a bi-level structure

Step (1) Overall Design Requirements: In this step assumptions for designing bi-level infrastructure networks with operational and strategic decisions are determined. In addition, values of input parameters and the system boundary are determined in this step. This step is explained in Section 3.5.

Step (2) Simulation Model: In this step, operations or entities in the lower level (node-level) are stimulated using simulation packages, algorithms or other similar approaches (e.g., queue models, etc.). The main purpose here is to capture the behavior of entities or operations in nodes of a network. This step is explained in detail in Section 3.6.

Step (3) Surrogate Model: All operations with a short/different time scale can be simulated in the previous step. The focus in the previous step is mainly on operations in the lower level (node-level) of networks. In order to have an integrated design method for bi-level infrastructure networks, it is encouraged to have a one-stage, integrated mathematical model. To do so, the results of the simulation model from Step (2) are estimated by mathematical models using surrogate modeling. This step is explained in detail in Section 3.7.

Step (4) compromise DSP: In this step, the one-stage, integrated mathematical model for designing bi-level infrastructure networks considering conflicting system goals are presented. The compromise Decision Support Problem (cDSP) is used for modeling the bi-level infrastructure networks, especially because considering the conflicts among goals of the system is inevitable. This step is explained in more detail in Section 3.8.

3.4 OVERALL DESIGN REQUIREMENTS- STEP (1)

As is shown in Figure 3-3, in this step the problem statement, data collection, and assumptions for designing bi-level infrastructure networks with operational and strategic decisions are determined. In addition, values of input parameters and the system boundary are determined in this step. Possible scenarios for different weights of system goals are defined in this step.

3.5 THE SIMULATION MODEL- STEP (2)

In this step, as in shown in Figure 3-3, operations or entities in the lower level (node-level) are stimulated using simulation packages, algorithms or other similar approaches (e.g., queue models, etc.). Capturing the behavior of entities or operations in nodes of a network is performed in this step.

Manufacturing processes (e.g., plant is a node and the company's supply chain is its network), assembly or disassembly processes (e.g., plant is a node and the company's supply chain is its network), flow of material in a production line (e.g., a manufacturing machine is a node and the plant's manufacturing machines is its network), heat transfer in a part of a product (e.g., one part of the product is a node and the product which consists of many parts is its network), charging electric cars in a station (e.g., a charging station is a node and all charging stations and their energy sources are its network), serving patients in a hospital or an agent care (e.g., a hospital or an agent care is a node and all facilities of the health care system in a region make its network) are some examples of operations or entities with short-time scale in the node-level of networks.

In this step, some of operations related to the operational decisions and related to the node-level decisions of networks, which their time scale is different with the general time scale in the network-level decisions, are selected. The simulation model is applied for stimulating the behavior of these operations or entities. The results of this step can be used in the next step of the MLIN method.

3.6 THE SURROGATE MODEL - STEP (3)

A surrogate model is a statistical approximation that is used to replace expensive computer analysis (Simpson and co-authors, 2001). For the exploration of the design space many possible alternatives for operational decisions in the lower level of networks exist. In order to speeding up computations and not having multi-stage mathematical models for the integrated design of bi-level infrastructure networks, a mathematical formulation is approximated using surrogate models.

The surrogate modeling process can be based on different approaches such as response surface and multi-variant regression splines (MARS). This process will let to perform analysis to fit the data and to get a function(s) that allow us estimate an approximated mathematical formulation for the cDSP (see Figure 3-4).

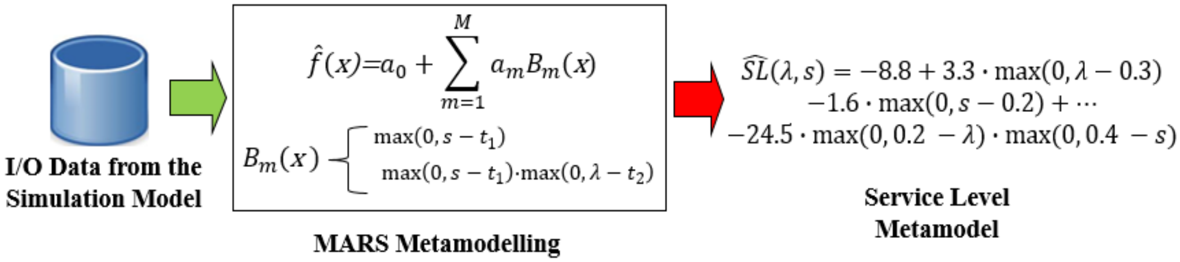


Figure 3-4 Surrogate modeling process in the MLIN – an example for the approximated service level formulation

3.7 COMPROMISE DECISION SUPPORT PROBLEM (cDSP) - STEP (4)

The last step – Step (4) in the MLIN is to identify integrated design for bi-level infrastructure networks. In this dissertation, for the bi-level, integrated operational and strategic level decisions, the compromise Decision Support Problem (cDSP) (Mistree and co-authors, 1992) is employed in order to design bi-level networks with conflicting system goals. The cDSP is a mathematical construct for identifying design solutions in the presence of multiple conflicting goals. The cDSP is a hybrid formulation that incorporates concepts from both traditional mathematical programming and goal programming. The cDSP and mathematical programming are similar to the extent that they refer to system constraints that must be satisfied for feasibility. They differ is in the way the deviation or objective function is modeled. In the cDSP, as in goal programming, multiple objectives are formulated as system goals involving deviation variables, and the deviation function is modeled using deviation variables rather than system or decision variables. The cDSP differs from goal programming, however, because it is tailored to handle common engineering design situations in which physical limitations are manifested as system constraints (mostly inequalities) and bounds on the system variables.

Table 3-2 The mathematical construct of the compromise Decision Support Problem (Mistree and co-authors, 1992)

Given
n, number of system variables
p, number of equality constraints
q, number of inequality constraints
m, number of system goals
$g_i(\mathbf{x})$, constraint functions
$G_{i,}$, system goals
$A_i(\mathbf{x})$, performance functions

Find
$\mathbf{x}$ (system variables)
d_i^-, d_i^+ (deviation variables)

Satisfy
System constraints:
$g_i(\mathbf{x}) \leq 0 \qquad i=p+1,...,p+q$
$g_i(\mathbf{x})=0 \qquad i=1,...,p$
System goals:
$A_i(\mathbf{x})/G_i + d_i^- - d_i^+ = 1 \qquad i=1,...,m$
Bounds:
$x_i^{min} \leq x_i \leq x_i^{max}$
$d_i^-, d_i^+ \geq 0$ and $d_i^- \cdot d_i^+ = 0 \quad i=1,\ldots,n$

Minimize
$Z = [f_1(d_i^-,d_i^+), \ldots, f_k(d_i^-,d_i^+)]$ *Preemptive*
$Z = \Sigma W_i (d_i^- + d_i^+)$ $\Sigma W_i=1, W_i >=0$ *Archimedean*

The conceptual basis of the compromise DSP is to minimize the difference between that which is desired (the goal, G_i) and that which can be achieved ($A_i(\mathbf{x})$) for multiple goals. This is accomplished by minimizing the deviation function, Z, expressed in terms of deviation variables. The deviation function provides a measure of the extent to which multiple goals are achieved. In the compromise DSP, multiple goals are considered conventionally by formulating the deviation function either with Archimedean weightings or preemptively (lexicographically) (Mistree and co-authors, 1992).

Through Sections 3.3 to 3.7, the MLIN method is explained in detail while it is tailored for a bi-level infrastructure network design. The proposed MLIN method is solved for an example of the network of electric charging stations of plug-in hybrid electric vehicles (PHEVs). The details of using the MLIN method for designing the bi-level network of PHEV charging stations are discussed in Chapter 5. However, in the following two sections, a problem statement for designing a network of electric charging stations for PHEVs and its word formulation, and the mathematical formulation for the cDSP (Step 4 of the MLIN method) are presented, respectively. These two sections can help making the development of the cDSP in the MLIN method more clear.

3.8 WORD FORMULATION FOR DESIGNING A BI-LEVEL NETWORK OF PHEV CHARGING STATIONS

In order to evaluate the MLIN method, an example of electric charging stations for plug-in hybrid electric vehicles is introduced. Plug-in hybrid electric vehicles (PHEVs) offer an approach to significantly lowering the consumption of fossil fuel and consequently the gas emission. There are two levels of decisions related to the design of a network of electric charging stations for plug-in hybrid electric vehicles: *a*) the node-level decisions consist of the strategic and operational decisions i.e., the number of charging spots and battery storage at each station as the strategic decisions, and the interactions of electricity between the power grid and renewable sources of energy as the operational decisions; *b*) the network-level decisions consist of the strategic and operational decisions i.e., the location of charging stations as the strategic decisions and the allocation of demand to the demand nodes as the operational decisions.

The problem that is considered is how a network of electric charging stations for PHEVs can be designed in a way that both node-level decisions (e.g., the number of charging spots, battery capacity, and interactions of electricity between sources of energy) and network-level decisions (e.g., location of charging stations and allocation of demand between charging stations and demand nodes) can be considered in an integrated method. In this problem, sustainability drivers with their conflicting goals (i.e., social, environmental and economic drivers) should be considered as the considered goals for the designed network. In this problem, not only the power grid is considered as a complimentary source of energy, but also the renewable sources of energy (i.e., wind power and solar power) are considered as the primary sources of energy.

In order to tackle the aforementioned problem statement, the following word formulation is proposed for the compromise Decisions Support Problem (i.e., Step 4 of the MLIN method).

The word formulation, same as is shown in Table 3-2, has four parts such as given, find, satisfy and minimize; the word formulation for the aforementioned problem statement is presented as follows.

Given

All input parameters include:

Demand of PHEVs

Generated electricity at wind farms and by photovoltaic cells

Price of electricity and renewable sources of energy

Storage efficiency and rate of charge and discharge of batteries

Environmental loads from charging infrastructures and electricity generation

Weight parameters and the target values of goals

Find

Number of charging spots at charging stations

Battery capacity

Trade-off electricity between sources of energy and charging stations

Deviation variables

Satisfy

Constraints

The stored electricity in the battery (see Equation 3-1 in Section 3.9)

Charging and discharging rates of batteries (see Equations 3-2, 3-3 in Section 3.9)

Available electricity by wind farms or photovoltaic cells at each period of time (see Equations 3-4, 3-5, 3-6 in Section 3.9)

Demand constraint (see Equations 3-7, 3-8 in Section 3.9)

Binary and non-negativity constraints (see Equations 3-12 to 3-14 in Section 3.9)

Goals

Goal 1: minimized the total cost (see Equation 3-9 in Section 3.9)

Goal 2: minimized the total gas emission (see Equation 3-10 in Section 3.9)

Goal 3: maximized the service level (see Equation 3-11 in Section 3.9)

Minimize

Minimize the deviation function (see Equations 5-15, 5-16 in Section 3.9)

In this section, the problem statement for designing a bi-level network of the electric charging stations for plug-in hybrid electric vehicles is presented. Then, the problem statement is followed by the word formulation. In the next section, the mathematical formulation for the presented problem statement and word formulation in this section is presented.

3.9 DRIVATING THE MATHEMATICAL FORMULATION FOR DESIGNING A BI-LEVEL NETWORK OF PHEV CHARGING STATIONS

As is shown in Figure 3-3, the forth step of the MLSN method is on modeling the integrated node-level and network-level decisions using the cDSP. In Step (*4*) of the proposed method, minimizing the strategic and operational cost (economic driver), minimizing gas emissions by charging infrastructures and fuel sources for generating electricity (environmental driver), and maximizing the service level (social driver) are three considered goals in the mathematical model. The mathematical model is formulated using the compromise Decision Support Problem (cDSP) construct in order to consider conflicts among sustainability drivers (Mistree and co-authors, 1993). Both the simulation and surrogate models are inputs for the mathematical model for Goal 3 (i.e., maximizing the service level defined based on the percentage of the met demand). The mathematical formulation is derived using the word formulation presented in Section 3.8.

Given (Input Parameters)

All input data and parameters are listed as follows.

D_t: PHEV demand at period t

h_t: Generated wind at wind farm(s) (potential wind power for utilization) at period t

k_t: Generated solar power by photovoltaic cells (potential solar power for utilization) at period t

c^+_t: The price of buying energy from the power grid at period t

c^-_t: The price of selling energy to the power grid at period t

E^{prod}: Environmental load from the production phase of charging infrastructure

E^{inst}: Environmental load from the installation phase of charging infrastructure

E^{elec}: Environmental load from electricity generation in the power grid

e^{bat}: Storage efficiency of the battery

e^{char}: Charging/discharging efficiency rate of the battery

cr: Rate of charging the battery

dr: Rate of discharging the battery

c^{stand}: Cost of each charging stand at a charging station

c^{bat}: Cost of battery (per module) at a charging station

G_k: Goal k (Aspiration level k)

w_k: weight parameter k

Find (Variables)

Strategic Decisions

X: Number of charging spots at a charging station i

Y: Capacity of the battery (battery size) at charging station i

Operational Decisions

M^+_t: Electricity bought from the grid at period t

M^-_t: Electricity sold back to the grid at period t

N_t: Electricity from wind farm(s) at period t

O_t: Electricity from photovoltaic cells at period t

R_t: Satisfied demand of PHEVs (met demand of PHEVs or sold electricity to PHEVs) at period t

Q_t: Stored electricity in the battery (battery level) at period t

Satisfy (Constraints)

Solar power, wind power and power grid are three sources of electricity (input electricity into the battery storage) for a PHEV station. Electricity may be sold back to the power grid, used to meet the PHEV demand or stored in the battery at each period of time. The level of stored electricity at period t is shown in Equation 3-1.

$$\mathrm{Q_t = e^{Bat}.Q_{t-1} + M_t^{+} + N_t + O_t - (R_t + M_t^{-})} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}1)$$

The storage efficiency of the battery is shown in Equation 3-1. In addition to the storage efficiency of the battery, charging and discharging rates are considered in the proposed model, Equations 3-2 and 3-3. The charging rate of the battery from three sources of energy and the discharging rate of the battery to the power grid and PHEVs are shown in Equations 3-2 and 3-3, respectively. The waste of energy through charging and discharging the battery is considered using the variable $\mathrm{e^{char}}$.

$$\mathrm{M_t^{+} + N_t + O_t \leq e^{char}.cr} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}2)$$

$$\mathrm{M_t^{-} + R_t \leq e^{char}.dr} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}3)$$

These two constraints are related to the maximum capacity of wind and solar power, respectively. The potential for utilizing electricity from wind farms is shown in Equation 3-4, and the potential for utilizing electricity from photovoltaic cells is shown in Equation 3-5.

$$\mathrm{N_t \leq h_t} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}4)$$

$$\mathrm{O_t \leq k_t} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}5)$$

The capacity of the battery storage is shown in Equation 3-6, and the fulfillment of the PHEV demand is considered in Equation 3-7. The electricity pulled out from the battery for fulfillment of the PHEV demand is flowing through charging spots shown in Equation 3-8.

$$\mathrm{Q_t \leq Y} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}6)$$

$$\mathrm{R_t \leq D_t} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}7)$$

$$R_t = X.\,dr^{stand} \qquad \forall t \in T \qquad (3\text{-}8)$$

Satisfy (Goals)

The three goals for designing a sustainable charging station are shown through Equations 3-9 to 3-11. Two deviation variables are defined (d^+_k, d^-_k) for each goal; the deviation of the actual value of goals from the target goal values set by system designers or policy makers (more explanation on setting values is presented in Section 4) are shown by the deviation variables. Overachievement of the goal is shown with d^+_k shows and d^-_k is underachievement of the goal. In Equation 3-9, for example, G_1 is a parameter in the model that shows the target value for goal 1 which can be set by policy makers or system designers. The actual value of goal 1 is $(c+_t M^+_t - c+_t M^+_t) + c^{stand}X + c^{bat}Y$. Deviation of the actual value from the target goal value is shown by $(d^-_1 – d^+_1)$. The interest is to minimize the deviation between the actual and goal values. The projected service level model is shown in Equation 3-11 where a_0 is the intercept and a_m is the regression parameter. In this formulation, $h_m(X, D_t)$ is a set of basis functions that are dependent of the number of charging spots (X) and PHEV demand (Cagliano and co-authors).

$$G_1 = \sum_t (c_t^+ M_t^+ - c_t^- M_t^-) + c^{stand}X + c^{bat}Y + d_1^- - d_1^+ \qquad \forall t \in T \qquad (3\text{-}9)$$

$$G_2 = \left(E^{prod} + E^{inst}\right).\,(X + Y) + E^{elec}\, M_t^+ + d_2^- - d_2^+ \qquad \forall t \in T \qquad (3\text{-}10)$$

$$G_3 = a_0 + \sum\nolimits_{i \in I} a_m h_m(X, D_t) + d_3^+ - d_3^- \qquad \forall t \in T \qquad (3\text{-}11)$$

The following are constraints (Equations 3-12 to 3-14) for non-negativity and binary variables

$$X, Y \in \{1,0\} \qquad (3\text{-}12)$$

$M_t^+, M_t^-, N_t, O_t, R_t, Q_t \geq 0 \qquad \forall t \in T \qquad (3\text{-}13)$

$d_t^+ . d_t^- = 0, \quad d_t^+, d_t^- \geq 0 \qquad \forall t \in T \qquad (3\text{-}14)$

In Equation 3-14 it is shows that only one of deviation variables may take a non-zero value since the actual value of each goal can be lower, upper or equal to the goal target value.

Minimize

Minimize the deviation function is a measure showing the deviation of the system performance from that implied by the set of goals and their associated relative weights. The deviation function and its associated weights are shown in Equations 3-15 to 3-16.

Minimize $w_1(d_1^+ + d_1^-) + w_2(d_2^+ + d_2^-) + w_3(d_3^+ + d_3^-) \qquad (3\text{-}15)$

$w_1 + w_2 + w_3 = 1 \qquad (3\text{-}16)$

In this section, the derivation of the mathematical formulation is presented based on the problem statement and word formulation in Section 3.8. In next section, the mathematical formulation is presented.

3.10 MATHEMATICAL FORMULATION FOR DESIGNING A BI-LEVEL NETWORK OF PHEV CHARGING STATIONS

As is shown in Figure 3-3, the forth step of the MLIN method is on modeling the integrated node-level and network-level decisions using the cDSP. In Step (*4*) of the proposed method, minimizing the strategic and operational cost (economic driver), minimizing gas emissions by charging infrastructures and fuel sources for generating electricity (environmental driver) and maximizing the service level (social driver) are three considered goals in the mathematical model. The mathematical model is formulated using the compromise Decision Support Problem (cDSP) construct in order to consider conflicts among sustainability drivers (Mistree and co-authors, 1993). Both the simulation model and surrogate model are inputs for the mathematical model as goal 3 (i.e., maximizing the service level defined based on the percentage of the met demand). The word formulation of the mathematical model is presented in Section 3.8, and the detail of the mathematical formulation is as follows.

Given (Input Parameters)

All input data and parameters are listed as follows.

D_t: PHEV demand at period t

h_t: Generated wind at wind farm(s) (potential wind power for utilization) at period t

k_t: Generated solar power by photovoltaic cells (potential solar power for utilization) at period t

c^+_t: The price of buying energy from the power grid at period t

c^-_t: The price of selling energy to the power grid at period t

E^{prod}: Environmental load from the production phase of charging infrastructure

E^{inst}: Environmental load from the installation phase of charging infrastructure

E^{elec}: Environmental load from electricity generation in the power grid

e^{bat}: Storage efficiency of the battery

e^{char}: Charging/discharging efficiency rate of the battery

cr: Rate of charging the battery

dr: Rate of discharging the battery

c^{stand}: Cost of each charging stand at a charging station

c^{bat}: Cost of battery (per module) at a charging station

G_k: Goal k (Aspiration level *k*)

w_k: weight parameter *k*

Find (Variables)

Strategic Decisions

X: Number of charging spots at a charging station *i*

Y: Capacity of the battery (battery size) at charging station *i*

Operational Decisions

M^+_t: Electricity bought from the grid at period *t*

M^-_t: Electricity sold back to the grid at period *t*

N_t: Electricity from wind farm(s) at period *t*

O_t: Electricity from photovoltaic cells at period *t*

R_t: Satisfied demand of PHEVs (met demand of PHEVs or sold electricity to PHEVs) at period *t*

Q_t: Stored electricity in the battery (battery level) at period *t*

Satisfy (Constraints)

$$\mathrm{Q_t = e^{Bat}.Q_{t-1} + M_t^+ + N_t + O_t - (R_t + M_t^-)} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}1)$$

$$\mathrm{M_t^+ + N_t + O_t \leq e^{char}.cr} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}2)$$

$$\mathrm{M_t^- + R_t \leq e^{char}.dr} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}3)$$

$$\mathrm{N_t \leq h_t} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}4)$$

$$\mathrm{O_t \leq k_t} \qquad \forall \mathrm{t} \in \mathrm{T} \qquad (3\text{-}5)$$

$$Q_t \leq Y \qquad \forall t \in T \tag{3-6}$$

$$R_t \leq D_t \qquad \forall t \in T \tag{3-7}$$

$$R_t = X.\mathrm{dr}^{\mathrm{stand}} \qquad \forall t \in T \tag{3-8}$$

Satisfy (Goals)

$$G_1 = \sum_t (c_t^+ M_t^+ - c_t^- M_t^-) + c^{\mathrm{stand}} X + c^{\mathrm{bat}} Y + d_1^- - d_1^+ \qquad \forall t \in T \tag{3-9}$$

$$G_2 = \left(E^{\mathrm{prod}} + E^{\mathrm{inst}}\right).(X + Y) + E^{\mathrm{elec}}\, M_t^+ + d_2^- - d_2^+ \qquad \forall t \in T \tag{3-10}$$

$$G_3 = a_0 + \sum_{i \in I} a_m h_m(X, D_t) + d_3^+ - d_3^- \qquad \forall t \in T \tag{3-11}$$

$$X, Y \in \{1,0\} \tag{3-12}$$

$$M_t^+, M_t^-, N_t, O_t, R_t, Q_t \geq 0 \qquad \forall t \in T \tag{3-13}$$

$$d_t^+ . d_t^- = 0, \qquad d_t^+, d_t^- \geq 0 \qquad \forall t \in T \tag{3-14}$$

Minimize

$$\text{Minimize } w_1(d_1^+ + d_1^-) + w_2(d_2^+ + d_2^-) + w_3(d_3^+ + d_3^-) \tag{3-15}$$

$$w_1 + w_2 + w_3 = 1 \tag{3-16}$$

In this section, the mathematical formulation is presented based on the problem statement and word formulation in Section 3.8. In the next section, both the theoretical structural validation (Quadrant 1) and empirical structural validation (Quadrant 2) are presented.

3.11 THEORETICAL AND EMPIRICAL STRUCTURAL VALIDATION OF THE MLIN

In this section, the theoretical structural validation and the empirical structural validation of the MLIN is checked (see Figure 3-5). The MLIN method is explained in detail through Sections 3.3 - 3.6. In this section, the theoretical structural validation of the MLIN is checked via exploring the advantages, disadvantages, and limitations of the method. Then the empirical structural validation of the MLIN is checked through performing two sensitivity analysis of the proposed cDSP in the MLIN method.

From a theoretical perspective, it is possible to establish the internal consistency of a method and identify explicitly the favorable and unfavorable properties of the method for particular application domains. The theoretical advantages and limitations of the MLIN method are summarized in Table 3-3, organized according to the research hypothesis.

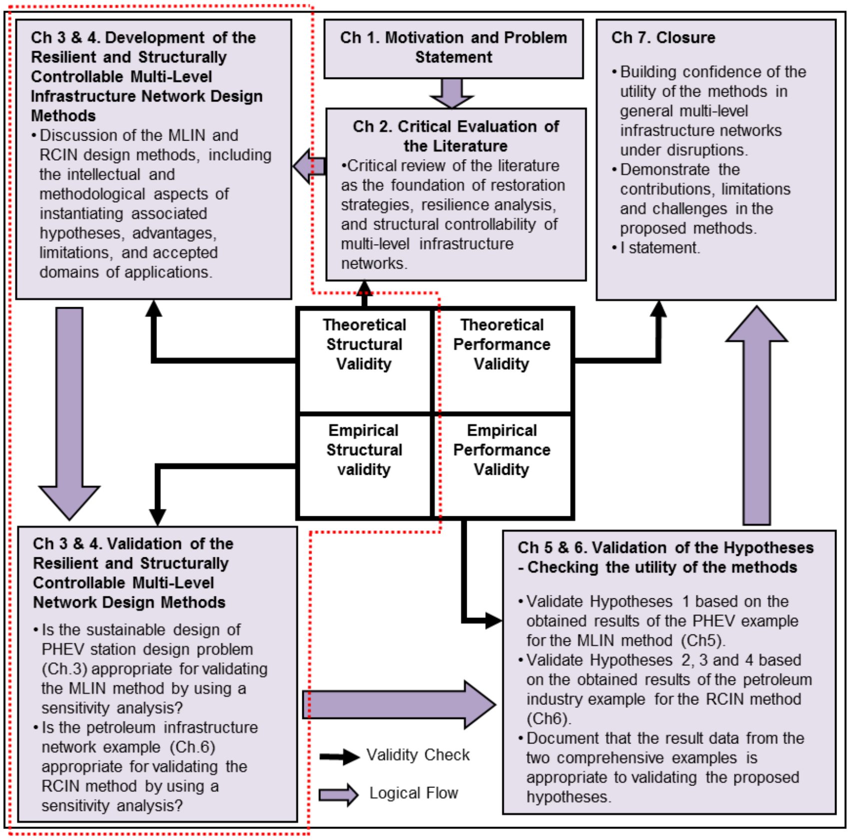


Figure 3-5 Validation strategy of the dissertation

As is listed in Table 3-3, in the proposed integrated MLIN method for designing bi-level networks both node and network levels is considered. Since the compromise Decision Support

Problem is used in MLIN, conflicts among system goals can be considered. Different design weights for the system goals result in having different design solution. Therefore, exploration of the solution space is essential in designing a system with conflicting system goal. Exploration of the solution space is considered in the proposed method (see Section 5.6.3). The stochastic behavior of entities or operations in nodes can be stimulated using the simulation models. This is a feasible way in order to consider the stochastic behaviors or probability functions in nodes. However, using the simulation models for various scenarios is costly. Using the surrogate models can help in order to approximate it with mathematical models.

Table 3-3 Theoretical capabilities and limitations MLIN

Capabilities and Advantages
• Consider both operational and strategic decisions in designing networks • Consider both network-level and node-level decisions in designing networks • Formulate the stochastic behavior of operations or entities in the node-level using the simulation model • Decrease the computational cost because of using the surrogate modeling for approximating mathematical models instead of running simulation models frequently • Consider conflicts among system goals because of using the compromise DSP
Limitations and Disadvantages
• Uncertainties and stochastic parameters are not considered in the MLIN method. • The robust design is not considered in the MLIN method. • The MLIN can be utilized for more than two levels. However, in this dissertation, The MLIN method is explained in Chapter 3 and solved with an example in Chapter 5 for only two levels (node-level and network-level).

On the other hand, uncertainty is not considered in the mathematical model formulated with the compromise DSP. Consequently, the robust design is not applied in the mathematical model. Although the proposed MLIN method can be easily applied for hierarchical structures with more than two levels, in Chapter 5, it is solve for a network with two levels.

Empirical studies are required to establish the usefulness and effectiveness of the method. A strategy for empirical validation of the method is provided by analyzing the MLIN methods when the demand parameter is changing. This sensitivity analysis can help in the empirical validation of this dissertation regarding the MLIN method.

The following sensitivity analysis is based on changing the demand parameter in the proposed cDSP (see Section 3.7 for the model and Section 5.3 for the input parameters). The effect of increase in the demand of PHEVs on charging station design is analyzed and shown in Figure 3-6. As is shown in Figure 3-6, 10% increase in the PHEV demand causes a 4% decrease in the service level and reach to 76%, and if the PHEV demand increases to 60%, the service level will decrease by 18% if the number of charging spots remains same.

In Figure 3-7, for the fixed level of service at charging stations, the impact of increasing the PHEV demand on the number of required charging spots is illustrated. As shown in Figure 3-7, in order to have 80% service level at PHEV stations, the number of required charging spots is calculated while the PHEV demand increases.

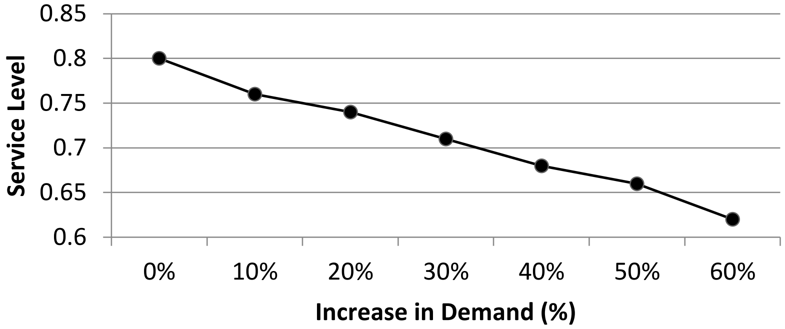


Figure 3-6 Comparison between the service level and increasing the demand with a fixed number of charging spots

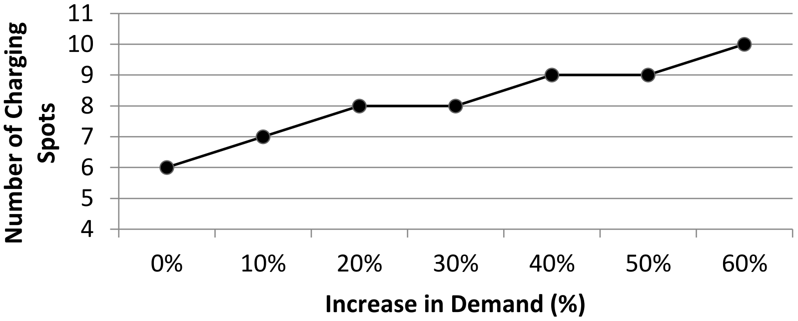


Figure 3-7 Comparison between the number of charging spots and increasing the demand with the fixed level of service

PHEVs are bridging vehicles between combustion vehicles and pure electric vehicles. Each year more citizens are buying PHEVs. According to the results presented in Figures 3-6 and 3-7, increases in the PHEV demand causes decreases in service level. Therefore, keeping the same or greater level of service over a long planning horizon can be achieved by both installing more charging spots in the located stations and locating more charging stations in each region.

Based on the presented sensitivity analysis in this section, the usefulness and effectiveness of the proposed MLIN method is demonstrated.

3.12 CHAPTER SYNOPSIS

In this chapter, detail of the multi-level infrastructure network (MLIN) method is addressed. The MLIN method is tailored and explained for a bi-level infrastructure network as an example of a multi-level structure in this chapter. As is shown in Figure 3-1, the MLIN method, its characteristics, limitations and applicability are addressed in this chapter. In Section 3.1, the problem statement for the multi-level infrastructure networks is presented and followed by the related requirement list and research question. In Section 3.2, an overview of the general structure for designing multi-level infrastructure networks is presented. In Section 3.3, the multi-level infrastructure network method (MLIN) in the context of the bi-level structure is proposed and the overall procedure of it is explained. In Sections 3.4 to 3.7, the steps of the MLIN method are explained in detail for a bi-level structure. In Section 3.8, an introduction of an example of the PHEV charging stations, the problem statement, and its word formulation are presented. Consequently, the mathematical formulation for the proposed problem statement is presented in Section 3.10. Finally, the internal consistency of the MLIN method is evaluated with identifying explicitly its favorable and unfavorable properties in Section 3.11.

In the next chapter, another aspect of the resilient and structurally controllable multi-level infrastructure networks is presented and explained as the RCIN method for managing disruptions in infrastructure networks.

CHAPTER 4 A METHOD FOR DESIGNING A RESILIENT AND STRUCTURALLY CONTROLLABLE INFRASTRUCTURE NETWORK UNDER DISRUPTION

In this chapter, the resilient and structurally controllable infrastructure network (RCIN) method is proposed and explained. The RCIN method is in response to Research Questions 2, 3, and 4. The problem statement and an overview of the resilient and structurally controllable multi-level network design are presented in Sections 4.1 and 4.2. In Section 4.3, the proposed RCIN method is explained. In Sections 4.4 to 4.6, details of the proposed RCIN method through its three stages is explained and supported by the word and mathematical formulations. The internal consistency of the RCIN method is evaluated with identifying explicitly the favorable and unfavorable properties of the method in Section 4.7. Not only the theoretical structural validation (Quadrant 1 of the validation square) is considered, but also using a sensitivity analysis for method’s parameters the empirical structural validation (Quadrant 2 of the validation square) is performed in Section 4.7.

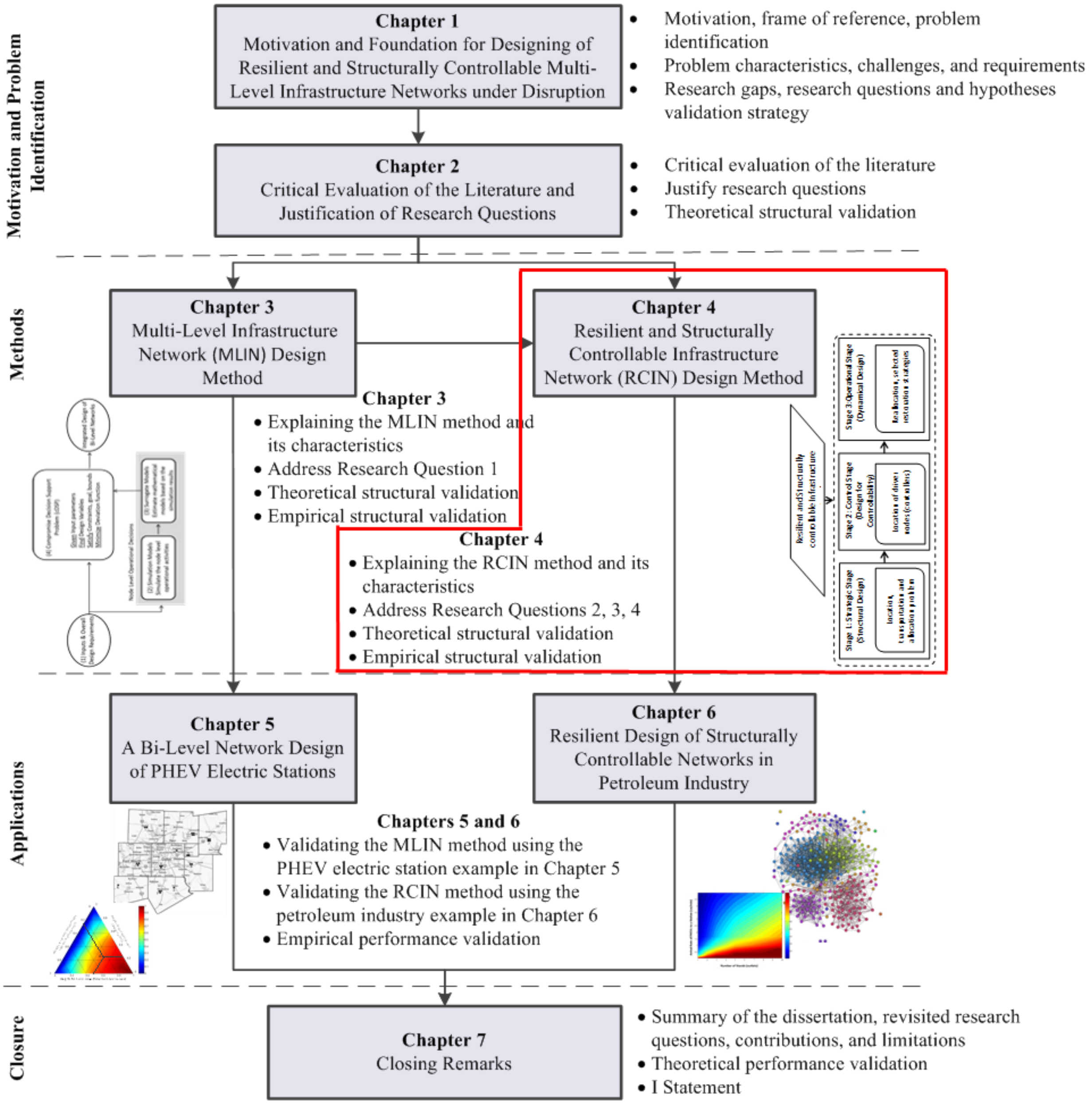


Figure 4-1 Dissertation structure

4.1 PROBLEM STATEMENT FOR MANAGING DISRUPTION IN INFRASTRUCTURE NETWORKS

Infrastructure network design involves determining the network structure and the distribution of resources over the structure while disruptions happen. In other words, disruptions are a fact of life, the larger an infrastructure network, the more difficult it is to cope with disruptions. In a multi-layer infrastructure network, disruptions can occur at any of facilities (nodes) or transportation routes (links). In order to manage disruptions, mitigate risk of disruptions, recover the system after occurrence of disruptive events, and protect the customer service level, designing resilient infrastructure networks is essential. Applying structural controllability is an approach to manage risk of disruptions and increase the resilience of infrastructure networks. Using the structural controllability means to identify driver nodes in infrastructure networks that from which all facilities are accessible.

In this chapter, *the problem of designing resilient infrastructure networks while structural disruptions happen is introduced. In this problem, structural controllability and restorations strategies are developed in order to manage the risk of disruptions with having controllability through driver nodes all over the infrastructure network structure. In other words, it is considered that how one can select the most effective (e.g., highest service level or lowest recovery time, transportation time or tardiness) and least redundant (e.g., least operational, strategic and control costs) pre-disruption and post-disruption restoration strategies, number and locations of driver nodes (see Sections 4.5 and 4.6 to know about driver nodes) in the face of disruption scenarios.*

In Section 4.3, the limitations and boundary of the considered problem are addressed in the context of the proposed RCIN method. In Table 4-1, which is a part of Table 1-3, the requirements for the addressed problem are shown and connected with the research questions, research hypotheses and outcomes.

Table 4-1 Connection between the problem, requirement, research question, and outcome

Aspect	Requirement	Research Questions	Research Hypotheses	Contributions
Restoration strategies	Selecting the appropriate pre-disruption and post-disruption restoration strategies for recovering a disrupted infrastructure network.	RQ2: What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?	Implement a method to select appropriate restoration strategies for possible occurrence of disruptions considering is dependent on anticipation, preparedness, adaptability, and recovery phases.	RCIN method with considering pre-disruption (e.g., fortification and back –up inventory) and post-disruption (e.g., reconfiguration, flexible inventory and production capacity) restoration strategies.
Resilience analysis	Quantitative measures which can represent the resilience of a recovered network after a disruptive event while considering the trade-off between redundancy and effectiveness.	RQ3: What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?	Implement a method that includes measures for analyzing resilience of disrupted networks while addressing redundancy and effectiveness.	RCIN method with considering effectiveness measures (e.g., tardiness, service level, and recovery time) and redundancy measure (e.g., control cost) as resilience analysis measures.
Structural controllability	Determining the location and minimum number of driver nodes to make networks structurally controllable	RQ4: What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?	Implement a method occupied with maximum matching and minimum input theorem to find the minimum number of driver nodes to control a disrupted network in order to increase the resilience.	RCIN method with considering location and minimum number of driver nodes in a disrupted network in order to restore the network by applying restoration strategies.

As is shown in Table 4-1, Research Questions 2, 3, and 4 are answered using the proposed RCIN method. The connection between the two aspects of designing resilient and controllable infrastructure networks, and two proposed methods are explained in the following section.

4.2 OVERVIEW OF THE RESILIENT AND STRUCTURALLY CONTROLLABLE INFRASTRUCTURE NETWORK METHOD

The main objective in this dissertation is the development of methods for the resilient and structurally controllable design of multi-level infrastructure networks with consideration of occurrence of disruptions. Two aspects are considered in this regard: (1) multi-level infrastructure network design aspect, and (2) disruption management aspect. In Figure 4-2, both of these two aspects are shown. As is shown in the right side of Figure 4-2, managing disruptions has two parts: one is the structural controllability of infrastructure networks that is related to the location and number of driver nodes (i.e., controllers), and the other one is the resilient of restoration strategies which is related to recovering disrupted infrastructure networks using various restoration strategies.

In this chapter, the disruption management aspect is considered and the proposed resilient and structurally controllable infrastructure network (RCIN) method is explained. In Section 4.1, the problem statement is presented, and in the next section, the problem statement is expanded in the context of the RCIN method and its limitations and boundaries are explained. The word and mathematical formulations are presented in this chapter, and then the RCIN method is exercised using an example of the petroleum industry network in Chapter 6.

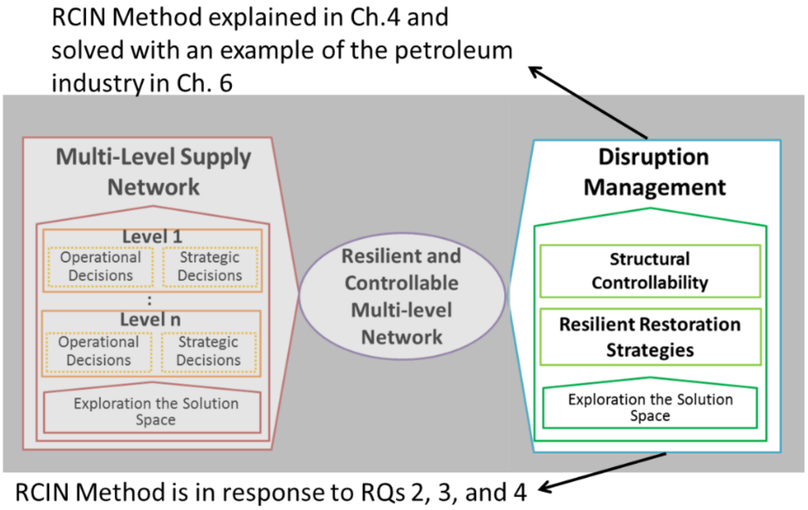


Figure 4-2 Resilient and structural controllability of a multi-level network

4.3 THE RCIN METHOD AND ITS ASSUMPTIONS AND LIMITATIONS

4.3.1 Assumptions and Limitations of the Problem Statement

In a multi-layer infrastructure network, disruptions can occur at facilities (nodes) or transportation routes (links). Occurrence of disruptions is considered as disruption scenarios in the method. Resilience strategies are defined for managing disruptions, mitigating risk of disruptions, recovering the system after occurrence of disruptive events, and protecting the customer service level. Applying the structural controllability is an approach to manage risk of disruptions, and the proposed resilience strategies are defined based on the structural controllability. Using the structural controllability means to identify driver nodes in infrastructure networks from which all facilities are accessible. In the proposed RCIN method, a driver node is fortified against disruptions and is equipped with restoration strategies. When disruptions happen, because of using driver nodes, and hence having access to all other facilities, the impact of disruptive events can be decreased tremendously. Making an infrastructure network controllable may need adding extra transportation arcs (links) that increase the redundancy and cost. Having fewer numbers of driver nodes means having the higher numbers of auxiliary transportation arcs, and having higher numbers of driver nodes means less number of auxiliary transportation arcs. Therefore, the tradeoff among numbers of driver nodes and redundant transportation arcs (links) is important to be considered in the proposed RCIN. The proposed RCIN method includes three stages; before explaining the three stages of the RCIN, the considered assumptions for the problem statement (see Section 4.1 for the problem statement) are explained as follows.

As is shown in Figure 4-3, only the forward infrastructure network is considered in this method. In the proposed method, distinct transportation arcs (links) between layers are considered. It is assumed that the transportation time between layers and production time are not zero. In other words, the transportation time between layers, production time in production facilities, and the expected inventory time in warehouses are considered. The structure of the considered infrastructure network is shown in Figure 4-3.

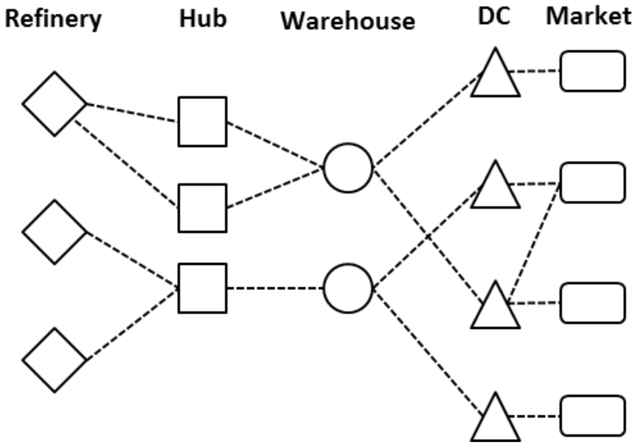


Figure 4-3 Petroleum infrastructure network structure

Petroleum components are produced in refineries from crude oil through the distillation and refining processes. In hubs, the petroleum products are produced from the petroleum components. Warehouses may store (if necessary) products and ship them to distribution centers. The function of distribution centers (DC) is to distribute the products to markets; no time activity is considered for DCs.

Each set of simultaneous disrupted facilities is called a disruption scenario and is associated with a finite probability of occurrence. Each disruption scenario occurs independently. Two types of states in the system are considered: steady state when no disruption happens and disrupted state when a disruption(s) happens in the network. It is assumed that after occurrence of a disruption, the network returns to its prior steady state before another disruption scenario occurs. In Figure 4-4, a possible disruption is shown. As is shown in Figure 4-4, a disruption happens in a warehouse in the third layer, and products cannot be shipped from the disrupted warehouse to DCs.

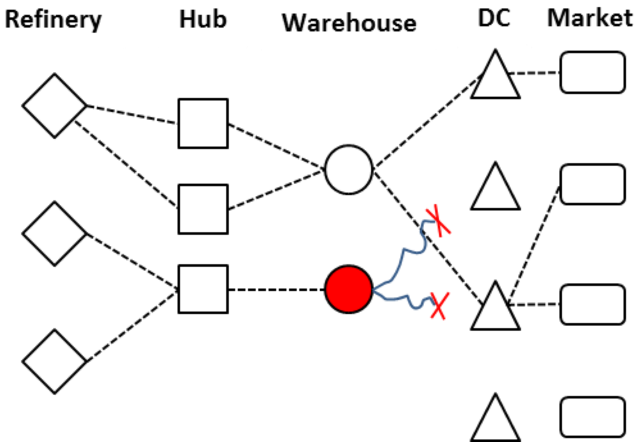


Figure 4-4 A possible disruption in the petroleum infrastructure network structure

In order to manage and mitigate risk of disruptions, resilience strategies are considered in the proposed RCIN method: (1) flexible production capacity for disrupted refineries and hubs, (2) flexible inventory capacity for disrupted warehouses, and (3) back-up inventory for disrupted distribution centers. The overall view of the proposed RCIN method includes three stages is presented, and then each stage is explained in detail through Sections 4.4 to 4.6.

4.3.2 Overall View of the RCIN Method

Designing infrastructure networks involves determining the network configuration and the distribution of resources over the network. Basically, designing infrastructure networks includes two types of decisions: first, decisions on the location and capacity of facilities and connections between facilities (strategic decisions); and, second, assigning the demand to available facilities and identifying production planning along the network (operational decisions).

In addition, designing infrastructure networks requires resilience as ‘the ability of a system to return to its original state or move to a new, more desirable state after being disturbed’. Using structural controllability as a feasible and convincing approach to mitigate risk of disruptive events in infrastructure networks (control decisions) is proposed in this dissertation. Considering these three aspects of decisions, such as the strategic decisions, control decisions, and operational decisions, the proposed three-stage method for designing resilient and structurally controllable infrastructure networks (RCIN) is shown in Figure 4-5.

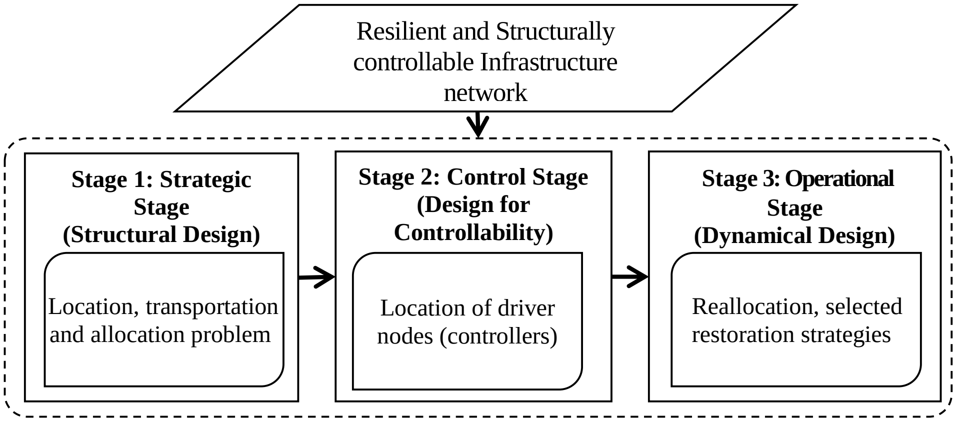


Figure 4-5 Three-stage method for resilient and structurally controllable infrastructure network design

As is shown in Figure 4-5, the proposed RCIN method includes three stages, such as the strategic stage, control stage, and operational stage. Each of these stages is explained with detail in the following sections.

4.4 STAGE 1 OF THE RCIN METHOD: STRATEGIC STAGE DECISIONS

In order to explain the mathematical model in the RCIN method in detail, a five-layer infrastructure network, as is shown in Figure 4-3, is considered. Refineries, hubs, warehouses, distribution centers and markets are the five layers of the infrastructure network, respectively. Although in this section, the RCIN method is developed for an oil petroleum infrastructure network with five layers, expanding or shrinking the network with more or less number of layers with even different functions for facilities can be implemented. The word formulation for the first stage of the RCIN method is developed based on the compromise Decisions Support Problem (cDSP) as follows.

4.4.1 The Word Formulation

The word formulation for Stage 1 is developed based on the problem statement presented in Section 4.1 as follows.

Given

All input parameters include:

Demand of products at markets
Number of components required for each product
Maximum allowed time for delivering demanded products to markets
Transportation time
Production time
Capacity of facilities
Production cost
Weight for goals

Find

Flow variables: amount of products flow between facilities
Transportation decisions
Opening and closing variables of facilities
Deviation variables

Satisfy

Constraints

Demand constraint (see Equation 4-1)
Network flow constraint (see Equations 4-2 to 4-4)
Capacity constraints (see Equations 4-5 to 4-8)
Structural and arc constraints (see Equations 4-9 to 4-14)
Deviation constraint (see Equation 4-15)

Goals

Goal one as minimized the total tardiness for all the markets (see Equation 4-16)
Goal two as minimized the total fixed and variable costs associated with operating the network (see Equation 4-17)
Goal three as the maximized total service level at markets (see Equation 4-18)

Minimize

Minimize the deviation function (see Equation 4-19, 4-20)

For the proposed word formulation, the mathematical formulation is developed and presented as follows.

4.4.2 The Mathematical Formulation

The mathematical formulation is developed based on the problem statement (see Section 4.1) and word formulation (see Section 4.4). In addition, the mathematical formulation is developed based on the compromise Decisions Support Problem (cDSP) construct includes of four parts such as *Given*, *Find*, *Satisfy*, and *Minimize*.

Given

Indices

$i \in I$: set of potential locations for refineries

$j \in J$: set of potential locations for hubs

$k \in K$: set of potential location for warehouses

$l \in L$: set of potential locations for distribution centers

$m \in M$: set of markets

$p \in P$: set of products

$q \in Q$: set of components used in different products

$h \in H$: set of transportation modes (truck, train, ship, etc.) between facility layers

Parameters

D_{pm}: demand of product *p* at market *m*

β_{qp}: number of component *q* is required for product *p*

τ: the maximum allowed time for delivering demanded products at markets

t_{ij}^{h}: transportation time between refinery *i* and hub *j* with transportation mode *h*

t_{jk}^{h} transportation time between hub *j* and warehouse *k* with transportation mode *h*

t_{kl}^{h}: transportation time between warehouse *k* and distribution center *l* with transportation mode *h*

t_{lm}^{h}: transportation time between distribution center *l* and market *m* with transportation mode *h*

t_{pj}: time required for producing product p in hub j

t_{qi}: time required for blending component q in refinery i

t_k: the average time a product can be stored in warehouse k

$capr_i$: capacity of refinery *i*

$caph_j$: capacity of hub *j*

$capw_k$: capacity of warehouse *k*

$capd_l$: capacity of distribution center *l*

c_{qi}: cost of blending component *q* at refinery *i*

c_{pj}: cost of producing product *p* at hub *j*

c_i: fixed cost of opening a refinery in candidate location *i*

c_i: fixed cost of opening a hub in candidate location *j*

c_k: fixed cost of opening a warehouse in candidate location *k*

c_l: fixed cost of opening a distribution center in candidate location *l*

w_1, w_2, w_3: weight for goals one to three, respectively (>=0)

Find

Continuous Variables

X_{ij}^{ph}: amount of product *p* flows from refinery *i* to hub *j* using transportation mode *h*

Y_{jk}^{ph}: amount of product *p* flows from hub *j* to warehouse *k* using transportation mode *h*

W_{kl}^{ph}: amount of product *p* flows from warehouse *k* to distribution center *l* using transportation mode *h*

V_{lm}^{ph}: amount of product *p* flows from distribution center *l* to market *m* using transportation mode *h*

d^+_1, d^-_1: the deviation of the actual value of goal one (tardiness) from the target goal value

d^+_2, d^-_2: the deviation of the actual value of goal two (cost) from the target goal value

d^+_3, d^-_3: the deviation of the actual value of goal three (service level) from the target goal value

Structural Variables

μ_{ij}: binary variable equal to 1 if there is a transportation arc between refinery *i* and hub *j* and 0 otherwise

γ_{jk}: binary variable equal to 1 if there is a transportation arc between hub *j* and warehouse *k* and 0 otherwise

β_{kl}: binary variable equal to 1 if there is a transportation arc between warehouse *k* and distribution center *l* and 0 otherwise

α_{lm}: binary variable equal to 1 if there is a transportation arc between distribution center *l* and market *m* and 0 otherwise

U_i: binary variable equal to 1 if a refinery is opened at location *i* and 0 otherwise

O_j: binary variable equal to 1 if a hub is opened at location *j* and 0 otherwise

G_k: binary variable equal to 1 if a warehouse is opened at location *k* and 0 otherwise

F_l: binary variable equal to 1 if a distribution center is opened at location *l* and 0 otherwise

Satisfy (Constraints)

$$\sum_{l=1}^{L}\sum_{h=1}^{H} V_{lm}^{ph} \le D_{pm} \qquad \forall m \in M, p \in P \qquad (4\text{-}1)$$

$$\sum_{k=1}^{K}\sum_{h=1}^{H} W_{kl}^{ph} = \sum_{m=1}^{M}\sum_{h=1}^{H} V_{lm}^{ph} \qquad \forall l \in L, p \in P \qquad (4\text{-}2)$$

$$\sum_{j=1}^{J}\sum_{h=1}^{H} Y_{jk}^{ph} = \sum_{l=1}^{L}\sum_{h=1}^{H} W_{kl}^{ph} \qquad \forall k \in K, p \in P \qquad (4\text{-}3)$$

$$\sum_{i=1}^{I}\sum_{h=1}^{H} X_{ij}^{ph} = \sum_{k=1}^{K}\sum_{h=1}^{H} Y_{jk}^{ph} \qquad \forall j \in J, p \in P \tag{4-4}$$

$$\sum_{j=1}^{J}\sum_{h=1}^{H}\sum_{q=1}^{Q}\sum_{p=1}^{P} \beta_{qp}\, X_{ij}^{ph} \leq capr_i\, U_i \qquad \forall i \in I \tag{4-5}$$

$$\sum_{k=1}^{K}\sum_{h=1}^{H}\sum_{p=1}^{P} Y_{jk}^{ph} \leq caph_j\, O_j \qquad \forall j \in J \tag{4-6}$$

$$\sum_{l=1}^{L}\sum_{h=1}^{H}\sum_{p=1}^{P} W_{kl}^{ph} \leq capw_k\, G_k \qquad \forall k \in K \tag{4-7}$$

$$\sum_{m=1}^{M}\sum_{h=1}^{H}\sum_{p=1}^{P} V_{lm}^{ph} \leq capd_l\, F_l \qquad \forall l \in L \tag{4-8}$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} X_{ij}^{ph} \leq N\mu_{ij} \qquad \forall i \in I, j \in J \tag{4-9}$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} Y_{jk}^{ph} \leq N\gamma_{jk} \qquad \forall j \in J, c \tag{4-10}$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} W_{kl}^{ph} \leq N\beta_{kl} \qquad \forall k \in K, l \in L \tag{4-11}$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} V_{lm}^{ph} \leq N\alpha_{lm} \qquad \forall l \in L, m \in M \tag{4-12}$$

$$X_{ij}^{ph}, Y_{jk}^{ph}, W_{kl}^{ph}, V_{lm}^{ph} \geq 0 \qquad \forall i \in I, j \in J, k \in K, l \in L, m \in M, p \in P, h \in H \tag{4-13}$$

$$\mu_{ij}, \gamma_{jk}, \beta_{kl}, \alpha_{lm}, U_i, O_j, G_k, F_l \in \{0,1\} \qquad \forall i \in I, j \in J, k \in K, l \in L, m \in M \tag{4-14}$$

$$d_1^{+}.\, d_1^{-} = 0, d_2^{+}.\, d_2^{-} = 0, d_3^{+}.\, d_3^{-} = 0 \tag{4-15}$$

Satisfy (Goals)

$$G_1 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{h=1}^{H} \max\Big[\Big(\big(t_{qi}\,\beta_{qp}\, X_{ij}^{ph}\big) + \big(t_{pj}\, Y_{jk}^{ph}\big) + \big(t_k\, W_{kl}^{ph}\big) + \big(t_{ij}^{h}\, X_{ij}^{ph}\big) + \big(t_{jk}^{h} Y_{jk}^{ph}\big) + \big(t_{kl}^{h}\, W_{kl}^{ph}\big) + \big(t_{lm}^{h}\, V_{lm}^{ph}\big)\Big) - \tau V_{lm}^{ph}, 0\Big] + d_1^{-} - d_1^{+} \tag{4-16}$$

$$G_2 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{q=1}^{Q}\sum_{p=1}^{P}\sum_{h=1}^{H} c_{qi}\,\beta_{qp}\, X_{ij}^{ph} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{h=1}^{H} c_{pj}\, Y_{jk}^{ph} + \sum_{i=1}^{I} c_i U_i + \sum_{j=1}^{J} c_j O_j + \sum_{k=1}^{J} c_k G_k + \sum_{l=1}^{L} c_l F_l + d_2^{-} - d_2^{+} \tag{4-17}$$

$$G_3 = \sum_{m=1}^{M} \sum_{p=1}^{P} \sum_{l=1}^{L} \sum_{h=1}^{H} \frac{V_{lm}^{ph}}{D_{pm}} + d_3^+ - d_3^- \qquad (4\text{-}18)$$

Minimize

$$\text{Minimize } \mathrm{w}_1(\mathrm{d}_1^+ + \mathrm{d}_1^-) + \mathrm{w}_2(\mathrm{d}_2^+ + \mathrm{d}_2^-) + \mathrm{w}_3(\mathrm{d}_3^+ + \mathrm{d}_3^-) \qquad (4\text{-}19)$$

$$\mathrm{w}_1 + \mathrm{w}_2 + \mathrm{w}_3 = 1 \qquad (4\text{-}20)$$

After solving the proposed mathematical model in Stage 1, results will be the designed structure for the supply chain, such as the location of opened/located facilities in each layer, selected transportation arcs between layers, and selected transportation modes between layers. In addition, the required production capacity in refineries and hubs, the required inventory capacity in warehouses, and amount of the delivered products at markets can be achieved after solving the mathematical model in Stage 1. All these results are achieved while three goals, such as minimizing the tardiness, minimizing the fixed and variable cost, and maximizing the service level, are considered. In next section, the second stage of the proposed RCIN method is explained.

4.5 STAGE 2 OF THE RCIN METHOD: CONTROL STAGE DECISION

From Stage 1, the structure of the designed infrastructure network is specified. Designing the structure of the network to be structurally controllable is considered in this stage. Applying the structural controllability in networks is anchored in selecting driver nodes (i.e., driver nodes or control nodes). The main benefit of using structural controllability is in having accessibility to all markets from selected driver nodes. If a disruptive event happens in a layer of an infrastructure network, the driver node can provide support to the network through using flexible production capacity (in refineries or hubs) or flexible inventory capacity (in warehouses). Therefore, using structural controllability is considered as an approach to mitigate the risk of disruptions.

Since a multi-layer structure is usually considered in infrastructure networks (i.e., unlike general networks), the notion of structural controllability for different layers of infrastructure networks is developed. In addition, the fortification strategy is considered for driver nodes that fortify them against probable disruptions. Therefore, disruptions on driver nodes are not considered. In the following of this section, several algorithms are explained in order to demonstrate the way of sleeting driver nodes and making the structure, which is achieved from Stage 1, a controllable structure.

The concept of structural controllability is developed based on the Lin's Theorem. Based on Lin's Theorem, in order to find the minimum number of driver nodes in each layer of infrastructure networks, a cactus with the minimum number of drivers should be spanned. In order to span the minimum number of drivers in a cactus, the Minimum Input Theorem is applied in which the minimum number of driver nodes is equal to the minimum number of unmatched nodes. Therefore, the following steps should be followed to find the minimum number of driver nodes in each layer of the supply chain and make it structurally controllable:

(*a*) Find the structure of the considered infrastructure network and represent it as $G(A) = (V,E)$, where $V = \{v_1, v_2, \ldots, v_N\}$ as facilities (nodes) and E as the set of transportation arcs (links). This Stage can be done using the inputs from Stage 1 of the proposed

RCIN method. Binary variables regarding the location of facilities and transportation arcs demonstrate the structure of the supply chain from Stage 1.

(*b*) The second step is to make a bipartite network of a given G(*A*) = (*V*,*E*) structure. For a given G(*V*,*E*), a bipartite representation is a graph such as BP(*A*) = (V^+ and V^-,£).

In BP(*A*) = (V^+ and V^-,£):

V^+ is the set of *N* facilities (nodes) $V^+ = \{v^+_1, v^+_2, \ldots, v^+_N\}$

V^- is the set of *N* facilities (nodes) $V^- = \{v^-_1, v^-_2, \ldots, v^-_N\}$

£ is the set of transportation arcs (links) £ = $\left\{(v_i^+, v_j^-)\middle|(v_i, v_j) \in E\right\}$

Each transportation arc (link) of the bipartite representation of a supply chain always contains a plus node and a minus node.

(*c*) In this step, the maximum matching theory is applied to find unmatched nodes in the structure. For the given G(*A*) = (*V*,*E*) from Stage 1, and the given BP(*A*) from Stage 2-Step (*b*), a matching is a subset of transportation arcs (links) that no two arcs (links) share a common starting facility (node) or an ending facility (node). Otherwise, the arc is unmatched. A matching with the maximum number of matched facilities is the maximum matching.

Based on the Minimum Input Theorem, unmatched facilities in each layer are chosen as driver nodes.

(d) Since the structural controllability is considered in designing controllable structures, different number of driver nodes may be located in each layer. Size of the networks, cost of fortifying driver nodes, and cost of redundant transportation arcs are main criteria in specifying the number of required driver nodes in each layer. For the size of the considered infrastructure network in this example, one driver node per network layer is considered.

At the end of Stage 2, the output will be controllable structures for infrastructure networks in the way that all markets in the last layer are accessible from driver nodes. This structure and the values from Stage 1 are given as parameters to Stage 3. The purpose of Stage 3 is to have the final design of the infrastructure network from structural, control and operational decisions considering disruptions.

4.6 STAGE 3 OF THE RCIN METHOD: OPERATIONAL DECISIONS

Designing a resilient and controllable infrastructure network is the output of the proposed three-stage RCIN method. In Stage 1, the structure of an infrastructure network is designed, and in Stage 2, the controllable structure of the considered network is designed. In Stage 3, the dynamics of the network and remaining operational decisions are considered. Outputs of Stage 1 and Stage 2 are considered as the given part (parameters) in the proposed RCIN method. The word formulation for the operational and dynamical design of resilient and structurally controllable infrastructure network is presented as follows. Three goals are considered: (1) minimize the cost of controllability; in other words, the cost of determining driver odes, fortifying them, and restoration strategies, (2) minimize the deviation of the disrupted and recovered service levels, and (3) minimize the recovery time (i.e., the transportation time in the recovered network). The output of the RCIN method in Stage 3 is to determine the selected pre-disruption and post-disruption restoration strategies while considering the three aforementioned measures of the resilience analysis. The word formulation of Stage 3 is as follows.

4.6.1 The Word Formulation

The word formulation for Stage 3 is developed based on the problem statement presented in Section 4.1 as follows.

Given

Demand of products at markets
Number of components required for products
Capacity of facilities
Flow variable from Stage 1
Opened/closed facilities from Stage 1
Selected transportation modes from Stage 1
Flexible capacity of facilities
Selected driver nodes from Stage 2
Probability of occurrence disruption scenarios

Find

Over and lower flow of products
Opened driver node
Added auxiliary transportation link
Deviation variables

Satisfy

Constraints

Demand constraint (see Equations 4-21, 4-22)
Network flow constraints (see Equations 4-23 to 4-25)
Capacity constraints (see Equations 4-26 to 4-29)
Structural and arc constraints (see Equations 4-30 to 4-37)

Driver node and variable constraints (see Equations 4-38 to 4-51)

Goal

Goal one that is the re-planning in the network (see Equation 4-52)

Goal two that is the control cost (see Equation 4-53)

Minimize

Deviation function (see Equation 4-54)

Based on the proposed word formulation, the mathematical formulation is developed as follows.

4.6.2 The Mathematical Formulation

The mathematical formulation for Stage 3 is developed based on the problem statement (see Section 4.1) and word formulation (see Section 4.6). In addition, the mathematical formulation is developed based on four parts such as *Given*, *Find*, *Satisfy*, and *Minimize*.

Given

Indices

$i \in I$: set of potential locations for refineries

$j \in J$: set of potential locations for hubs

$k \in K$: set of potential location for warehouses

$l \in L$: set of potential locations for distribution centers

$m \in M$: set of markets

$p \in P$: set of products

$q \in Q$: set of components used in different products

$h \in H$: set of transportation modes (truck, train, ship, etc.) between facility layers

$s \in S$: set of scenarios

Parameters

D_{pm}: demand of product *p* at market *m*

β_{qp}: number of component *q* is required for product *p*

$capr_i$: capacity of refinery *i*

$caph_j$: capacity of hub *j*

$capw_k$: capacity of warehouse *k*

$capd_l$: capacity of distribution center *l*

The flow parameters from Stage 1

$\overline{x_{ij}^{ph}}$: amount of product *p* flowed from refinery *i* to hub *j* using transportation mode *h*

$\overline{y_{jk}^{ph}}$: amount of product *p* flowed from hub *j* to warehouse *k* using transportation mode *h*

$\overline{w_{kl}^{ph}}$: amount of product *p* flowed from warehouse *k* to distribution center *l* using transportation mode *h*

$\overline{v_{lm}^{ph}}$: amount of product *p* flowed from distribution center *l* to market *m* using transportation mode *h*

The structural parameters from Stage 1

$\overline{\mu_{ij}}$: binary parameter equal to 1 if there was a transportation arc between refinery *i* and hub *j* and 0 otherwise

$\overline{\gamma_{jk}}$: binary parameter equal to 1 if there was a transportation arc between hub j and warehouse *k* and 0 otherwise

$\overline{\beta_{kl}}$: binary parameter equal to 1 if there was a transportation arc between warehouse *k* and distribution center *l* and 0 otherwise

$\overline{\alpha_{lm}}$: binary parameter equal to 1 if there was a transportation arc between distribution center *l* and market *m* and 0 otherwise

$\overline{u_i}$: binary parameter equal to 1 if refinery *i* was opened and 0 otherwise

$\overline{o_j}$: binary parameter equal to 1 if hub *j* was opened and 0 otherwise

$\overline{g_k}$: binary parameter equal to 1 if warehouse *k* was opened and 0 otherwise

$\overline{f_l}$: binary parameter equal to 1 if distribution center *l* was opened and 0 otherwise

$cap\varphi_i^n$: level *n* of flexible production capacity at refinery *I*

$cap\omega_j^n$: level *n* of flexible production capacity at hub *j*

$cap\theta_k^n$: level *n* of flexible inventory capacity at warehouse *k*

$cap\alpha_l^n$: level *n* of extra inventory at distribution center *l*

$c\varphi_i$: cost of flexible production capacity at refinery *i*

$c\omega_j$: cost of flexible production capacity at hub *j*

$c\theta_k$: cost of flexible inventory capacity at warehouse *k*

$c\alpha_l$: cost of keeping inventory at distribution center *l*

cfr_i: cost of driver node fortification at refinery *i*

cfh_j: cost of driver node fortification at hub *j*

cfw_k: cost of driver node fortification at warehouse *k*

cfd_l: cost of driver node fortification at distribution center *l*

$ca\mu_{ij}$: cost of auxiliary transportation arc between refinery *i* and hub *j*

$ca\gamma_{jk}$: cost of auxiliary transportation arc between hub *j* and warehouse *k*

$ca\beta_{kl}$: cost of auxiliary transportation arc between warehouse *k* and distribution center *l*

$ca\alpha_{lm}$: cost of auxiliary transportation arc between distribution center *l* and market *m*

Control variables from Stage 2

$c\mu_{ij}$: binary parameter equal to 1 if a control (auxiliary) extra transportation arc is added for the controllability purpose between refinery *i* and hub *j* and 0 otherwise

$c\gamma_{jk}$: binary parameter equal to 1 if a control (auxiliary) extra transportation arc is added for the controllability purpose between hub *j* and warehouse *k* and 0 otherwise

$c\beta_{kl}$: binary parameter equal to 1 if a control (auxiliary) extra transportation arc is added for the controllability purpose between warehouse *k* and distribution center *l* and 0 otherwise

$c\alpha_{lm}$: binary parameter equal to 1 if a control (auxiliary) extra transportation arc is added for the controllability purpose between distribution center *l* and market *m* and 0 otherwise

cu_i: binary parameter equal to 1 if refinery *i* is selected as the driver refinery and 0 otherwise

co_j: binary parameter equal to 1 if hub *j* is selected as the refinery hub and 0 otherwise

cg_k: binary parameter equal to 1 if warehouse k is selected as the driver warehouse and 0 otherwise

cz_l: binary parameter equal to 1 if distribution center *l* is selected as the driver distribution center and 0 otherwise

Disruption parameters

P_s: probability of occurrence Scenario *s*

dr_i^s: binary parameter equal to 1 if refinery *i* is disrupted in scenario *s* and 0 otherwise

dh_j^s: binary parameter equal to 1 if hub *j* is disrupted in scenario *s* and 0 otherwise

dw_k^s: binary parameter equal to 1 if warehouse k is disrupted in scenario s and 0 otherwise

<u>Find</u>

${X_{ijph}^s}^+$: over flow of product *p* from refinery *i* to hub *j* using transportation mode *h*

${X_{ijph}^s}^-$: lower flow of product *p* from refinery *i* to hub *j* using transportation mode *h*

${Y_{jkph}^s}^+$: over flow of product *p* from hub *j* to warehouse *k* using transportation mode *h*

${Y_{jkph}^s}^-$: lower flow of product *p* from hub *j* to warehouse *k* using transportation mode *h*

${W_{klph}^s}^+$: over flow of product p from warehouse k to distribution center *l* using transportation mode h

${W_{klph}^s}^-$: lower flow of product p from warehouse k to distribution center *l* using transportation mode h

${V_{lmph}^s}^+$: over flow of product *p* from distribution center *l* to market *m* using transportation mode *h*

${V_{lmph}^s}^-$: lower flow of product *p* from distribution center *l* to market *m* using transportation mode h

φ_i^n: binary variable equal to 1 if driver refinery (driver node) *i* is opened for blending components with flexible production capacity *n*

ω_j^n: binary variable equal to 1 if driver hub (driver node) *j* is opened for producing products with flexible production capacity *n*

θ_k^n: binary variable equal to 1 if driver warehouse (driver node) *k* is opened for inventorying products with flexible inventory capacity *n*

α_l^n: binary variable equal to 1 if driver distribution center (driver node) *l* is opened for keeping extra inventory capacity *n*

Satisfy

Constraints

$$\sum_{l=1}^{L}\sum_{h=1}^{H}\left(\overline{v_{lm}^{ph}}+{V_{lmph}^{s}}^{+}-{V_{lmph}^{s}}^{-}\right)\leq D_{pm} \qquad \forall m\in M, p\in P, s\in S \tag{4-21}$$

$$\sum_{l=1}^{L}\sum_{h=1}^{H}\left(\overline{v_{lm}^{ph}}+{V_{lmph}^{s}}^{+}-{V_{lmph}^{s}}^{-}\right)\geq \sum_{l=1}^{L}\sum_{h=1}^{H}\overline{v_{lm}^{ph}} \qquad \forall m\in M, p\in P, s\in S \tag{4-22}$$

$$\sum_{k=1}^{K}\sum_{h=1}^{H}\left(\overline{w_{kl}^{ph}}+{W_{klph}^{s}}^{+}-{W_{klph}^{s}}^{-}\right)=\sum_{m=1}^{M}\sum_{h=1}^{H}\left(\overline{v_{lm}^{ph}}+{V_{lmph}^{s}}^{+}-{V_{lmph}^{s}}^{-}\right) \qquad \forall l\in L, p\in P, s\in S \tag{4-23}$$

$$\sum_{j=1}^{J}\sum_{h=1}^{H}\left(\overline{y_{jk}^{ph}}+{Y_{jkph}^{s}}^{+}-{Y_{jkph}^{s}}^{-}\right)=\sum_{l=1}^{L}\sum_{h=1}^{H}\left(\overline{w_{kl}^{ph}}+{W_{klph}^{s}}^{+}-{W_{klph}^{s}}^{-}\right) \qquad \forall k\in K, p\in P, s\in S \tag{4-24}$$

$$\sum_{i=1}^{I}\sum_{h=1}^{H}\left(\overline{x_{ij}^{ph}}+{X_{ijph}^{s}}^{+}-{X_{ijph}^{s}}^{-}\right)=\sum_{j=1}^{J}\sum_{h=1}^{H}\left(\overline{y_{jk}^{ph}}+{Y_{jkph}^{s}}^{+}-{Y_{jkph}^{s}}^{-}\right) \qquad \forall j\in J, p\in P, s\in S \tag{4-25}$$

$$\sum_{j=1}^{J}\sum_{h=1}^{H}\sum_{q=1}^{Q}\sum_{p=1}^{P}\beta_{qp}\left(\overline{x_{ij}^{ph}}+{X_{ijph}^{s}}^{+}-{X_{ijph}^{s}}^{-}\right)\leq\left[capr_i\,\overline{u_i}+\sum_{n=1}^{N}cap\varphi_i^n\,\varphi_i^n\right]\left(1-dr_i^s\right) \qquad \forall i\in I, s\in S \tag{4-26}$$

$$\sum_{k=1}^{K}\sum_{h=1}^{H}\sum_{p=1}^{P}(\overline{y_{jk}^{ph}} + {Y_{jkph}^{s}}^{+} - {Y_{jkph}^{s}}^{-}) \leq [caph_j\,\overline{o_J} + \sum_{n=1}^{N} cap\omega_j^n\,\omega_j^n](1 - dh_j^s)$$

$$\forall j \in J, s \in S \qquad (4\text{-}27)$$

$$\sum_{l=1}^{L}\sum_{h=1}^{H}\sum_{p=1}^{P}(\overline{w_{kl}^{ph}} + {W_{klph}^{s}}^{+} - {W_{klph}^{s}}^{-}) \leq [capw_k\,\overline{g_k} + \sum_{n=1}^{N} cap\theta_k^n\;\theta_k^n](1 - dw_k^s)$$

$$\forall k \in K, s \in S \qquad (4\text{-}28)$$

$$\sum_{m=1}^{M}\sum_{h=1}^{H}\sum_{p=1}^{P}(\overline{v_{lm}^{ph}} + {V_{lmph}^{s}}^{+} - {V_{lmph}^{s}}^{-}) \leq capd_l\,\overline{f_l} + \sum_{n=1}^{N} cap\alpha_l^n\;\alpha_l^n$$

$$\forall l \in L, s \in S \qquad (4\text{-}29)$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} {X_{ijph}^{s}}^{+} \leq N\,(\overline{\mu_{iJ}} + c\mu_{ij})\,(1 - dr_i^s)(1 - dh_j^s) \qquad \forall i \in I, j \in J, s \in S \qquad (4\text{-}30)$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} {X_{ijph}^{s}}^{-} \leq N\,\overline{\mu_{iJ}}(1 - dr_i^s)\,(1 - dh_j^s) \qquad \forall i \in I, j \in J, s \in S \qquad (4\text{-}31)$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} {Y_{jkph}^{s}}^{+} \leq N(\overline{\gamma_{Jk}} + c\gamma_{jk})(1 - dh_j^s)(1 - dh_j^s) \qquad \forall j \in J, c \in C, s \in S \qquad (4\text{-}32)$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} {Y_{jkph}^{s}}^{-} \leq N(\overline{\gamma_{Jk}})(1 - dh_j^s)(1 - dw_k^s) \qquad \forall j \in J, c \in C, s \in S \qquad (4\text{-}33)$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} {W_{klph}^{s}}^{+} \leq N(\overline{\beta_{kl}} + c\beta_{kl})(1 - dw_k^s) \qquad \forall k \in K, l \in L, s \in S \qquad (4\text{-}34)$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} {W_{klph}^{s}}^{-} \leq NN(\overline{\beta_{kl}})(1 - dw_k^s) \qquad \forall k \in K, l \in L, s \in S \qquad (4\text{-}35)$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} {V_{lmph}^{s}}^{+} \leq N(\overline{\alpha_{lm}} + c\alpha_{lm}) \qquad \forall l \in L, m \in M, s \in S \qquad (4\text{-}36)$$

$$\sum_{h=1}^{H}\sum_{p=1}^{P} {V_{lmph}^{s}}^{-} \leq N\overline{\alpha_{lm}} \qquad \forall l \in L, m \in M, s \in S \qquad (4\text{-}37)$$

$$\sum_{n=2}^{N} \varphi_i^n \leq cu_i \qquad \forall i \in I \qquad (4\text{-}38)$$

$$\sum_{n=2}^{N} \omega_j^n \leq co_j \qquad \forall j \in J \qquad (4\text{-}39)$$

$$\sum_{n=2}^{N} \theta_k^n \leq cg_k \qquad \forall k \in K \qquad (4\text{-}40)$$

$$\sum_{n=2}^{N} \alpha_l^n \leq cz_l \qquad \forall k \in K \qquad (4\text{-}41)$$

$$\sum_{n=1}^{N} \varphi_i^n = 1 \qquad \forall i \in I \qquad (4\text{-}42)$$

$$\sum_{n=1}^{N} \omega_j^n = 1 \qquad \forall j \in J \qquad (4\text{-}43)$$

$$\sum_{n=1}^{N} \theta_k^n = 1 \qquad \forall k \in K \tag{4-44}$$

$$\sum_{n=1}^{N} \alpha_l^n = 1 \qquad \forall k \in K \tag{4-45}$$

$$X_{ijph}^{s}{}^{+}\, X_{ijph}^{s}{}^{-} = 0 \qquad \forall i \in I, j \in J, p \in P, h \in H, s \in S \tag{4-46}$$

$$Y_{jkph}^{s}{}^{+}\, Y_{jkph}^{s}{}^{-} = 0 \qquad \forall j \in J, k \in K, p \in P, h \in H, s \in S \tag{4-47}$$

$$W_{klph}^{s}{}^{+}\, W_{klph}^{s}{}^{-} = 0 \qquad \forall k \in K, l \in L, p \in P, h \in H, s \in S \tag{4-48}$$

$$V_{lmph}^{s}{}^{+} V_{lmph}^{s}{}^{-} = 0 \qquad \forall l \in L, m \in M, p \in P, h \in H, s \in S \tag{4-49}$$

$$X_{ijph}^{s}{}^{+}, X_{ijph}^{s}{}^{-}, Y_{jkph}^{s}{}^{+}, Y_{jkph}^{s}{}^{-}, W_{klph}^{s}{}^{+}, W_{klph}^{s}{}^{-}, V_{lmph}^{s}{}^{+}, V_{lmph}^{s}{}^{-} \geq 0$$

$$\forall i \in I, j \in J, k \in K, l \in L, m \in M, p \in P, h \in H, s \in S \tag{4-50}$$

$$\varphi_i^n, \omega_j^n, \theta_k^n, \alpha_l^n \in \{0,1\} \qquad \forall i \in I, j \in J, k \in K, l \in L \tag{4-51}$$

Minimize

$$Z_4 = \sum_{s=1}^{S} \sum_{m=1}^{M} P_s \left[\sum_{p=1}^{P} \sum_{h=1}^{H} \sum_{l=1}^{L} \frac{V_{lm}^{ph}}{D_{pm}} - \sum_{p=1}^{P} \sum_{h=1}^{H} \sum_{l=1}^{L} \frac{V_{lmph}^{s}{}^{+} + V_{lmph}^{s}{}^{-}}{D_{pm}} \right] \tag{4-52}$$

$$\begin{aligned} Z_5 = {} & \Big[\sum_{i=1}^{I} \sum_{n=1}^{N} c\varphi_i \; cap\varphi_i^n \; \varphi_i^n + \sum_{j=1}^{J} \sum_{n=1}^{N} c\omega_j \; cap\omega_j^n \; \omega_j^n + \\ & \sum_{k=1}^{K} \sum_{n=1}^{N} c\theta_k \; cap\theta_k^n \; \theta_k^n + \sum_{k=1}^{K} \sum_{n=1}^{N} c\alpha_l \; cap\alpha_l^n \; \alpha_l^n \Big] + \Big[\sum_{i=1}^{I} cfr_i \, cu_i + \\ & \sum_{j=1}^{J} cfh_j \, co_j + \sum_{k=1}^{K} cfw_k cg_k + \sum_{l=1}^{L} cfd_l \, cz_l \Big] + [\sum_{i=1}^{I} \sum_{j=1}^{J} ca\mu_{ij} \, c\mu_{ij} + \\ & \sum_{j=1}^{J} \sum_{k=1}^{K} ca\gamma_{jk} \, c\gamma_{jk} + \sum_{k=1}^{K} \sum_{l=1}^{L} ca\beta_{kl} \, c\beta_{kl} + \sum_{l=1}^{L} \sum_{m=1}^{M} ca\alpha_{lm} \, c\alpha_{lm}] \end{aligned} \tag{4-53}$$

The two considered resilience measures in evaluating the control policies are the deviation in the service level and control cost. In the deviation goal, minimizing the deviation in the service level between the service level from Stage 1 and Stage 3 are considered. In the control cost goal, minimizing the cost of fortifying driver nodes and having extra transportation arcs is considered.

The outputs of the Stage 3 of the proposed RCIN method are (1) the required flexible production and inventory capacity at refineries, hubs and warehouses as resilience strategies in the face of disruptions, and (2) the deviation between the designed infrastructure network in Stage 1 and the required changes because of the occurrence of disruptions in Stage 3.

In Chapter 6, the proposed RCIN method is exercised using an example from the petroleum industry example. In next section, the theoretical structural validation of the RCIN method is proposed.

4.7 THEORETICAL AND EMPIRICAL STRUCTURAL VALIDATION OF THE RCIN METHOD

In this section, the theoretical and empirical validity of the RCIN method is checked (see Figure 4-6). The problem statement, an overview of the general structure of the resilient and controllable multi-level infrastructure networks, and the overall view of the RCIN method are explained in Sections 4.1 to 4.3. The RCIN method is explained in detail through Sections 4.4 – 4.7. In this section the theoretical structural validity of the RCIN is investigated by exploring the advantages, disadvantages, and accepted domain of applications of the RCIN method. In addition, the empirical structural validity of the RCIN method is checked using a sensitivity analysis of the RCIN method.

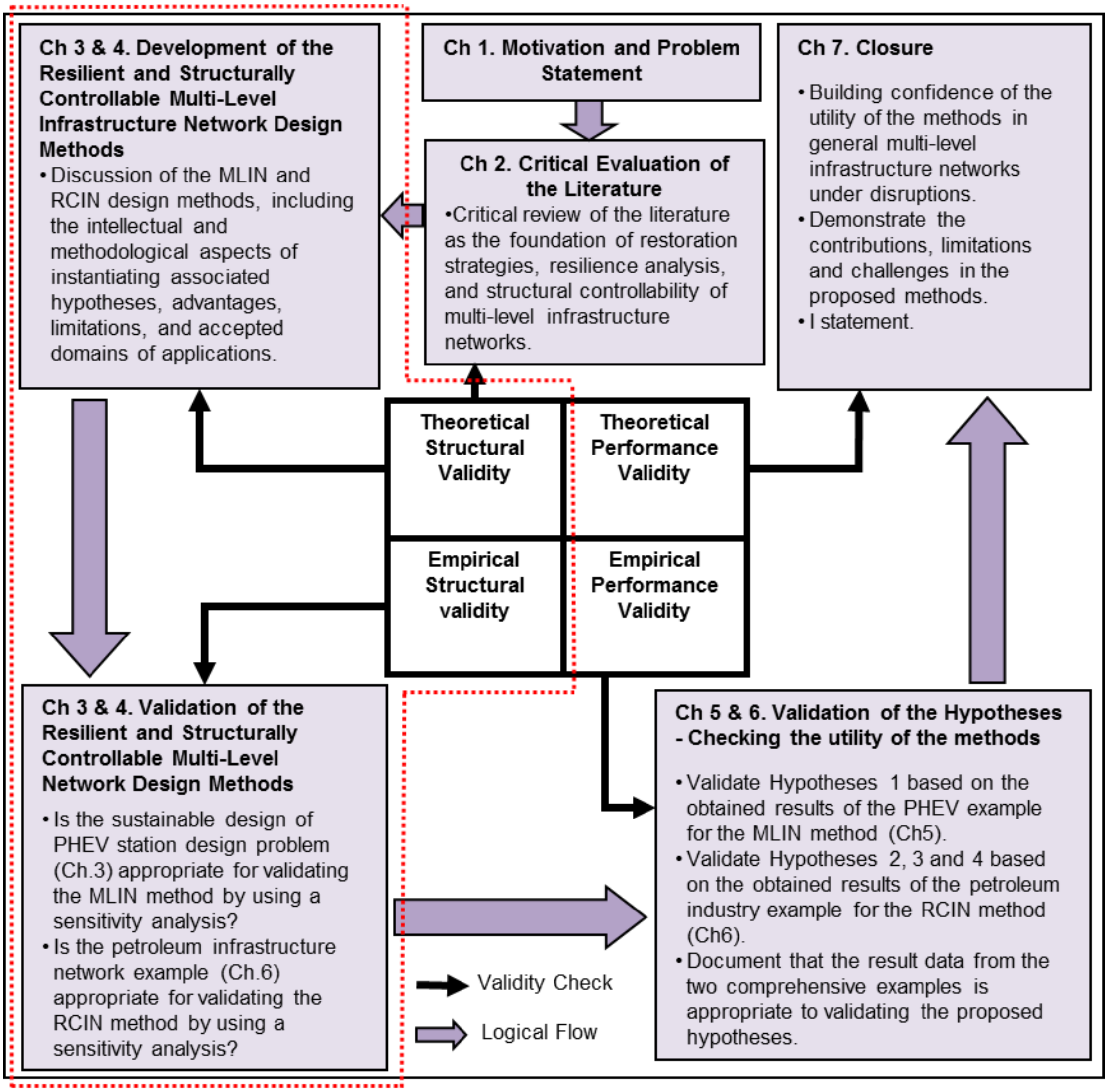


Figure 4-6 Validation strategy of the dissertation

From the theoretical perspective, it is possible to establish the internal consistency of the method and identify explicitly the favorable and unfavorable properties of the method for particular application domains. Empirical studies are required to establish the usefulness and effectiveness of the method. A strategy for empirical validation of the method is provided in this section using sensitivity analysis of the strategic stage of the RCIN method.

The theoretical advantages and limitations of the RCIN method are summarized in Table 4-2.

Table 4-2 Theoretical capabilities and limitations RCIN

Capabilities and Advantages
• Design forward infrastructure networks considering strategic and operational decisions • Consider disruptions on facilities (nodes) • Consider robustness in RCIN in the face of uncertainty • Consider multiple disruption scenarios • Consider trade-off between system efficiency and redundancy • Consider trade-off between number of driver nodes and redundant links • Consider both proactive and reactive restoration strategies in order to mitigate the risk of disruptions
Limitations and Disadvantages
• Disruptions on links are not considered • Consider only three restoration strategies (back-up inventory and back-up driver node) for recovering the system after disruptions • The mathematical model does not represent all aspects of the system; the solution of this model is not necessarily the best solution for the system

As listed in Table 4-2, in the proposed RCIN method an integrated model is presented for designing resilient and controllable infrastructure networks. The key element in this method is on selecting driver nodes in each layer of the network. Hence, if a disruption happens in a layer of the network, the driver node will back-up disrupted facilities and mitigate the risk of those disruptions. In addition, the trade-off among the number of driver nodes and redundant arcs required to make the structure controllable is considered in the RCIN. The RCIN method is verified through a sensitivity analysis as follows using a sensitivity analysis of the maximum allowed time for delivering products in the strategic stage (Stage 1) of the RCIN method.

The compromise Decisions Support Problem (cDSP) for Stage 1 is presented in Section 4.4, and the input parameters for the example is presented in Section 6.1.1. The maximum allowed time for delivering the products in the market is considered as 5 days (see Section 6.3 for results in Stage 1). However, the results can be sensitive to this parameter. Therefore, the tardiness when the maximum allowed time is changing is analyzed. As is shown in Figure 4-7, if the maximum allowed time is 6 days or more, there is not any tardiness in meeting the current demand of the markets. However, the network cannot have the real time delivery (i.e., zero maximum allowed time) of the products to the market since the tardiness will have its highest possible value.

When 4 days is considered as the maximum allowed time for delivering products, the normalized value of the service level is 0.545, and only one refinery is located. However, if 5 days is considered as the maximum allowed time, two refineries will operate and the service level increases up to 83%.

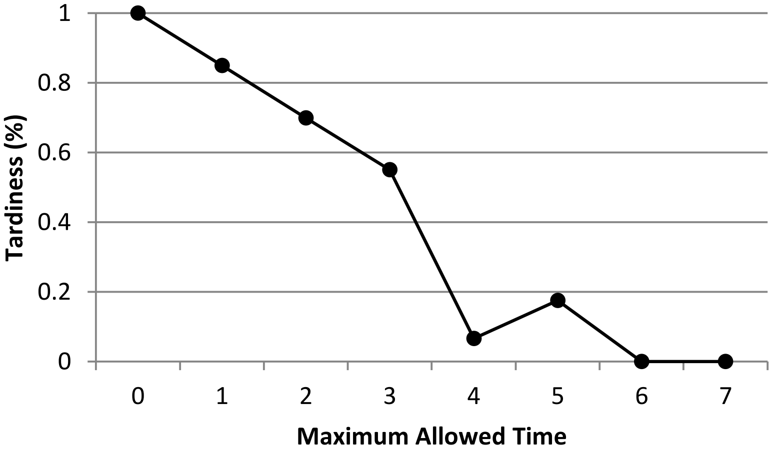


Figure 4-7 Analyzing the normalized value of the tardiness by changing the maximum allowed time

According to the results presented in Figures 4-7, changing the maximum allowed time for delivering products as a sensitivity analysis results in getting different results for the tardiness. Based on the presented sensitivity analysis in this section, the usefulness and effectiveness of the proposed RCIN method is demonstrated.

4.8 CHAPTER SYNOPSIS

In this chapter, the resilient and structurally controllable infrastructure network (RCIN) is proposed and explained. The problem statement and the overview of the resilient and structurally controllable multi-level network design are presented in Sections 4.1 and 4.2. In Section 4.3, the proposed RCIN method is explained. In Section 4.4 to 4.6, detail of the proposed RCIN method through its three stages is explained and supported by the word and mathematical formulations. The internal consistency of the RCIN method is evaluated with identifying explicitly the favorable and unfavorable properties of the method in Section 4.7. In Chapter 6, a comprehensive example of the petroleum industry is employed to fully validate the usefulness of the RCIN method.

CHAPTER 5 INTEGRATED MULTI-LEVEL NETWORK DESIGN OF ELECTRIC CHARGING STATIONS FOR PLUG-IN HYBRID ELECTRIC VEHICLES

In this chapter (see Figure 5-1) the usefulness of the MLIN method is validated using a comprehensive example on designing a network of electric charging stations for plug-in hybrid electric vehicles. Both node-level and network-level decisions are considered in this example while the focus is on considering both the operational and strategic decisions with conflicting system goals. In Section 5.1, an introduction to the PHEV charging station design example is presented. It is argued that this is an appropriate example for validating the MLIN method. In Section 5.2, the overall procedure of the MLIN method, which is discussed earlier in Chapter 3, is reviewed in terms of the PHEV charging station network design example. In Sections 5.3 to 5.6, details of the MLIN steps are explained in context of the PHEV charging station network design example. In Section 5.7, results of the design are discussed, and Hypothesis 1 is revisited and the usefulness of the MLIN method is argued (Empirical Performance Validation).

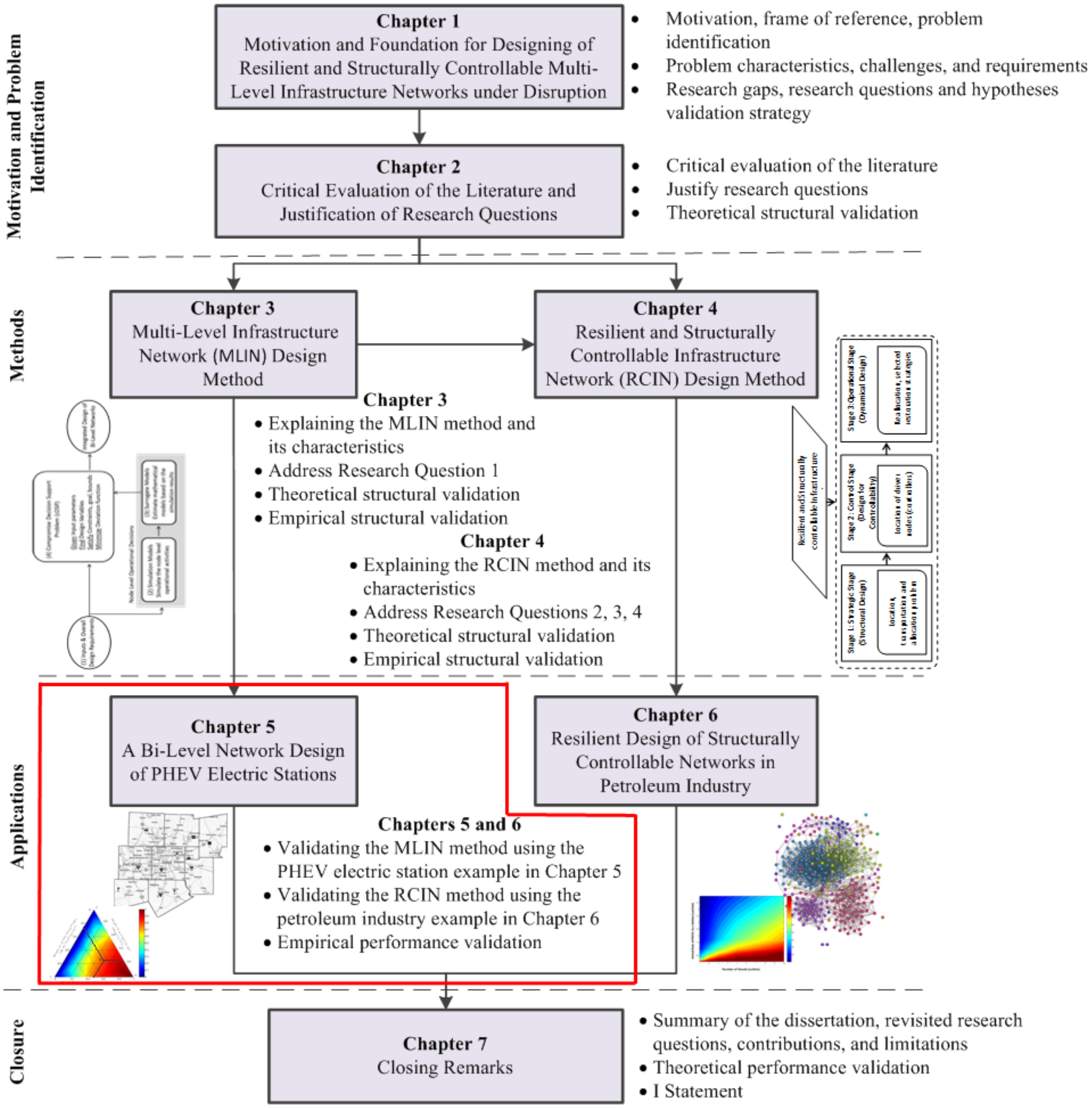
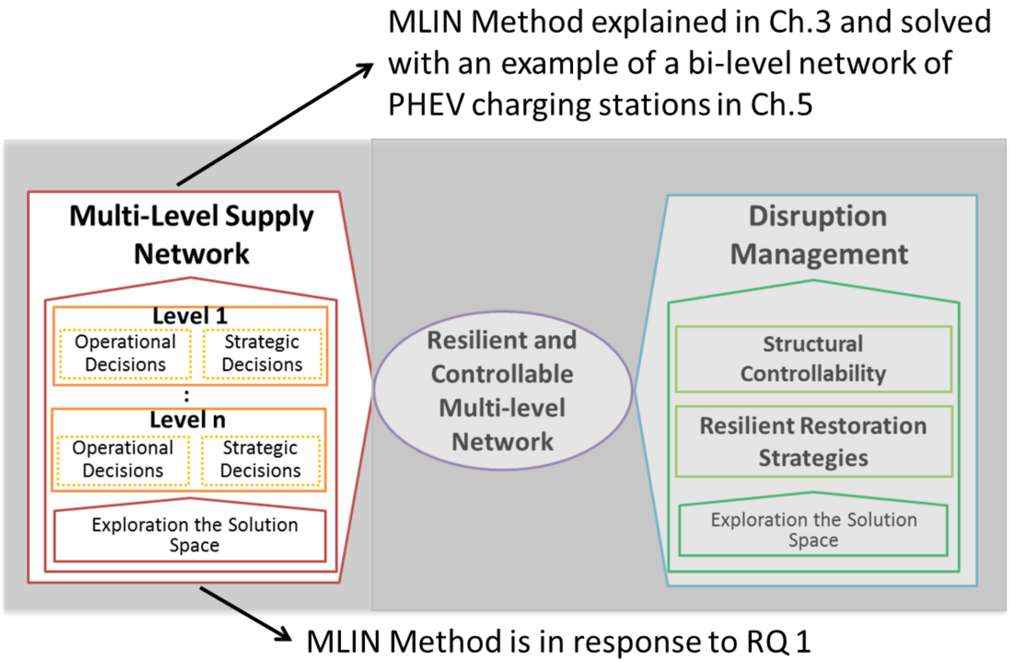


Figure 5-1 Dissertation structure

5.1 INTRODUCTION AND PROBLEM STATEMENT TO DESIGNING BI-LEVEL NETWORKS OF PHEV ELECTRIC CHARGING STATIONS

As it is discussed earlier in Section 1.6, the problem of designing a resilient and structurally controllable multi-level infrastructure networks under disruptions has two parts: (1) multi-level infrastructure network design, and (2) disruption management. The MLIN method related to the multi-level infrastructure network design is explained in Chapter 3 and exercised in this chapter by solving an example of the electric vehicle charging stations. However, disruption management is explained in Chapter 4 and exercised in Chapter 6 by solving an example of the petroleum industry.

Infrastructure network design involves determining the network structure and the distribution of resources over its structure. As is shown in the left side of Figure 5-2, all levels of decisions (i.e., Level 1... Level n), such as operational and strategic decisions, should be considered in designing multi-level infrastructure networks. For example, both decisions on locations and capacities of facilities (strategic decisions) and supplying the demand to available facilities through available transportation routes (operational decisions) should be considered in designing multi-level infrastructure networks. In designing multi-level infrastructure networks, the focus in the lower level of decisions (e.g., node-level decisions) is more on the operational decisions, and the focus in the higher level of decisions (e.g., network-level decisions) is more on the strategic decisions.


MLIN Method explained in Ch.3 and solved with an example of a bi-level network of PHEV charging stations in Ch.5

MLIN Method is in response to RQ 1

Figure 5-2 Resilient and structural controllability of a multi-level network

As is shown in Table 5-1, which is a part of Table 1-3, the requirement for designing multi-level infrastructure networks is having an integrated method for designing such networks. The Research Question 1 and Research Hypothesis 1 are shown in Table 5-1. The multi-level infrastructure network (MLIN) method is developed to respond to the proposed research question (RQ1) as the first outcome of this dissertation and is explained in Chapter 3.

In order to evaluate the MLIN method, an example of electric charging stations for plug-in hybrid electric vehicles is introduced in this chapter (see Section 5.1.1). Plug-in hybrid electric vehicles (PHEVs) offer an approach to significantly lowering the consumption of fossil fuel and consequently the gas emission. There are two levels of decisions related to the design of a network of electric charging stations for plug-in hybrid electric vehicles: *a*) the node-level decisions consist of the strategic and operational decisions i.e., the number of charging spots and battery storage at each station as the strategic decisions, and the interactions of electricity between the power grid and renewable sources of energy as the operational decisions; *b*) the network-level decisions consist of the strategic and operational decisions i.e., the location of charging stations as the strategic decisions and the allocation of demand to the demand nodes as the operational decisions.

Table 5-1 Connection between the problem, requirement, research question, and outcome

Aspect	Requirement	Research Questions	Research Hypotheses	Outcome
Multi-level network design	Integrated formulation for designing a multi-level network considering operational (short term) and strategic (long term) decisions with conflicting goals.	RQ1: What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?	Implement an integrated simulation model (for operational decisions in the node-level) and mathematical model (using the compromise Decision Support Problem) to design a multi-level network with conflicting goals.	The MLIN method: integrated node-level and network-level decisions considering both operational and strategic decisions with conflicting design goals

***The problem that is considered** is to design a network of electric charging stations for PHEVs in a way that both node-level decisions (e.g., the number of charging spots, battery capacity, and interactions of electricity between sources of energy) and network-level decisions (e.g., location of charging stations and allocation of demand between charging stations and demand nodes) are considered in an integrated method. In this problem, sustainability drivers with their conflicting goals (i.e., social, environmental and economic drivers) should be the considered as goals for the* *designed network. In this problem, the power grid is considered as a complimentary source of energy, and the renewable sources of energy (i.e., wind power and solar power) are considered as the primary sources of energy.*

In order to tackle the aforementioned problem statement, the in Section 5.1.1, the overall introduction to the example of the PHEV charging stations is presented. In Section 5.1.2, operational and strategic decisions associated with the bi-level station network problem are discussed. The appropriateness of this example for validating the MLIN method is justified in Section 5.1.3.

5.1.1 Network of Electric Charging Stations for PHEVs

Plug-in hybrid electric vehicles (PHEVs) offer an approach to significantly lowering the consumption of oil and improving fuel economy and are critically important for a fundamental transformation that shifts the transportation sector from traditional oil based fleets to electrical power vehicular technologies. The federal government is encouraging purchases of PHEVs through the Energy Independence and Security Act (EISA), the American Reinvestment and Recovery Act (ARRA), and other bills aimed at stimulating the U.S. economy. Congress has approved tax credits amounting to $758 million to subsidize the purchase of up to 250,000 PHEVs over the next few years. This amounts to about $3,000 per vehicle, although the precise amount may range from $2,500 to $7,500 depending on vehicle attributes (Skerlos and Winebrake, 2010). However, the environmental benefits of PHEVs depend on the availability of fuel for electric generation and emissions by its supporting infrastructure.

With electricity generation principally based on coal, PHEVs may lead to even higher emissions (the environmental driver). In addition, PHEVs face a chicken-egg infrastructure dilemma. PHEV charging station investors will not develop new charging infrastructure that citizens will not use (the economic driver), at the same time, citizens will be reluctant to buy PHEVs until a sufficient number of electric charging stations with high levels of service have been installed (the social driver). This highlights the need for an appropriate sustainable design (the integrated environmental, economic and social driver) for electric charging stations to reach the maximum climate benefits, economic profits and social welfare from PHEVs.

Sustainability, in terms of development, is defined as the ability to meet current needs, without jeopardizing the future needs. In order to ensure that both present and future needs can be met and compromises among them, three drivers of sustainability must be addressed in the creation of a design or configuration. These three drivers are economic, environmental and social.

In this PHEV example, investors in charging infrastructure, government and environmental NGOs, and PHEV drivers are considered as stakeholders of the economic, environmental and social drivers of sustainability, respectively. The focus of the economic driver of sustainability is the cost of implementing a design. In terms of designing a PHEV station, the economic driver includes the operating cost (sources of energy) and strategic cost (charging spots and battery storage). The environmental driver of sustainability is focused on reducing gas emissions and the carbon footprint. In terms of designing a PHEV station, the environmental driver focuses on emissions by production, installation and maintenance of the charging infrastructure and the generation of electricity by fossil fuels in the power grid. The focus of the social driver of sustainability is to improve the quality of life of the people affected by the design. In terms of designing a PHEV station, this would mean that a charging infrastructure would sufficiently cover the demand of PHEVs. In Figure 5-3, sustainability drivers, stakeholders and their focuses are shown. However, there are some conflicts among the driver of sustainability; these conflicts in designing PHEV charging stations are discussed in Table 5-2.

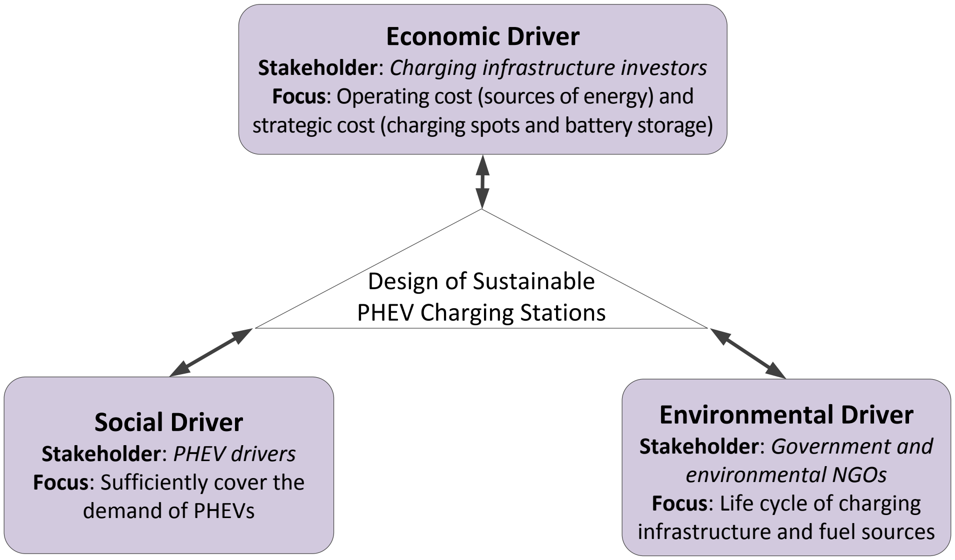


Figure 5-3 Sustainability triangle with focuses and stakeholders for PHEV stations

In addition, there are two issues related to designing PHEV charging stations. The first issue is the location and allocation facility decision problem addressed as decision problem related to the network of charging stations (network-level decisions). In Figure 5-4, the candidate location of charging stations for Dallas-Fort Worth metroplex is shown. Decisions on locations of charging stations, allocating demand from charging stations to demand nodes, and number of charging stands at stations are strategic decisions in this example.

Table 5-2 Conflicting sustainable goals in designing PHEV charging stations

Sustainability Driver	**Stakeholder**	**Goal**	**Conflicting Driver**	**Explanation**
Economic driver	Charging station investors	Minimize strategic and operational cost	Social driver	Minimize the strategic cost (economic driver) means fewer number of charging spots at stations that cause a smaller service level (social driver).
Environmental driver	Government and environmental NGOs	Minimize gas emissions (LCA of energy sources and charging infrastructures)	Social driver	Minimize gas emission (considering the LCA of energy sources) means relying more on the renewable energy (Which has higher fluctuations and uncertainty in availability) that causes a smaller service level; Minimize gas emission (considering the LCA of charging infrastructure) which means installing fewer charging spots which causes a smaller service level.
Social driver	PHEV drivers	Maximize service level	Economic and environmental driver	Maximize the level of service means higher numbers of charging spots at stations (conflicts with both minimizing the strategic cost or economic driver, and minimizing gas emissions by charging infrastructure or environmental driver); Maximize the service level means relying more on the electricity with less fluctuation and uncertainty (relying more on the electricity from the power grid than directly from renewable energies) that causes higher gas emission.

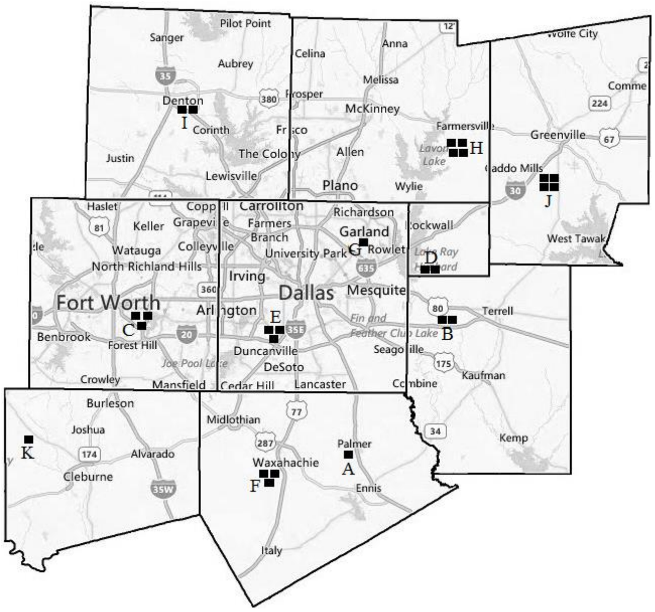


Figure 5-4 Twenty-six settlement points in Dallas-Fort Worth (NCTCOG, 2013)

The second issue is the capacity of each station (battery storage and number of slots per station), and interactions of electricity between the power grid and stations (node-level decisions). Connection between the charging infrastructure and sources of energy is shown in Figure 5-5. As illustrated in Figure 5-5, in order to maximize the utilization of renewable sources, an on-site installed photovoltaic (PV) cells and an off-side wind farm are used as the main power supply to charge the battery units. Grid electricity plays an auxiliary role in the station when there is mismatch between renewable sources and demand. In addition, power trading can (Battery-to-Grid or Grid-to-Battery) reduce the operating cost of the charging stations. Power trading between charging stations and sources of energy are operational decisions in this example.

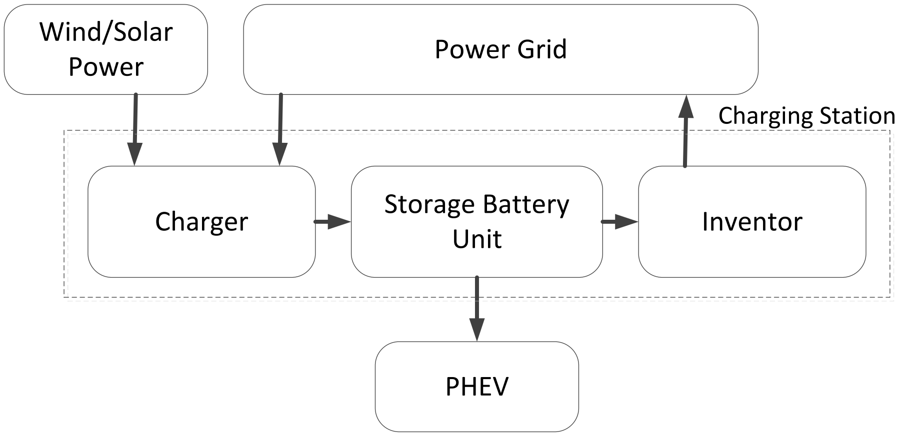


Figure 5-5 The exchange of electricity between charging infrastructure, sources of energy and PHEVs

In this example, the outputs (decision variables) of through using the proposed MLIN method for designing sustainable charging stations in both strategic (long term decisions) and operational (short term decisions) levels are:

Strategic decisions (long term decisions)

- Location of charging stations
- Number of charging spots at each station
- Battery capacity

Operational decisions (short term decisions)

- Level of stored electricity in the battery in each period of time
- Amount of electricity bought from the grid (Grid-to-Battery) in each period of time
- Amount of electricity sold back to the grid (Battery-to-Grid) in each period of time

- Amount of electricity used (sold to the grid or PHEV users) from the renewable sources (wind farms and photo voltaic cells) in each period of time.

In addition, the focus of the social driver is on meeting the demand of PHEV users, and the goal in designing PHEV charging stations is to maximize service level of the charging infrastructure. The service level at charging stations is a function of various stochastic parameters such as number of charging stands, PHEV demand, arrival rates of PHEVs to stations, patient limit of PHEV drivers (waiting time at stations), etc. All these stochastic behaviors should be considered in order to design PHEV charging stations. However, considering all stochastic possibilities is computationally expensive.

5.1.2 Appropriateness and Challenges in the PHEV Charging Station Design Example based on the MLIN Method: Empirical Structural Validation

This PHEV charging station design problem is an appropriate example for validation of the MLIN method because of the following challenges. As it is mentioned in Section 5.1.1, one of the main challenges in designing PHEV charging stations is the importance of considering network-level and node-level decisions, and both strategic and operational decisions. Although the time-scale for these decisions is different, they should be considered in an integrated method in order to design PHEV charging stations.

Another challenge in the PHEV charging station design problem is in considering conflicts among system goals. As it is explained in Table 5-2, there are conflicts among sustainability drivers in designing PHEV stations. Therefore, in order to design PHEV stations these conflicts should be considered.

The third challenge in designing PHEV stations is in considering the stochastic behavior of PHEV drivers. Since the PHEV demand and decisions by PHEV drivers are uncertain, considering these uncertainties are important. In addition, another challenge is related to the high computational cost in calculating all possible scenarios for stochastic parameters.

As mentioned in this section, there are some challenges related to the design of PHEV electric charging stations such as necessitate of considering both operational and strategic decisions, both network-level and node-level decisions, conflicting system goals and stochastic behavior in the node-level of charging stations. On the other hand, as it is discussed in Chapter 3, the conflicting system goals are considered in the MLIN method using the compromise Decision Support Problem (cDSP), the stochastic behavior of PHEV driver using the simulation model, decreasing the computational time, and both node-level and network-level decisions using the surrogate modeling. Therefore, this example is an appropriate bi-level network design problem for demonstrating the usefulness of the MLIN method, which is the validation of Hypothesis 1.

5.1.3 Planning Tasks for Empirical Performance Validation

As discussed in the previous section, the PHEV charging station design problem is an appropriate example for validating the MLIN method based on Hypothesis 1. In this section, the necessary tasks for the empirical performance validation are planned; this is used to build confidence in the usefulness of the MLIN method discussed in Chapter 3. The following three main tasks are necessary for the Empirical Performance Validation – validating the usefulness of the MLIN method for the example problem – in the Validation Square discussed in Section 1.7.

<u>Task 1</u>: Validate that using the surrogate modeling approach in integrated estimation of the simulation model discussed in Sections 3.4 and 3.5 help in simulating the stochastic behavior of PHEV drivers and decreasing the computational time. This task is the demonstration for validating Hypothesis 1 discussed in Chapter 1.

<u>Task 2</u>: Validate that using the compromise Decisions Support Problem (cDSP) in considering conflicts among the system goals discussed in Section 3.7. This task is the demonstration for validating Hypothesis 1 discussed in Chapter 1.

<u>Task 3</u>: Validate that using the MLIN method explained in Section 3.4 – 3.7 can help in considering both the operational and strategic decisions with both the node and network levels considerations. This task is the demonstration for validating Hypothesis 1 discussed in Chapter 1.

In this section, tasks for the empirical performance validation are planned. These tasks are revisited in Section 5.7 for the empirical performance validation and are based on the results achieved in Section 5.6.

5.1.4 Solution Algorithms

In this section, the computational complexity of the MLIN method and the applied solution algorithm for the MLIN method is explained. The proposed compromised Decisions Support Problem is coded in Python 2.7 and solved with Gurobi Optimizer 6.0 on a PC with two 3.16 GHz processors and 4 GB of RAM. There are 254 binary variables for the location of located charging stations and 144 continuous variables for the trade-off of electricity between sources of energy and charging stations. The code for the cDSP is presented in Appendix A.

5.2 THE MLIN METHOD FOR DESIGNING BI-LEVEL NETWORK OF PHEV CHARGING STATIONS CONSIDERING SUSTAINABILITY

The MLIN method is discussed in Section 3.4. In this section, the procedure of the MLIN method for designing bi-level networks of PHEV charging stations considering sustainability is discussed. As is shown in Figure 5-6, the procedure of the design task is identical to the procedure described in Section 3.4.

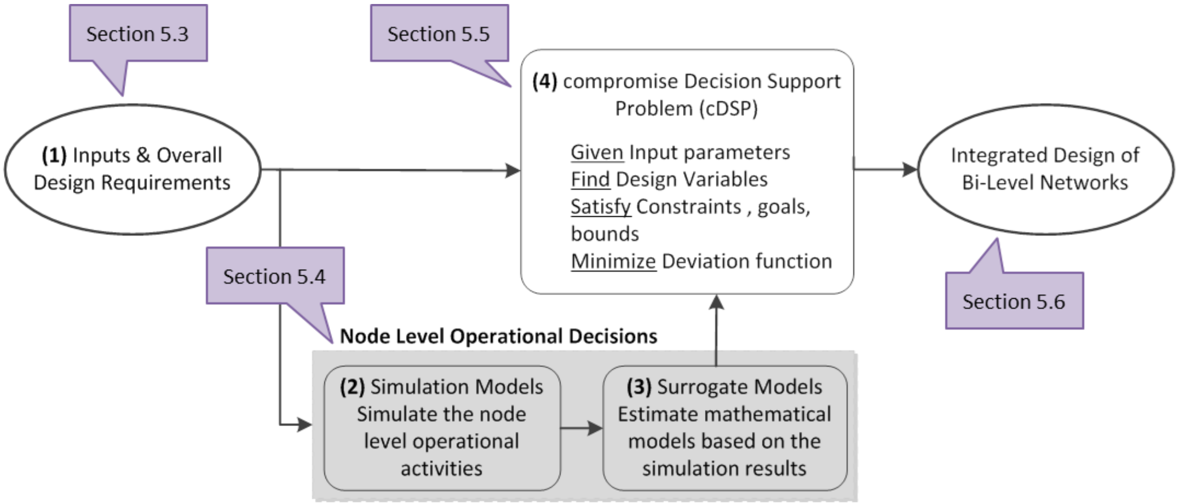


Figure 5-6 The MLIN method for designing PHEV charging stations

In Section 5.3, the overall inputs and requirements for the PHEV charging station network design are listed. Some interesting input parameters (e.g., demand of PHEVs over time) are explained in detail. In Section 5.4, the simulation model for simulating the behavior of PHEV drivers is explained, and then the surrogate modeling approach for estimating the simulation results is described.

In Section 5.5, the compromise Decision Support Problem construct for designing the bi-level network of PHEV charging stations is explained. Finally, in Section 5.6, some of the results with focus on challenges described in Section 5.1.2 are reported. As mentioned, in the following section, the steps of the MLIN method for the PHEV charging station design are explained in detail. Finally, the usefulness of the MLIN in designing PHEV charging stations is validated and summarized in Section 5.7.

5.3 INPUTS AND OVERALL REQUIREMENTS OF DESIGNING A NETWORK OF PHEV CHARGING STATIONS CONSIDERING SUSTAINABILITY – STEP (1) OF MLIN METHOD

As it is shown in Figure 5-6, the first step of the MLIN method is the inputs and overall requirements. In designing electric charging stations for PHEVs, an example from Dallas-Fort Worth (DFW) metropolitan area of Texas including Collin, Dallas, Denton, Ellis, Hunt, Johnson, Kaufman, Rockwall and Tarrant Counties is considered. A planning horizon of one year at one hour intervals is considered. Availability of high voltage of electricity and accessibility to highways from settlement points (source nodes in the power grids) of the power grid are two reasons that settlement points as candidates for locating charging facilities are considered. Twenty-six settlement points (candidate locations for charging stations) in this area are shown in Figure 5-3.

Light-duty vehicle projections from IRC (2010) is used to estimate the number of PHEVs on the roads in 2020. The IRC report provides a projection of PHEVs on roads in the DFW metropolitan area. Population data from Census Bureau (2014) is used to allocate vehicle projections into each region of the DFW region. Based on the annual report of EIA Annual Energy Outlook 2013 the estimated average annual miles driven per car will be almost 11,500 miles per year in 2020 (EIA, 2013). This means that the average daily miles per car is about 31.5 miles. Based on the battery range of electric vehicles in the market, the average of one charge per day for each PHEV is assumed.

The National Household Travel Survey (NHTS) survey conducted by the US department of Transportation represents a total of 203 million vehicles in the United States (US DOT, 2011). It reports on hundreds of thousands of vehicle trips made across the United States in 2009. The NHTS 2011 data contains a daily trip data set and a vehicle data set. It is assumed that driving behavior would not change were PHEVs to replace the sampled vehicles. From the full survey, only trips are selected which are taken by private and light-duty vehicles, with complete records of start time, end time, driver ID and vehicle ID in Texas. It is assumed that the average PHEV hourly demand is in direct relation to the average hourly driving mileage (Weiller, 2011). Therefore, the vehicles trip-mile from NHTS 2011 data is used to project the hourly demand of PHEVs (D_t in the mathematical model, see appendix) and is shown in Figure 5-7.

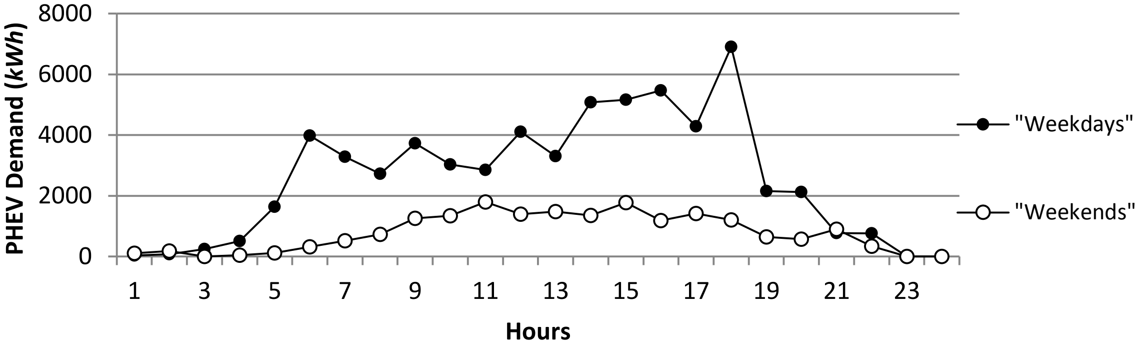


Figure 5-7 Percentage of hourly demand based on hourly vehicle trip-mile (US DOT, 2011)

Battery storage units require a tremendously large capacity and discharge rate. There are various types of energy storage technologies available today; the potential battery storage technologies that can support DC level 3 fast charging consists of Sodium-Sulfur (NaS), Lead Acid (Pb), Lithium-ion (Li-ion), and Nickel-Metal Hydride (NiMH). The characteristics of batteries are shown in Table 5-3 (Vazquez and co-authors, 2010). In this example, the sodium-sulfur battery is used in the design of PHEV stations since it has a high energy density, high efficiency of charge/discharge (89%-92%) and long cycle life, and is fabricated from inexpensive materials. The NaS battery is a modular battery in which the charging (C_r) and discharging rates (d_r) are 0.6 and 0.075 MWh per module. Efficiencies are assumed to be same and equal to 79.8% (e^{char}), and the cost for each charging spot (c^{stand}) is $15,000 (Huang, 2010).

ERCOT was established by Texas Interconnected System (TIS) in 1970 and became a deregulated energy generation market in 1995. In this example, the historical data of hourly settlement point prices (SPPs) of electricity selling back and buying from the power grid in Texas is considered in September 2013. In Figure 5-8, the average hourly price of electricity (c^{+}_{t}, c^{-}_{t}) in Year 2013 and September 2013 is shown.

Table 5-3 Properties of battery storages for electric charging stations (Huang, 2010; Vazquez and co-authors, 2010)

Technology	**Efficiency**	**Advantage**	**Disadvantage**
NaS	89 – 92%	• Good for industrial and commercial sectors • High efficiency	Operates with high temperatures
Li-ion	70 – 85%	• High density • Low self-discharge rate • No memory effect in positive side	Expensive
NiMH	50 – 80%	• High density • Good abuse tolerance	Damage may occur with complete discharge
Lead Acid • Flooded • VRLA	 70 – 80% 70 – 80%	Inexpensive	Limited cycling capacity

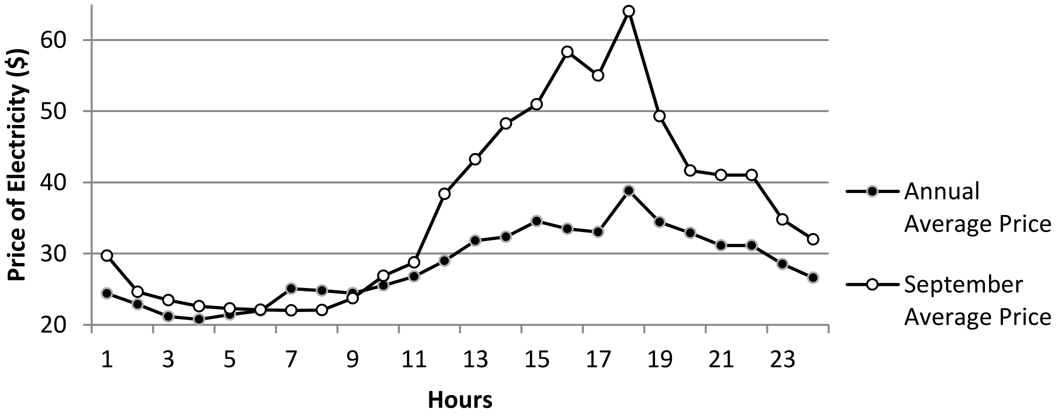


Figure 5-8 Average real-time settlement point prices (SPPs) of electricity (ERCOT, 2014)

Wind and solar power are treated as zero-cost energy sources, and hence it is generally preferable to use all available renewable energy. However, volatile and intermittent renewable energy may require greater rapid supply capabilities from the power grid. Wind and solar power play an increasingly important role in Texas. With more than 10,000 MW generated from 46 wind farms by 2012, Texas has the highest installed capacity in the United States. Texas has also enacted a Renewable Portfolio Standard (RPS) that specifies, through 2025, an annually increasing amount of electricity that must be generated from renewable sources (NGA, 2011).

Data from the Electric Reliability Council of Texas (ERCOT) and National Renewable Energy Laboratory to project the wind and solar power output, respectively, is used and it is assumed that the wind and solar power profiles will remain the same. Using wind and solar power historical data, a site from the north general geographic region in Texas (DFW area) is selected. In order to capture wind and solar power fluctuations and to obtain a good representation of power flows among the grid and vehicles, an hourly time resolution is chosen. Single crystalline PV technology because of its high efficiency compared to other commercially available technologies is considered. The PV generation (k_t) profiles a 180 m^2 installation area is considered as a roof-top PV for the PHEV charging station, Figure 5-9.

Life-cycle emissions from charging infrastructures is calculated based on an input-output approach conducted by Nansai and co-authors (2001). Data for calculating emissions in the production and installation phases of projects is obtained from Nansai and co-authors (2001) and modified based on the example from DFW area.

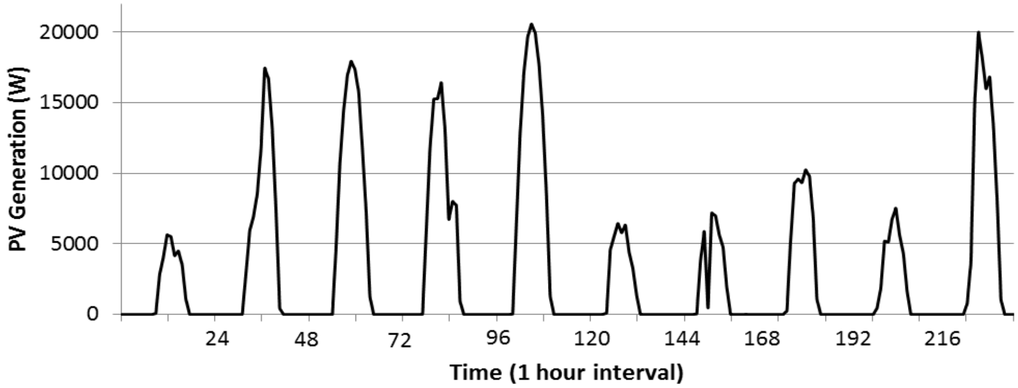


Figure 5-9 PV generation based on data from 21 January 2008 to 30 January 2008 (NREL, 2012)

Gas emissions for generating electricity to charge PHEVs is considered based on the CO2 emission of fuel sources. The typical types of fuel sources are coal, natural gas, oil, nuclear, wind, solar and hydropower. Based on the Air Emissions report by the Environmental Protection Agency, the amount of CO2 produced for each of these types of energy is listed in Table 5-4. In addition, based on the data provided by the Electric Reliability Council of Texas (ERCOT), the percentage of each type of energy used to generate electricity in Texas is presented in Table 5-5. The average emission of the electricity generated in the DFW area is calculated by multiplying the fuel type percentage and its CO2 emission.

Table 5-4 CO2 emission by fuel sources in generating electricity (EIA, 2014a)

Fuel Type	Coal	Natural Gas	Oil	Nuclear	Wind	Solar	Hydro
Lbs-CO_2 per *kWh*	2.18	1.22	1.68	0	0	0	0

Table 5-5 Percentage of fuel sources used in generating electricity in Texas (EIA, 2014b)

Fuel Type	Coal	Natural Gas	Oil	Nuclear	Wind	Solar	Hydro
%	32.98	47.83	1.05	12.31	5.33	0	0.15

Three drivers of sustainability (economic, environmental and social) are considered in designing PHEV electric charging stations. In order to manage conflicts between the sustainability goals (see Table 5-2), policy makers may either put the same importance weights on all goals or give different priorities to them. The distribution of importance weights between goals for different policies is shown in Figure 5-10.

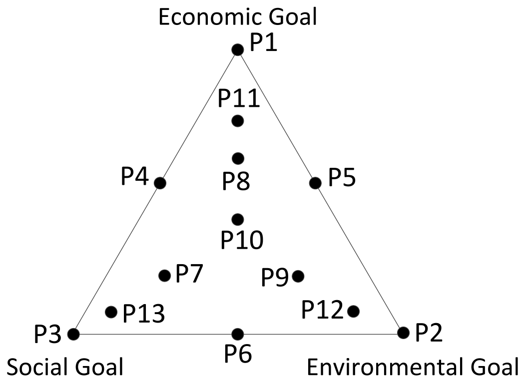


Figure 5-10 Schematic of different design scenarios for individual and quad goals

In each vertex, one of goals is given the full weight of one, e.g., in Policy *P1*, corresponds to the minimum cost, the cost goal is given the weight of one and other two goals (minimum emissions and maximum service level) each have weights of zero. Inside the triangle, all goals are assigned weights between zero and one, but the sum of weights must always equal one. Detail of goal weights for different policies is listed in

Table 5-6, while all policies are defined in accordance with the conflicts between goals presented in Table 5-2.

Table 5-6 Policies for sustainable design of PHEV stations considering stakeholders' goal conflicts (W1, W2 and W3 are the importance of economic, environmental and social drivers respectively)

Policy Scenarios	**Conflicts between sustainability drivers**	$\mathbf{W_1}$	$\mathbf{W_2}$	$\mathbf{W_3}$	$\sum_{i=1}^{4} W_i = 1$
P1	Minimum strategic and operational cost (G1)	1.0	0.0	0.0	1.0
P2	Minimize gas emissions (G2)	0.0	1.0	0.0	1.0
P3	Maximize service level (G3)	0.0	0.0	1.0	1.0
P4	Minimize cost (G1) and maximize service level (G3)	0.5	0.0	0.5	1.0
P5	Minimize cost (G1) and gas emissions (G2)	0.5	0.5	0.0	1.0
P6	Minimize gas emissions (G2) and maximize service level (G3)	0.0	0.5	0.5	1.0
P7	All goals (G1 – G2 – G3), G3 emphasized	0.25	0.25	0.5	1.0
P8	All goals (G1 – G2 – G3), G1 emphasized	0.5	0.25	0.25	1.0
P9	All goals (G1 – G2 – G3), G2 emphasized	0.25	0.5	0.25	1.0
P10	All goals (G1 – G2 – G3)	0.33	0.33	0.33	~1.0
P11	All goals (G1 – G2 – G3), G1 emphasized	0.8	0.1	0.1	1.0
P12	All goals (G1 – G2 – G3), G2 emphasized	0.1	0.8	0.1	1.0
P13	All goals (G1 – G2 – G3), G3 emphasized	0.1	0.1	0.8	1.0

5.4 THE SIMULATION MODEL AND SURROGATE MODELING OF PHEV CHARGING STATIONS – STEPS (2) AND (3) OF MLIN METHOD

As is shown in Figure 5-6, the second and third steps of the MLIN method is on modeling the node-level decisions using the simulation and surrogate models. In the second step, the stochastic behavior of PHEV drivers is simulated to determine the value of service for different number of charging spots, arrival rates of vehicles to stations, required charging demand and waiting time limit of drivers. The model is developed based on discrete-event simulation modeling and illustrated in Figure 5-11.

PHEVs can be charged via charging spots (item *b* in Figure 5-11) after entering the station (item *a* in Figure 5-11) if any empty spot is available. In case no empty charging spot is available, they may stay in a line (item *c* in Figure 5-11) or leave the station (item *d* in Figure 5-11). Some other PHEVs may stay in a line for a while, but after reaching to their patient limit leave the station (item *e* in Figure 5-11). Adding more charging spots to a station increases the service capacity and leads to shorter waiting time. The service level is calculated as the percentage of the met demand.

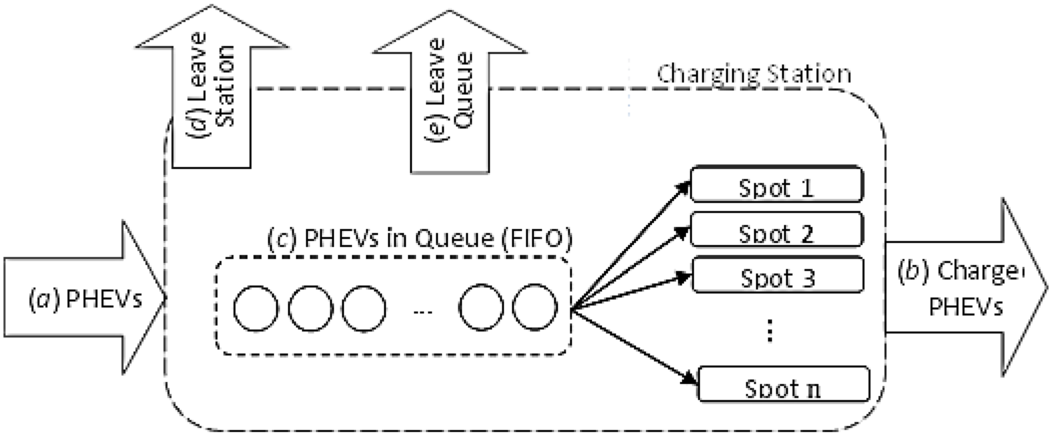


Figure 5-11 Schematic of the simulation of PHEVs in a charging station

Based on the results of the simulation model for the service level and by using the multi-variant adaptive regression splines (MARS) as a surrogate model, a mathematical model is developed to demonstrate the service level as the third goal in the mathematical model. This estimated mathematical model decrease the computational time. The reason for decreasing in the computational time is that using this estimation prevents in running the simulation model several times. Therefore, instead of running the simulation model for much iteration, estimation for it obtained from the surrogate model can be used.

5.5 THE COMPROMISE DECISION SUPPORT PROBLEM FOR DESIGNING PHEV CHARGING STATIONS–STEP (4) OF MLIN METHOD

As is shown in Figure 5-6, the forth step of the MLIN method is on modeling the integrated node-level and network-level decisions using the cDSP. In Step (*4*) of the proposed method, minimizing the strategic and operational cost (economic driver), minimizing gas emissions by charging infrastructures and fuel sources for generating electricity (environmental driver) and maximizing the service level (social driver) are three goals in the proposed multi-objective mathematical model. The mathematical model is formulated using the compromise Decision Support Problem (cDSP) construct in order to consider the conflicts among sustainability drivers (Mistree and co-authors, 1993). Both the simulation model and surrogate model are inputs for the mathematical model. The problem statement and word formulation, and the mathematical model are explained in Sections 3.8 and 3.9, respectively. In next section, the achieved results are presented.

5.6 INTEGRATED DESIGN OF BI-LEVEL NETWORK OF PHEV CHARGING – RESULTS OF MLIN METHOD

In this section, results of the integrated design of bi-level network of PHEV charging station considering sustainability are presented. Results are addressed based on two tasks defined in Section 5.1.3.

5.6.1 Service Level at PHEV Charging Stations

Maximizing the service level (the ratio of the met demand and total demand) is the considered intent in the social driver. Two parameters that have the greatest effect on the service level at charging stations: the number of charging spots and arrival rate of PHEVs (PHEV demand) at the stations. Results of the simulation model are presented in Figure 5-12. Service level and time between arrivals of PHEVs are shown on the vertical and horizontal axis, respectively, for different number of charging spots (outlets).

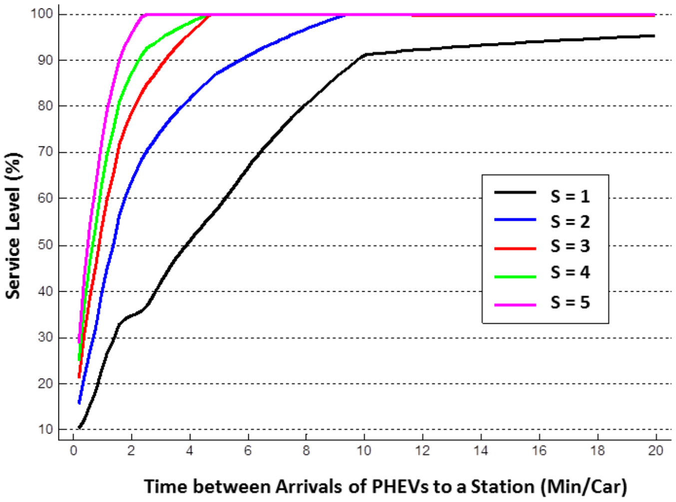


Figure 5-12 Service level at charging stations for different numbers of charging spots (outlets)

As is shown in Figure 5-12, there is a significant increase in the level of service by increasing the number of charging spots (outlets) from one to two and two to three. However, the improvement decreases with the increase in the number of spots, especially when the arrival time between vehicles is greater than 6 minutes. On the other hand, When there is a higher demand (time between arrival rate is less than 4 minutes) increasing in the number of spots (outlets) makes a significant difference in the service level.

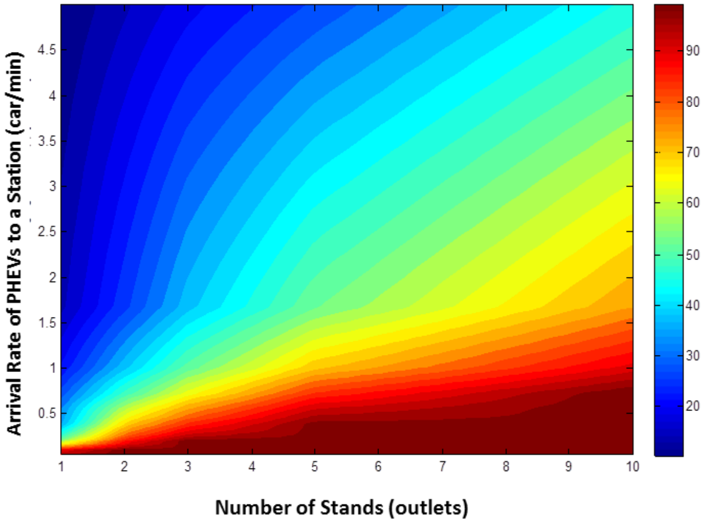


Figure 5-13 Contour plot of the service level for number of charging spots and PHEV demand

In Figure 5-13, a contour plot of the service level is illustrated while number of charging spots and arrival rates of PHEVs at stations take on different values. As is shown on the vertical bar on the right, the highest value of the service level in the contour plot is shown by red and the lowest value is shown by blue. Using this contour plot helps designers and policy makers visualize the service level for different alternatives. In addition, it helps designers of PHEV stations to estimate changes in the service level for different values of demand during a day for a station with a fixed number of charging spots (outlets).

5.6.2 Conflicting Goals in a Sustainable Design (Policy Scenarios)

Results of all thirteen policy scenarios, which are defined based on conflicts between sustainability goals presented in Table 5-6, are shown in Figure 5-14. All goals are normalized, and the results are in line with the known properties of sustainability. For example, when policy makers/designers consider only the service level (the social driver), in Policy P3, the cost (the economic driver) and gas emissions (the environmental driver) take high values. Comparing policies P7 and P8 show that, as expected, charging stations have a higher service level in P7 but the lower cost and emissions than the design in P8. This also can be seen in Table 5-7 where the results for all thirteen policy scenarios are presented.

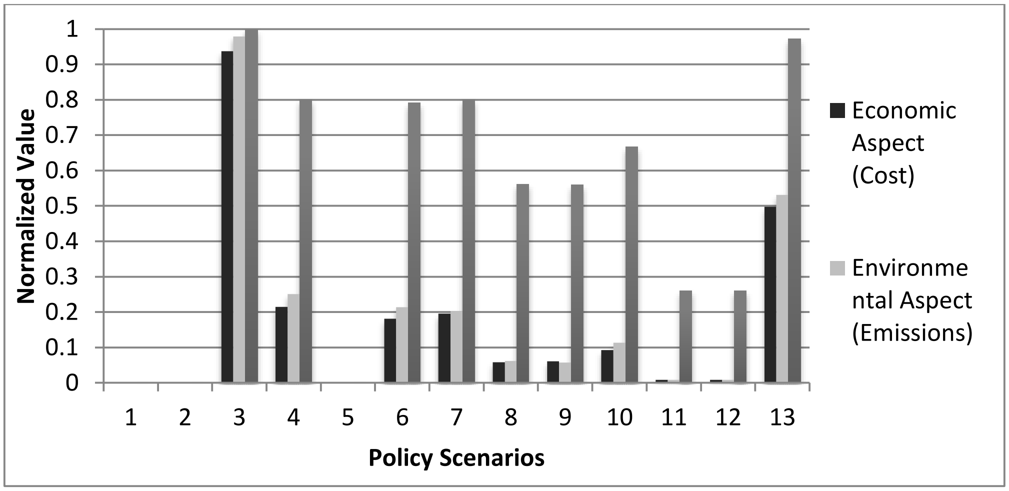


Figure 5-14 Comparison between sustainability drivers for different policy scenarios

Table 5-7 A designed station (number of charging spots and battery capacity) and its interaction with energy sources for policy scenarios

Policy Scenarios	w_1	w_2	w_3	$\sum_{i=1}^{4} w_i = 1$	**Number of charging spots**	**Battery capacity (kW)**	**Renewable Energy**	**Power Grid (kW)**
P1	1.0	0.0	0.0	1.0	0	0	0	0
P2	0.0	1.0	0.0	1.0	0	0	0	0
P3	0.0	0.0	1.0	1.0	20	1400	836.90	845.50
P4	0.5	0.0	0.5	1.0	7	490	490.33	75.97
P5	0.5	0.5	0.0	1.0	0	0	0	0
P6	0.0	0.5	0.5	1.0	7	490	444.28	63.77
P7	0.25	0.25	0.5	1.0	6	420	474.58	78.05
P8	0.5	0.25	0.25	1.0	3	210	207.21	5.32
P9	0.25	0.5	0.25	1.0	3	210	160.24	3.60
P10	0.33	0.33	0.33	~1.0	4	280	419.4	6.58
P11	0.8	0.1	0.1	1.0	1	70	81.33	0
P12	0.1	0.8	0.1	1.0	1	70	6.79	0
P13	0.1	0.1	0.8	1.0	14	980	176.77	364.54

Results of thirteen policy scenarios are shown in Table 5-7. The importance of economic driver, environmental driver and social drivers is shown by w1, w2 and w3, respectively. For those policy scenarios that economic or environmental drivers have larger weights (importance), the percentage of provided electricity from renewable sources (wind and solar) is greater than the provided electricity from the grid. As is shown in P6, for example, the social and the environmental drivers have the same weight, which results in meeting demand mainly by using renewable energy. However, in P13 the environmental driver has a smaller weight that results in having the less demand provided from renewable sources.

Looking at different policies demonstrates that assigning a larger weight for the social driver (service level) results in having larger number of installed charging spots (outlets) in PHEV stations. Because this requires having a larger number of charging spots, and consequently, a higher capacity is required for meeting the demand (compare P3 with P11). These results indicate that the model is behaving consistently.

5.6.3 Visualization of the trade-off between Sustainability Drivers in Designing PHEV Charging Stations

In order to further develop the trade-off between sustainability drivers for policy makers/designers, a visible representation of the trade-offs is presented in Figures 5-16 to 5-18 using ternary contour plots. Ternary plots are created to show the interdependence among sustainability goals, and to understand possible compromises among individual goals. These plots can help a policy maker/designer visually explore possible opportunities for sustainable design of PHEV charging stations. Using ternary plots helps to decrease the time required to provide results of all possible policy scenarios in the decision making process for policy makers/designers and allows the rapid, convenient exploration of various alternative configurations. In other words, instead of solving the proposed method for all possible policy scenarios which requires a high computational cost and time, ternary plots can be created with a few sample points.

In Figure 5-15, the visualization of the normalized value of the social driver (level of service at designed charging stations) is shown. As indicated in Figure 5-15, red indicates the highest normalized value of the service level (the value equal one) and the blue color shows the lowest normalized value of the service level (the weight equals zero). The intent for the social driver in the sustainable design of charging stations is maximizing the service level or equivalently the red area in the triangle. Each side of the triangle and number on it show one of drivers of sustainability and its weights. As is shown in Figure 5-15, at any point in the interior of the triangle, the value of the weights for the various sustainability goals are determined by finding the intersection of lines drawn parallel to the gridlines.

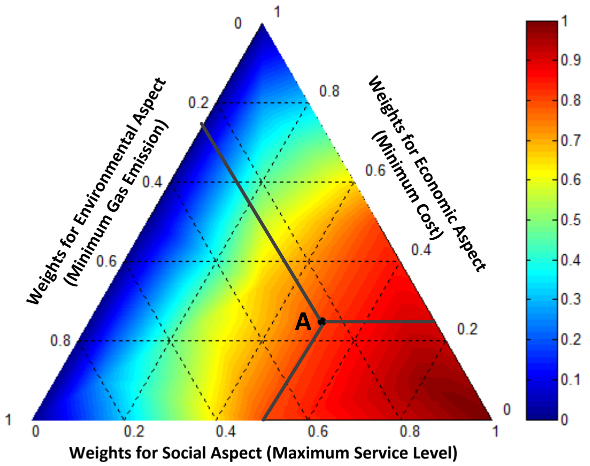


Figure 5-15 Visualization of policy scenarios for the social driver – the red area is desired

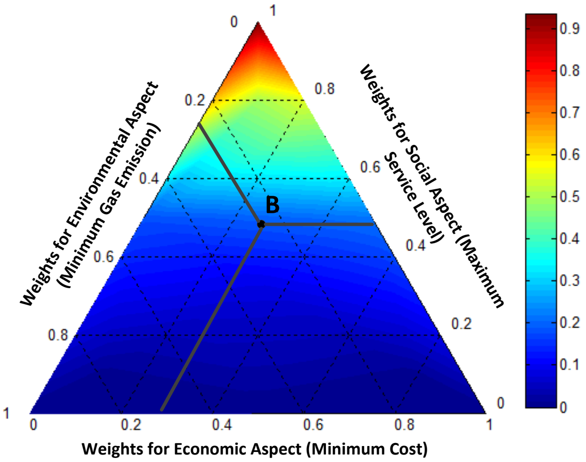


Figure 5-16 Visualization of policy scenarios for the economic driver – the blue area is desired

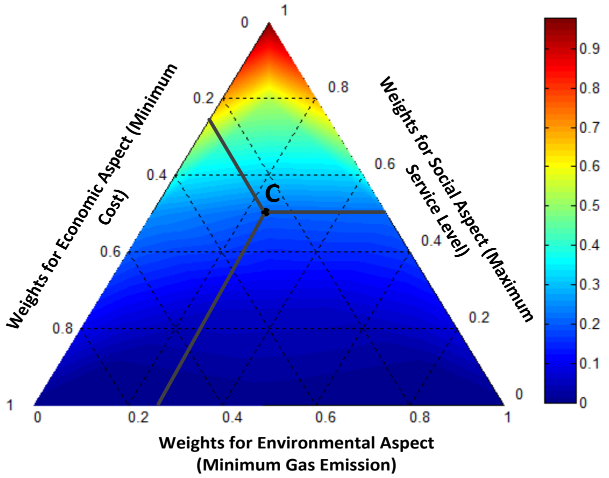


Figure 5-17 Visualization of policy scenarios for the environmental driver (gas emissions) – the blue area is desired

Visualizations of economic and environmental considerations are shown, in Figures 5.17 and 5.18. The intent for both the environmental and economic drivers in the sustainable design of charging stations is minimization or equivalently the blue area in the triangle.

Point *A* in Figure 5-15, Point *B* in Figure 5-16 and Point *C* in Figure 5-17 represent Policy Scenario P7 in which social consideration are weighted 0.5 and the economic and environmental drivers are equally weighted 0.25. In order to interpret the ternary plot in Figure 5-15, each point inside the triangle represents a normalized value of the service level. By drawing lines from each point to the triangle sides, an associated importance weight for each driver of sustainability can be determined. In Point *A*, for example, the normalized value for the service level is 0.8 (comparing the color inside the triangle with its associated value in the column bar on right). Drawing lines from Point *A* to triangle sides, as is shown in Figure 5-15, helps in finding the importance weights for economic, environmental and social drivers which are 0.25, 0.25 and 0.5, respectively, which are the same as the importance weights in Table 5-6. Point *B* in Figure 5-16 represents policy scenario P7 and its normalized value for the economic driver is almost 0.2, and Point C in Figure 5-17 represents P7 and its normalized value for the environmental driver is 0.2 (see Figure 5-14 for P7). Following the same procedure can help to determine the normalized values and their associated importance weights of all other possible policy scenarios. Using ternary plots is a useful approach for visualizing the results of different policy decisions in designing PHEV charging stations.

5.6.4 Interactions between Charging Stations and Sources of Energy

Three sources of energy, the wind power, solar power and power grid are considered here in order to meet the PHEV demand. Availability of solar power in comparison with wind power is negligible. Improving the current technology and efficiency of solar cells will result in increasing the use of solar power. In Figures 5.19-5.21interactions of electricity between the designed station and sources of the energy for policies P13, P10 and P7 are shown for both a weekday (hours 1 to 24) and a weekend day (hours 25 to 48).

The emphasis of the policy P13 is on meeting the PHEV demand and increasing the service level. As is shown in Figure 5-18, there is no selling of electricity to the grid (no B2G), and the electricity bought from the grid is considerable. As illustrated in Figure 5-19 and 5.21, in both P10 and P7 policy scenarios, there is selling of the electricity to the grid (B2G). However, in both policy scenarios B2G occurs in the early morning or late at night when there is a less PHEV demand at stations. Therefore, the percentage of B2G is higher when the economic driver has a greater importance than other drivers.

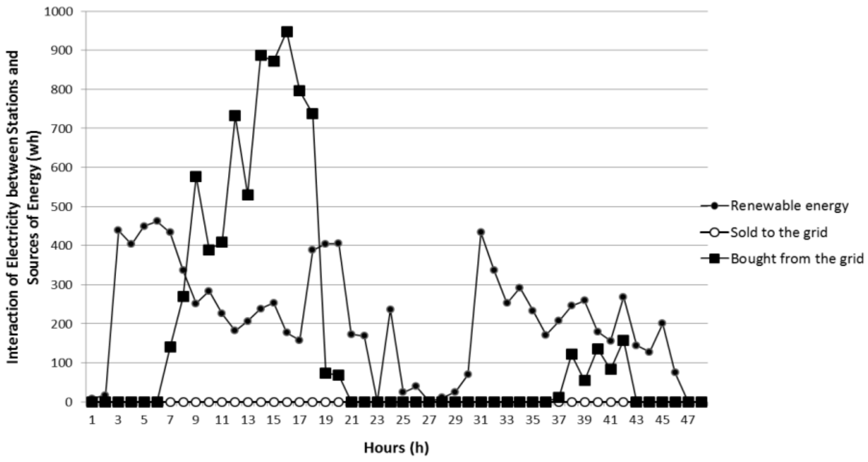


Figure 5-18 Power sources for designed station for policy P13

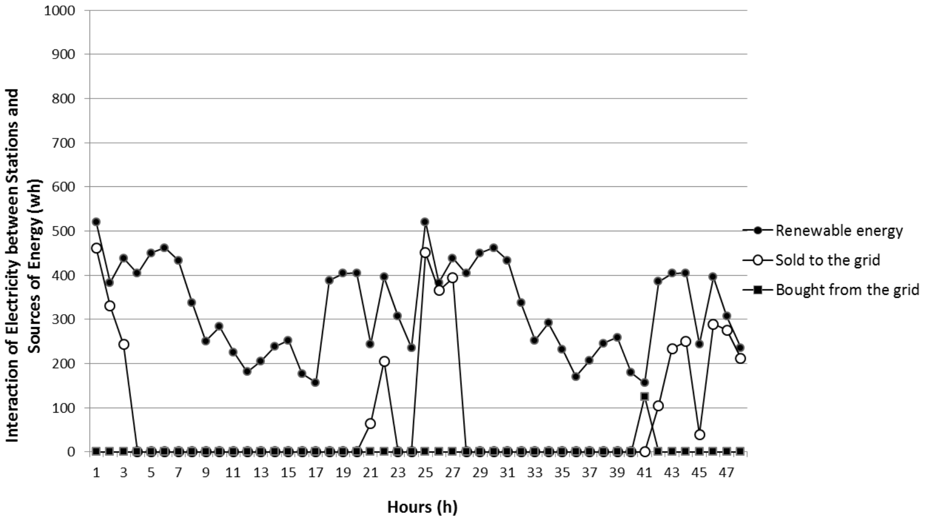


Figure 5-19 Interaction of electricity between a station and power sources for policy P10 in which all goals are weighted equally (w1=0.33, w2=0.33, w3=0.33)

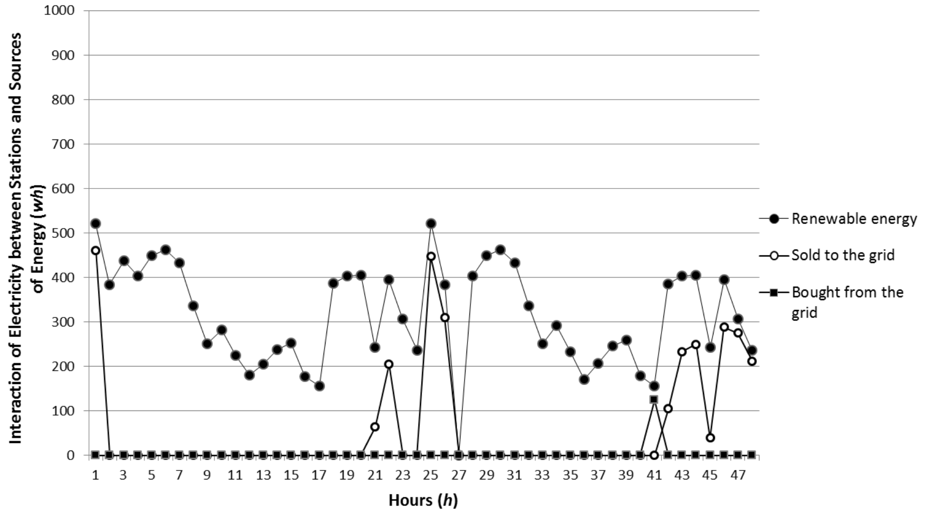


Figure 5-20 Interaction of electricity between a designed station and power sources for policy P7 (w1, economic drivers =0.25, w2, environmental drivers =0.25, w3, social drivers =0.5)

<u>Results related to Task 3 (Section 5.1.3)</u>: In the previous sections, the results related to designing a PHEV charging station are shown and explained. In Figure 5-23, the results related to the location of charging stations and their installed charging spots for three years are shown.

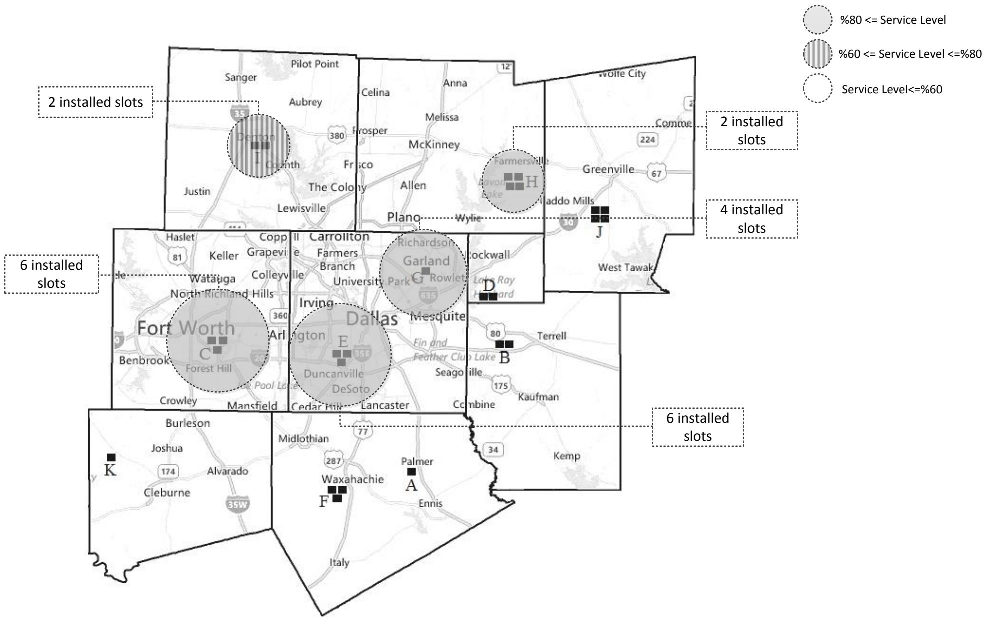


Figure 5-21Selected clusters for locating charging stations with the installed charging spots 2015

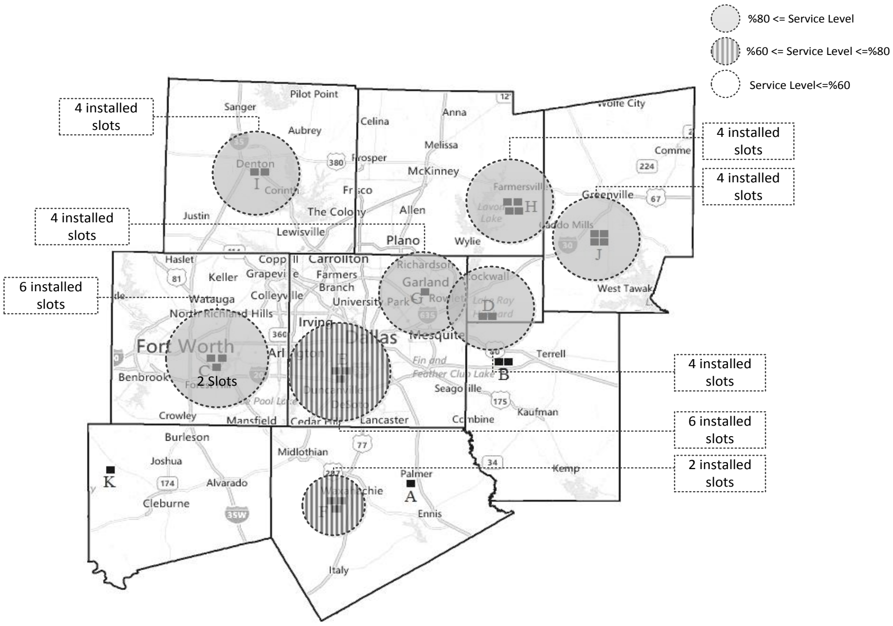


Figure 5-22 Selected clusters for locating charging stations with the installed charging spots 2016

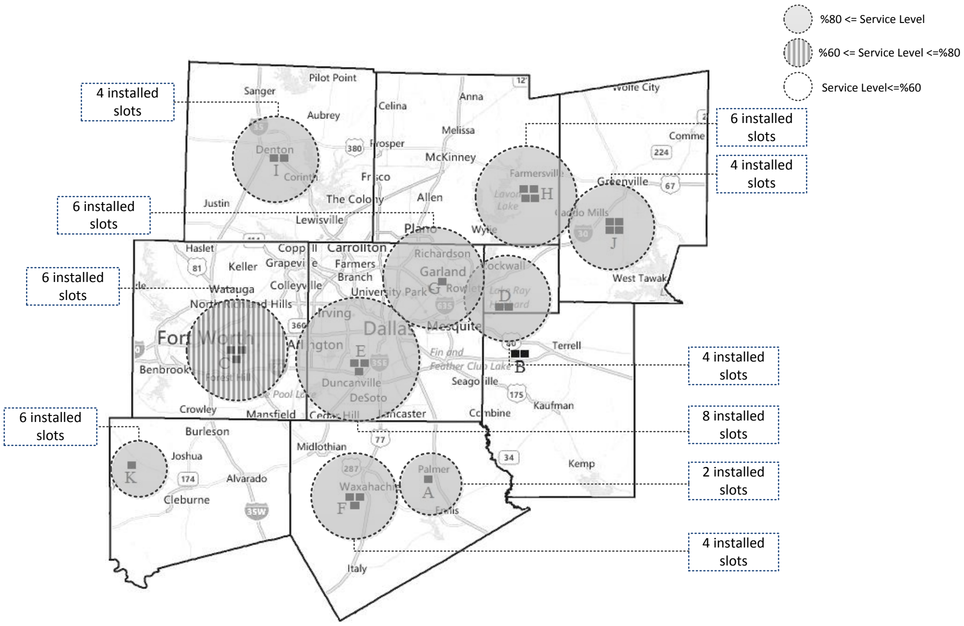


Figure 5-23 Selected clusters for locating charging stations with the installed charging spots 2017

As is shown in Figures 5-21 to 5-23, by increasing the demand of PHEVs, higher numbers of charging stations with higher number of installed charging spots are located in the region.

5.7 EMPIRICAL PERFORMANCE VALIDATION

In this chapter, the MLIN method is demonstrated based on the example of designing a bi-level network of PHEV electric charging stations considering sustainability. In this section, the usefulness of the MLIN method is argued via validating Hypothesis 1, which is the empirical performance validation in the validation square shown in Figure 5-24.

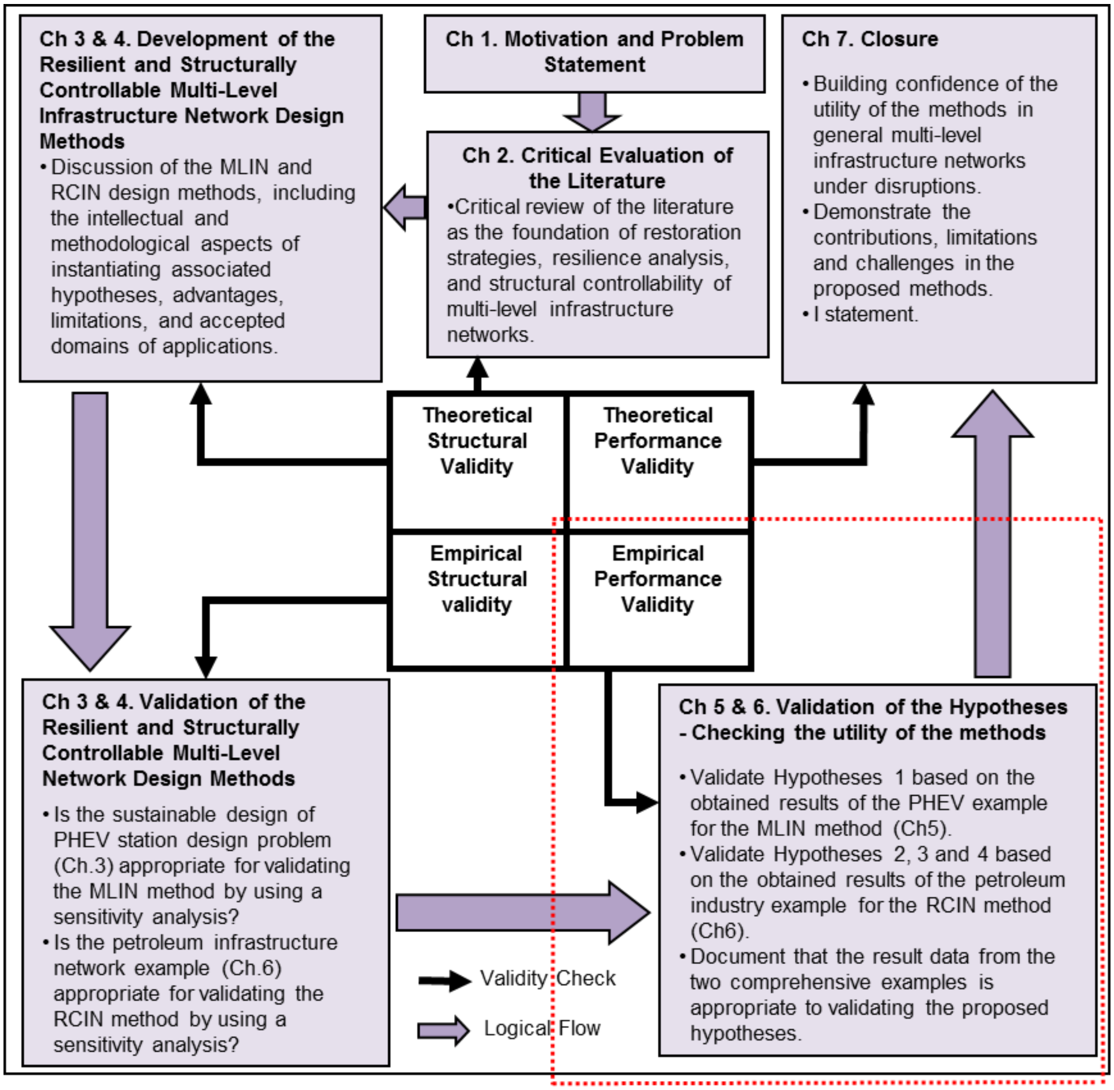
As it is shown earlier in Table 5-1, Research Hypothesis 1 is defined as follows.

Both operational and strategic decisions in multi-level decisions (e.g., the node-level (e.g., scheduling of the production line) and network-level (e.g., connection between suppliers, production facilities, and distributers) decisions are dependent on having an integrated design method.

Three tasks are defined in Section 5.1.3 in order to evaluate Hypothesis 1 and consequently the MLIN method as the empirical performance validation in the validation sqaure. Each of the tasks are interpreted based on the achieved results in Section 5.6 as follows.

Task 1: Validate that using the surrogate modeling approach in integrated estimation of the simulation model discussed in Sections 3.4 and 3.5 help in simulating the stochastic behavior of PHEV drivers and decreasing the computational time. This task is the demonstration for validating Hypothesis 1 discussed in Chapter 1.

***Result 1*:** In order to consider the stochastic behavior by PHEV drivers a simulation model is developed. Arrival rates of drivers, number of charging spots per station and waiting time limits are considered as stochastic parameters in the simulation model (see Section 5.4). For different values of stochastic parameters, the simulation model should be ran and results should be analyzed. However, in order to decrease the computational time, Multi-Variant Adaptive Regression Splines (MARS) as a surrogate modeling is used. Results are shown in Figures 5.13 and 5.14.



Ch 3 & 4. Development of the Resilient and Structurally Controllable Multi-Level Infrastructure Network Design Methods

- Discussion of the MLIN and RCIN design methods, including the intellectual and methodological aspects of instantiating associated hypotheses, advantages, limitations, and accepted domains of applications.

Ch 1. Motivation and Problem Statement

Ch 2. Critical Evaluation of the Literature

- Critical review of the literature as the foundation of restoration strategies, resilience analysis, and structural controllability of multi-level infrastructure networks.

Ch 7. Closure

- Building confidence of the utility of the methods in general multi-level infrastructure networks under disruptions.
- Demonstrate the contributions, limitations and challenges in the proposed methods.
- I statement.

Ch 3 & 4. Validation of the Resilient and Structurally Controllable Multi-Level Network Design Methods

- Is the sustainable design of PHEV station design problem (Ch.3) appropriate for validating the MLIN method by using a sensitivity analysis?
- Is the petroleum infrastructure network example (Ch.6) appropriate for validating the RCIN method by using a sensitivity analysis?

Ch 5 & 6. Validation of the Hypotheses - Checking the utility of the methods

- Validate Hypotheses 1 based on the obtained results of the PHEV example for the MLIN method (Ch5).
- Validate Hypotheses 2, 3 and 4 based on the obtained results of the petroleum industry example for the RCIN method (Ch6).
- Document that the result data from the two comprehensive examples is appropriate to validating the proposed hypotheses.

Figure 5-24 Validation strategy of the dissertation

<u>Task 2</u>: Validate that using the compromise Decisions Support Problem (cDSP) in considering conflicts among the system goals discussed in Section 3.7. This task is the demonstration for validating Hypothesis 1 discussed in Chapter 1.

<u>Results 2</u>: Using the compromise Decision Support Problem (cDSP) can help in considering the conflicts among system goals. As it is shown in Figure 5-15 and Table 5-7, the conflicts among system goals (sustainability drivers) are considered. One feasible approach toward analyzing the solution space among conflicting system goals is using Ternary plots. As is shown in Figure 5-16 – 5-18, there is possibility in exploring the solution space with the help of the cDSP.

<u>Task 3</u>: Validate that using the MLIN method explained in Section 3.4 – 3.6 can help in considering both the operational and strategic decisions with both the node and network levels considerations. This task is the demonstration for validating Hypothesis 1 discussed in Chapter 1.

<u>Results 3</u>: There are some operational and strategic decisions associated with the network of PHEV charging stations. Through Figures 5-19 – 5-23, results of several operational decisions are addressed which are mainly related to the node-level decisions. In addition, as is shown in Figure 5-24, the results of the strategic decisions related to the network-level decisions are obtained via using the MLIN method. These results, both the operational and strategic – both the node-level and network-level decisions, indicate the importance of using the MLIN method in designing integrated bi-level infrastructure network.

All these results indicate the advantages of using the MLIN method. In summary, it is important to decrease the complexity in designing network. However, when both operational and strategic decisions in both node and network levels should be considered, the proposed MLIN method help designers in doing that.

5.8 CHAPTER SYNOPSIS

In this chapter the usefulness of the MLIN method is established (Empirical Performance Validation) with an example of the bi-level network design PHEV charging stations considering sustainability.

In Section 5.1, the introduction and problem statement to the PHEV charging station network design is provided. The purpose and capability of the design problem are discussed. It is argued that why the PHEV charging station network design is an appropriate example for validating the MLIN method (Empirical Structure Validation). In Section 5.1.3, the three tasks for validating the functionality of the MLIN method based on this example is planned.

In Section 5.2, the overall procedure of the MLIN method, which is discussed earlier in Chapter 3, is reviewed in terms of the PHEV example. In Section 5.3, the first step of the proposed MLIN method. The inputs and overall requirements, is discussed. In Section 5.4, both the simulation model and surrogate model are explained. In Section 5.5, the cDSP construct for designing PHEV charging stations considering sustainability is explained.

In Section 5.6, results gained from the simulation model, the surrogate modeling approach (MARS) and the cDSP are compared and discussed. In Section 5.7, the validation results are summarized checking the empirical performance validity.

In the next chapter, a network of the petroleum industry is applied to validate the RCIN method discussed in Chapter 4.

CHAPTER 6 RESILIENT AND STRUCTURALLY CONTROLLABLE INFRASTRUCTURE NETWORKS OF THE PETROLEUM INDUSTRY

In Section 6.1, an introduction and the problem statement of designing resilient and controllable infrastructure networks, and an overview of the proposed RCIN method are presented. The purpose and capability of the design problem are discussed. It is argued why the petroleum infrastructure network example is an appropriate example for validating the RCIN method (Empirical Performance Validation). In addition, three tasks for validating the functionality of the RCIN method based on this example are planned.

In Section 6.2, the RCIN method is reviewed and explained in the context of the example of the petroleum industry. In Section 6.3, the first stage of the RCIN method (i.e., strategic design of the infrastructure network) is applied for the petroleum example and all results are discussed, and the related mathematical model is presented. In Section 6.4, the example of the petroleum industry is used, and results for all five-control policies are discussed for it. In Section 6.5, the results of the operational stage of the RCIN method for the petroleum example are discussed. In addition to considering the occurrence of disruptions on infrastructure network, both the supply and demand uncertainties are considered as well and addressed in Section 6.6. In Section 6.7, the exploration of the solution space for the petroleum example is explained, and finally in

Section 6.8, Empirical Performance Validation of the RCIN method via the petroleum example is performed.

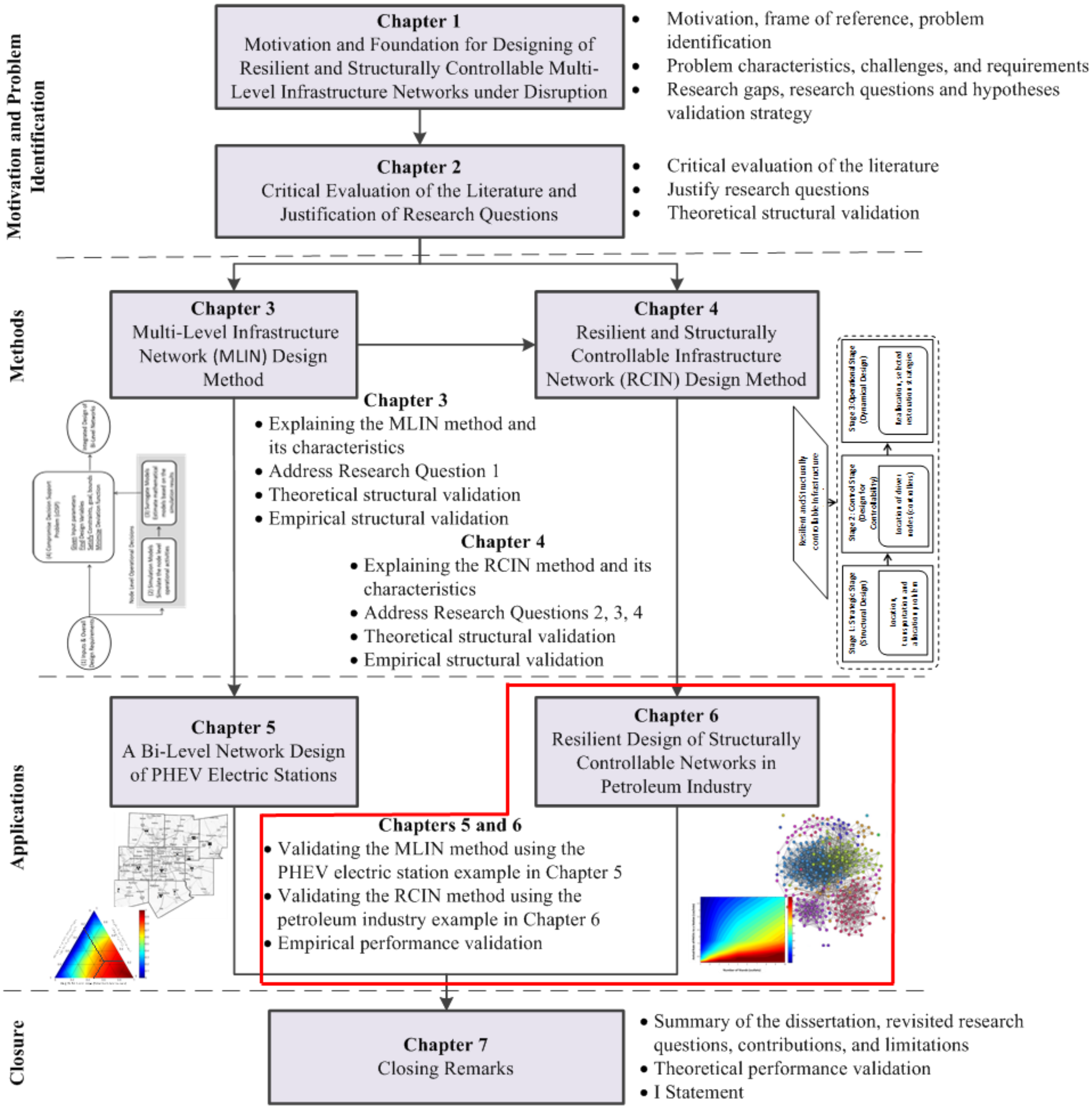


Figure 6-1 Dissertation structure

6.1 INTRODUCTION AND PROBLEM STATEMENT OF DESIGNING THE INFRASTRUCTURE NETWORK OF THE PETROLEUM INDUSTRY

Infrastructure network design involves determining the network structure and the distribution of resources over the structure while disruptions happen. In other words, disruptions are a fact of life, the larger an infrastructure network, the more difficult it is to cope with disruptions. In a multi-layer infrastructure network, disruptions can occur at any of facilities (nodes) or transportation routes (links). In order to manage disruptions, mitigate risk of disruptions, recover the system after occurrence of disruptive events, and protect the customer service level, designing resilient infrastructure networks is essential. Applying structural controllability is an approach to manage risk of disruptions and increase the resilience of infrastructure networks. Using the structural controllability means to identify driver nodes in infrastructure networks that from which all facilities are accessible.

In this chapter, *the problem of designing resilient infrastructure networks is introduced when structural disruptions happen in the infrastructure network of the petroleum. In this problem, notions of the structural controllability and resilience strategies are developed in order to manage the risk of disruptions with having driver nodes all over infrastructure network structures. In other words, it is considered how one can select the most efficient (e.g., highest service level or lowest tardiness) and least redundant (e.g., least operational, strategic and control costs) resilience strategies, number and locations of driver nodes (see Sections 4.5 and 4.6 to know about driver nodes and resilience strategies) in the face of disruption scenarios to* *mitigate the risk of disruptions in the infrastructure network of the petroleum industry example.*

In Table 6-1, which is a part of Table 1-3, the requirements for the addressed problem are shown and connected with the research questions, research hypotheses and outcomes.

Table 6-1 Connection between the problem, requirement, research question, and outcome

Problem	**Requirement**	**Research Questions**	**Research Hypotheses**	**Outcome**
Resilience analysis	• Quantitative measures for analyzing resilience; • Method for evaluating the trade-off between redundancy and effectiveness.	RQ2: What is the method to evaluate the system resilience as a function of time considering redundancy and flexibility measures?	Implemented the method for the resilient design of infrastructure networks under disruptions while the time is considered, provides an effective and efficient method to consider the redundancy and effectiveness of the proposed method.	RCIN method with considering “tardiness”, “service level”, and “cost” as resilience measures - The method is explained in Chapter 4 - An example is solved based on the RCIN method in Chapter 6
Structural controllability with driver nodes	Algorithms to select the minimum number of driver nodes.	RQ3: What is the method to select the minimum number of driver nodes to get structural control of the infrastructure network?	The development of algorithms for maximum matching and minimum input theory results in finding the location and the minimum number of driver nodes.	RCIN method with considering the minimum number of driver nodes - The method is explained in Chapter 4 - An example is solved based on the RCIN method in Chapter 6
Restoration strategies	Method for designing resilient and controllable infrastructure networks through selecting the best restoration strategies.	RQ4: What is the method to design a resilient infrastructure network through selecting best restoration strategies?	Defining possible restoration strategies is dependent on anticipation, preparedness, adaptability, and recovery phases.	RCIN method with considering resilience strategies - The method is explained in Chapter 4 - An example is solved based on the RCIN method in Chapter 6

As is shown in Table 6-1, Research Questions 2, 3, and 4 are answered using the proposed RCIN method and are verified using an example of the infrastructure network of the petroleum industry in this chapter.

As it is mentioned in Chapter 4, the main objective in this dissertation is the development of methods for the resilient and structurally controllable design of multi-level infrastructure networks with consideration of occurrence of disruptions. Two aspects are considered in this regard: (1) multi-level infrastructure network design aspect, and (2) disruption management aspect. In Figure 6-2, both of these two aspects are shown. The multi-level infrastructure network aspect is addressed in Chapters 3 and 5. As is shown in the right side of Figure 6-2, managing disruptions has two parts: one is the structural controllability of infrastructure networks that is related to the location and number of driver nodes (i.e., controllers), and the other one is the resilient of restoration strategies which is related to recovering disrupted infrastructure networks using various restoration strategies.

In this chapter, the disruption management aspect (see Figure 6-2) is considered and the proposed resilient and structurally controllable infrastructure network (RCIN) method is solved and verified using a comprehensive example of the infrastructure network of the petroleum industry. In Section 6.1.1, the considered example in this chapter, its assumptions and limitations, and its appropriateness for the RCIN method are addressed. In Section 6.1.2, several tasks are defined in order to verify the model from the empirical performance validation perspective.

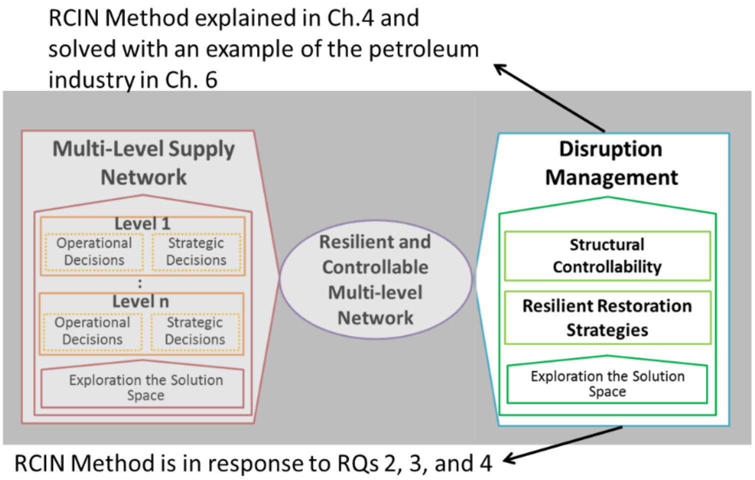


Figure 6-2 Resilient and structural controllability of multi-level networks

6.1.1 Infrastructure network of the Petroleum Industry: Assumptions and Limitations

In this section, based on the presented problem statement in Section 6.1, through explaining the petroleum example, the considered boundary, assumptions, limitations, and input data are described. A five-layer infrastructure network includes refinery, hub, warehouse, distribution center, and market layers are modeled. As is shown in Figure 6-3, only the forward infrastructure network is considered in this network.

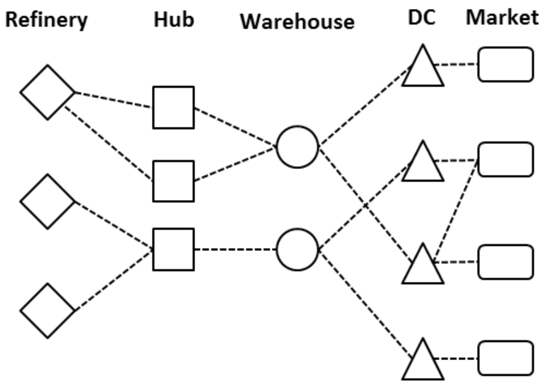


Figure 6-3 Petroleum infrastructure network structure

Petroleum components are produced in refineries from crude oil through the distillation and refining processes. In hubs, the petroleum products are produced using components. Warehouses may store (if necessary) products and ship them to distribution centers. The function of distribution centers (DC) is to distribute the products to markets; no time activity is considered for DCs. It is assumed that the transportation time between layers and production time in refineries, and hubs are not zero. In other words, the transportation time between layers, production time in production facilities, and expected inventory time in warehouses are considered. 3 refineries in the first layer, 3 hubs in the second layer, 3 warehouses in the third layer, 4 distribution centers in the fourth layer, and 8 markets in the last layer of the infrastructure network are considered. The capacity production time, cost of production and the setup cost of the production line for different layers are addressed in Tables 6-2 to 6-5.

Table 6-2 Characteristics of refineries in the petroleum infrastructure network

	Refinery 1 (Sweden)	**Refinery 2 (Sweden)**	**Refinery 3 (Sweden)**
Production Capacity (parts)	12000	12000	12000
Production time (*hr*)	10		
Setup cost of production lines ($)	1000	1000	1000
Production cost per component ($)	0.15	0.15	0.15

Table 6-3 Characteristics of hubs in the petroleum infrastructure network

	Hub 1 (USA)	**Hub 2 (Belgium)**	**Refinery 3 (Germany)**
Production Capacity (parts)	4000	3500	4500
Production time (*hr*)	4	6	4
Setup cost of production lines ($)	750	750	750
Production cost per product ($)	0.4	0.4	0.4

Table 6-4 Characteristics of warehouses in the petroleum infrastructure network

	Warehouse 1 (Germany)	**Warehouse 2 (Turkey)**	**Warehouse 3 (USA)**
Inventory Capacity (parts)	4000	3500	4500
Average inventory time for a product (*hr*)	4	6	4
Cost of operating a warehouse ($)	500	500	500

Table 6-5 Characteristics of distribution center in the petroleum network

	Distribution Center 1 (Brazil)	**Distribution Center 2 (France)**	**Distribution Center 3 (UAE)**	**Distribution Center 4 (USA)**
Capacity (parts)	2000	4000	3000	4000
Cost of operating a distribution center ($)	200	200	200	200

Occurrence of disruptions is considered as disruption scenarios. Each set of simultaneous disrupted facilities is called a disruption scenario and is associated with a finite probability of occurrence. Each disruption scenario occurs independently. In other words, dependence among disruption scenarios is not considered in the RCIN method. Two types of states are considered: the steady state when no disruption happens and the disrupted state when a disruption(s) happens. It is assumed that after a disruption event, the network returns to its prior steady state before that another disruption scenario occurs. In Figure 6-4, a possible disruption in the infrastructure network is shown. As is shown in Figure 6-4, a disruption happens in a warehouse in the third layer, and no product can be shipped from the disrupted warehouse to DCs. 10 disruption scenarios are considered to solve the RCIN method.

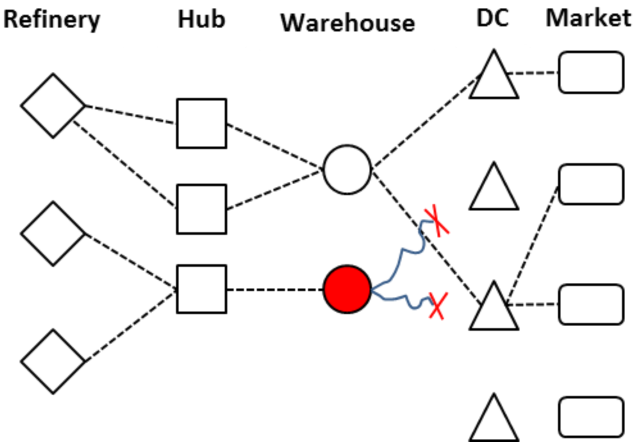


Figure 6-4 A possible disruption in the petroleum infrastructure network structure

In addition to disruptions, the demand and supply uncertainty is considered as the scenario-based approach, which is explained in Section 6.6. Resilience strategies are considered in order to manage disruptions, mitigate risk of disruptions, recover the system after occurrence of disruptive events, and protect the customer service level. In order to manage and mitigate risk of disruptions, two resilience strategies are considered in the proposed RCIN method: (1) flexible inventory capacity for disrupted distribution centers, and (2) flexible production or inventory capacity for disrupted refineries, hubs or warehouses. Holding flexible inventory capacity at warehouses is a strategy in order to mitigate the risk of disruptive events on warehouses. Flexible production capacity is a considered strategy for mitigating risk of disruptive events on production facilities such as refineries and hubs.

In this section, the considered example, its appropriateness, assumptions, and limitations are addressed. In next section, several tasks are defined for the proposed RCIN method and its empirical performance validation.

6.1.2 Planning Tasks for Empirical Performance Validation

As discussed in the previous section, the petroleum industry problem is an appropriate example for validating the RCIN method based on Hypotheses 2, 3, and 4. However, to build confidence in the usefulness of the RCIN method (Empirical Performance Validation) discussed in Chapter 4, three tasks are defined in this section. These tasks are performed through this Chapter using the petroleum industry example, and the results are discussed in Section 6.8.

Task 1: Validate that using the Lin's Theorem and Minimum Input Theorem (discussed in Section 2.3.3) in determining the location and minimum number of driver nodes discussed in Section 4.5 help in structural controllability of a disrupted infrastructure network. This task is the demonstration for validating Hypothesis 3 discussed in Section 1.5.

Task 2: Validate that using the tardiness, service level, and control cost as resilience measures can help in evaluating the resilience discussed in Sections 6.3 and 6.5. This task is the demonstration for validating Hypothesis 2 in Section 1.5.

Task 3: Validate that using flexible production capacity, flexible inventory capacity and back-up inventory are effective restoration strategies for mitigating the risk of disruptions discussed in Section 6.5. This task is the demonstration for validating Hypothesis 4 in Section 1.5.

In this section, tasks for the empirical performance validation are planned. These tasks are revisited in Section 6.9 for the empirical performance validation and based on the results achieved through Sections 6.4 to 6.6. In next section, first an overview of the proposed RCIN method is given, and then results of applying the example for the RCIN method are presented in Section 6.3 to 6.5.

6.1.3 Solution Algorithms

In this section, the computational complexity of the RCIN method and applied solution approaches for each stage of the RCIN method is explained.

Strategic Stage (Stage 1): The model presented in this stage is a non-linear mixed integer programming model. There are 21 binary variables for opening/closing of locations in different layers of the supply chain and 186 binary variables for the selected transportation arcs and modes between different layers of the supply chain. There are 192 continuous variables in Stage one which represent the flow of products through the network. The model is linearized and solve using Gurobi Optimizer. The model and input data are coded using Python 2.7 and linked with Gurobi Optimizer. The code for the RCIN method is presented in Appendix B.

Structural Controllability Stage (Stage 2): In this stage two heuristic algorithms are used for finding the minimum number of driver nodes in the network. One heuristic algorithm is the maximum matching algorithm, and the second one is spanning cacti algorithm. The code for the RCIN method is presented in Appendix B.

Operational Stage (Stage 3): In this stage the number of binary variables decreased by 21 binary variables, but number of continuous variables increased by 372. This helps in decreasing the computational time. The model and input parameters are codes in Python 2.7 and is solved suing Gurobi Optimizer. The code for the RCIN method is presented in Appendix B.

6.2 THE RCIN METHOD FOR DESIGNING A RESILIENT AND CONTROLLABLE PETROLEUM NETWORK UNDER DISRUPTIONS

Designing infrastructure networks involves determining the network configuration and the distribution of resources over the network. Basically, designing infrastructure networks includes two types of decisions: first, decisions on the location and capacity of facilities and connections between facilities (strategic decisions); and, second, assigning the demand to available facilities and identifying production planning along the network (operational decisions).

In addition, designing infrastructure networks requires not only robustness to cope with errors during its operations, but also resilience as ‘the ability of a system to return to its original state or move to a new, more desirable state after being disturbed’. Using structural controllability as a feasible and convincing approach to mitigate risk of disruptive events in infrastructure networks (control decisions) is proposed in this dissertation. Considering these three aspects of decisions, such as the strategic decisions, control decisions, and operational decisions, the proposed three-stage method for designing resilient and structurally controllable infrastructure networks (RCIN) is shown in Figure 6-5.

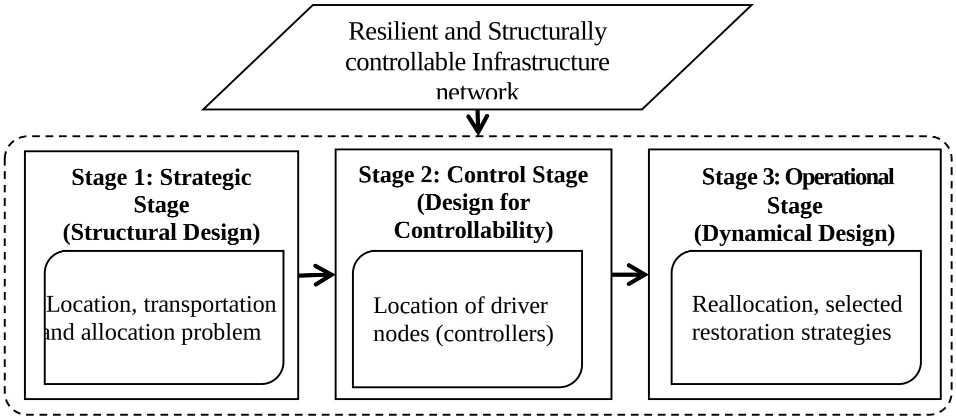


Figure 6-5 Three-stage method for resilient and structurally controllable infrastructure network design

As is shown in Figure 6-5, the proposed RCIN method includes three stages, such as the strategic stage, control stage, and operational stage. Each of these stages is explained with detail in Sections 4.4 to 4.6. Using the proposed comprehensive example of the petroleum infrastructure network (see Section 6.1.1), the results of each of these stages are presented in Sections 6.3 to 6.5 as follows.

6.3 STAGE 1 OF THE RCIN METHOD: STRATEGIC DESIGN OF THE RESILIENT AND STRUCTURALLY CONTROLLABLE INFRASTRUCTURE NETWORK OF THE PETROLEUM INDUSTRY

The focus of the first stage is on the strategic design of infrastructure networks as is explained in Section 4.4. In Figure 6-6, the potential locations for all facilities in the considered infrastructure network are shown. Refineries, hubs, warehouses, distribution centers and markets are the five layers of the infrastructure network, respectively. Although in this section, the RCIN method is developed for an oil petroleum infrastructure network with five layers, expanding or shrinking the network with more or less number of layers with even different functions for facilities can be implemented. The word formulation and mathematical formulation are presented in Section 4.4. In order to explore the solution space, different weight sets for three goals are defined in the first stage. More explanation on the solution space exploration is described in Section 6.7. All weight sets are addressed in Table 6-6.

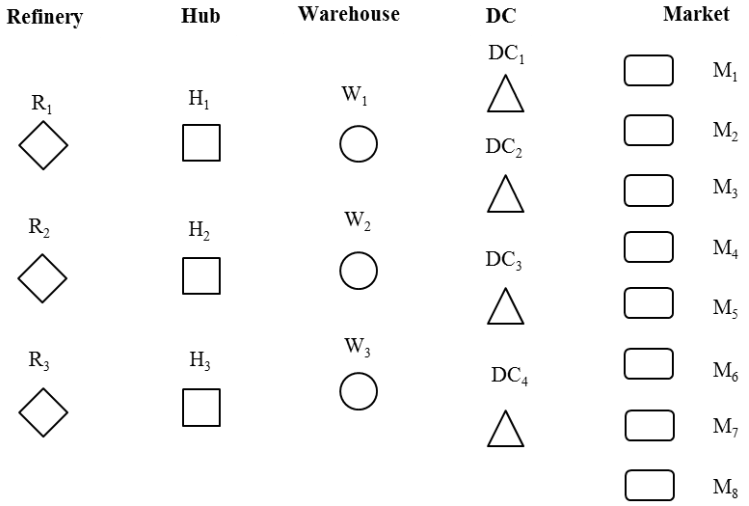


Figure 6-6 The potential structure of the petroleum example

Table 6-6Weight sets for three goals in Stage 1

Weight Set	**Conflicts between Goals**	**W_1**	**W_2**	**W_3**	$\sum_{i=1}^{3} W_i = 1$
WS_1	Lower tardiness (G_1)	1	0	0	1
WS_2	Lower cost (G_2)	0	1	0	1
WS_3	Higher service level (G_3)	0	0	1	1
WS_4	All goals, G_3 emphasized	0.1	0.1	0.8	1
WS_5	All goals, G_2 emphasized	0.1	0.8	0.1	1
WS_6	All goals, G_1 emphasized	0.8	0.1	0.1	1
WS_7	All goals, G_3 emphasized	0.2	0.2	0.6	1
WS_8	All goals, G_2 emphasized	0.2	0.6	0.2	1
WS_9	All goals, G_1 emphasized	0.6	0.2	0.2	1
WS_{10}	All goals	0.33	0.33	0.33	~1
WS_{11}	All goals, G_3 emphasized	0.25	0.25	0.5	1
WS_{12}	All goals, G_2 emphasized	0.25	0.5	0.25	1
WS_{13}	All goals, G_1 emphasized	0.5	0.25	0.25	1

According to the 13 weight-sets defined in Table 6-6, the normalized values for three goals are shown in Figure 6-7.

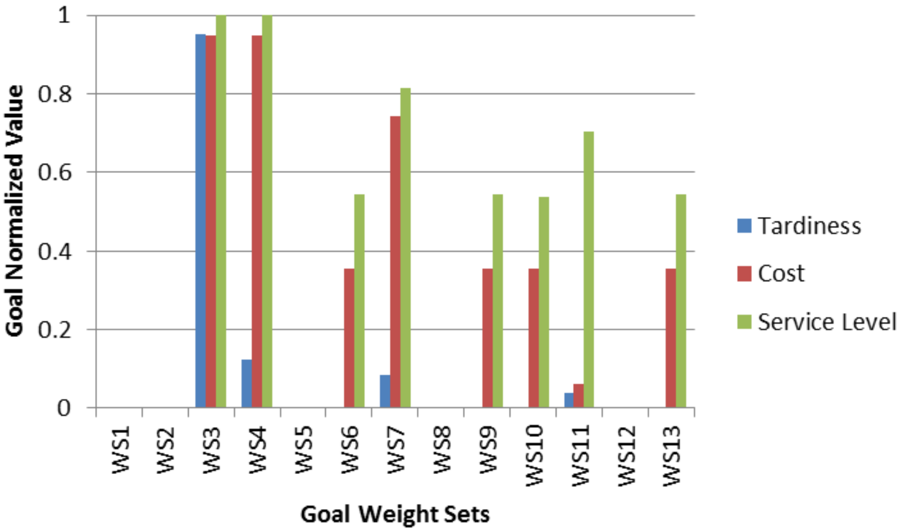


Figure 6-7 Normalized value of three goals of Stage 1

As is shown in Figure 6-7, the normalized values of total cost and tardiness goals increase when the weight of the third goal (i.e., service level) increases. When the normalized value of the service level is more than 75%, there will be tardiness in meeting the demand of customers. It can be concluded that the method is sensitive to the changing of weights of these three goals; consecutively, because of this sensitivity, the exploration of the solution space is required (see Section 6.7).

In Figure 6-8, as an example, the normalized value of the three goals for the seventh weight set is presented. As is shown in Figure 6-8, since the weight of the service level is more than two other goals, more than 83% of the demand in the markets is met, while there is lateness in delivering the demand to the market.

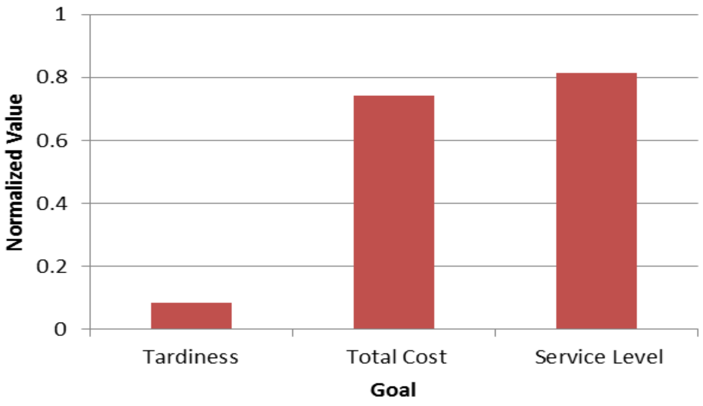


Figure 6-8 Normalized value of goals in Stage 1 (W1=0.2, W2=0.2, W3=0.6)

For this weight set, the flow of products is shown on the infrastructure network in Figure 6-9. As is shown, for meeting 83% of the demand two refineries and two hubs are located in the network. The demand in Market M7 is not fully met which it is because of the transportation consideration in delivering the products to customers (i.e., increase in the tardiness). This structure is used as an input for the Stage 2.

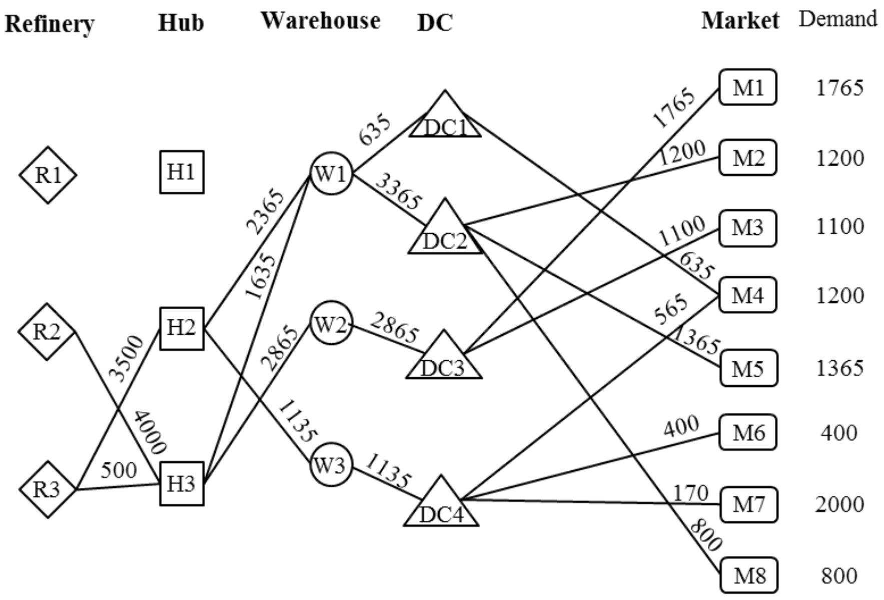


Figure 6-9 Product flow in the infrastructure network (W1=0.2, W2=0.2, W3=0.6)

The maximum allowed time for delivering the products in the market is considered as 5 days. However, the results can be sensitive to this parameter. Therefore, the tardiness when the maximum allowed time is changing is analyzed. As is shown in Figure 6-10, if the maximum allowed time is 6 days or more, there is not any tardiness in meeting the current demand of the markets. However, the network cannot have the real time delivery (i.e., zero maximum allowed time) of the products to the market since the tardiness will have its highest possible value.

When 4 days is considered as the maximum allowed time for delivering products, the normalized value of the service level is 0.545, and only one refinery is located. However, if 5 days is considered as the maximum allowed time, two refineries will operate and the service level increases up to 83%.

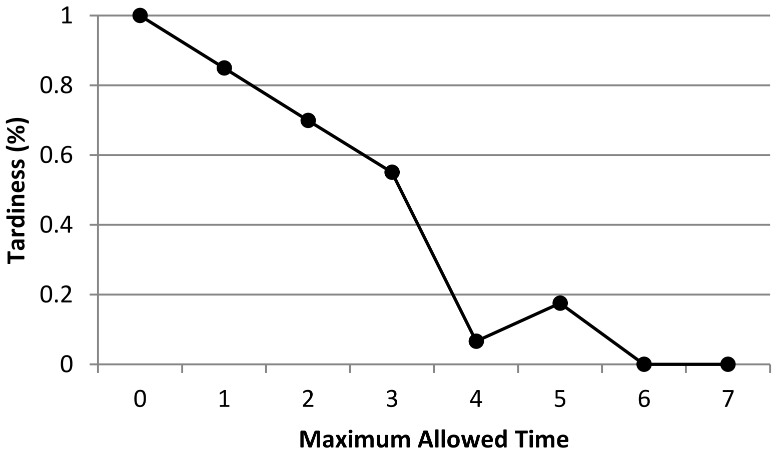


Figure 6-10 Analyzing the normalized value of the tardiness by changing the maximum allowed time

The designed structure as the output of Stage 1 (i.e., strategic design) for Stage 2 is analyzed from the network perspective. In Figure 6-11, an illustration of the designed infrastructure network is shown.

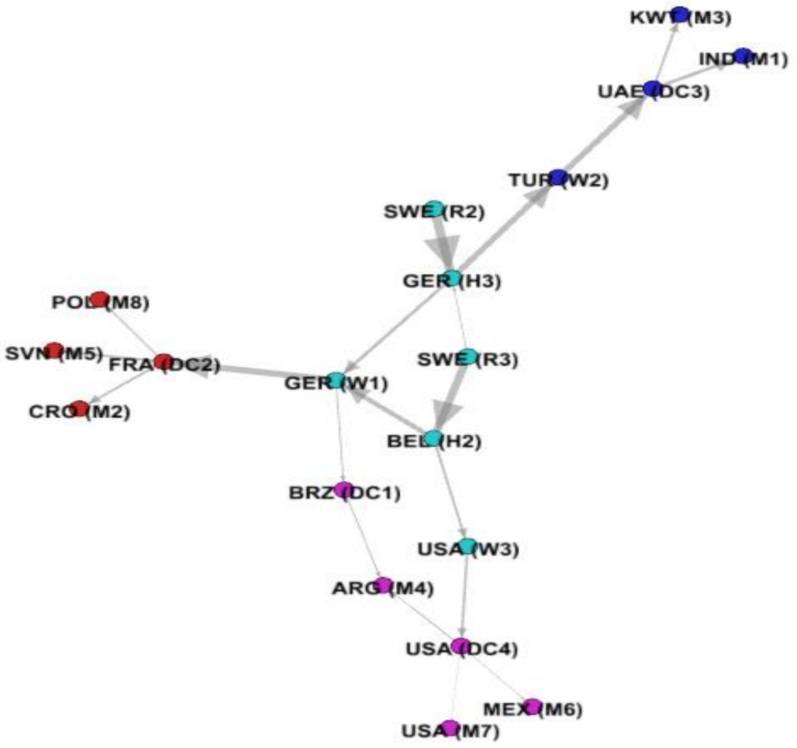


Figure 6-11 Illustration of the designed infrastructure network (W1=0.2, W2=0.2, W3=0.6)

The diameter of this network structure is 4 nodes, and it has three connected components. The volume flow of products is shown as the thickness of each link. The modularity of this structure is 0.495 and shown by four different colors. The modularity measures the strength of division of a network into modules (also called groups, clusters or communities). Networks with high modularity have dense connections between the nodes within modules but sparse connections between nodes in different modules. The value of the modularity lies in the range [−1/2, 1).

In this section, the results of Stage 1 are explained. The output of Stage 1 is the designed structure of the infrastructure network. The designed structure is used as an input for Stage 2.

6.4 STAGE 2 OF THE RCIN METHOD: STRUCTURALLY CONTROLLABLE DESIGN OF THE RESILIENT AND STRUCTURALLY CONTROLLABLE INFRASTRUCTURE NETWORK OF THE PETROLEUM INDUSTRY

The input for the second stage of the RCIN method is the designed structure from Stage 1. In Stage 2, the focus is on the structurally controllable design of infrastructure networks. The proposed resilience strategies are defined based on the structural controllability. The structural controllability is based on identifying a driver node(s) in each layer of a disrupted infrastructure network. All facilities are accessible through selected driver nodes. A driver node is fortified against disruptions and is equipped with flexible back-up inventory or flexible production capacity. Fortifying driver nodes result in decreasing the impact of disruptions on these facilities to 25%. When disruptions happen, because of using driver nodes, and hence having access to all markets, the impact of disruptive events can be decreased tremendously.

As is addressed in Section 4.3, three steps are proposed to design a structurally controllable structure. Following each of these steps, it is shown as follows that how the number and location of driver nodes can be identified.

The designed structure from Stage 1 is shown in Figure 6-12. This structure is used and its bipartite structure is determined. The bipartite structure can be used in order to specify matched and unmatched nodes in the structure.

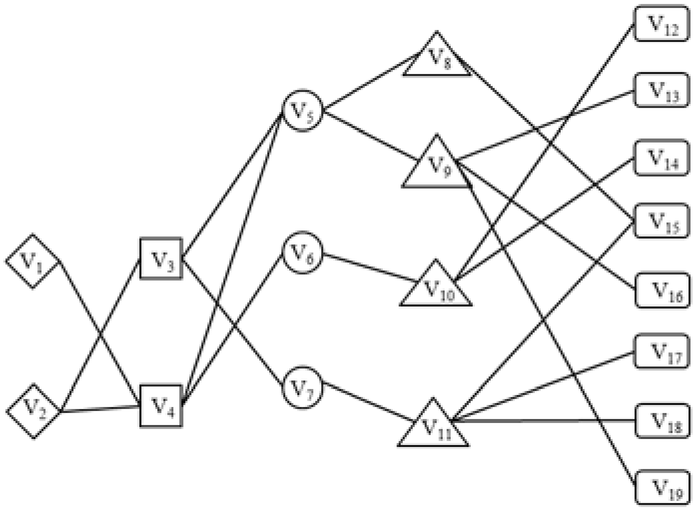


Figure 6-12 Designed structure from Stage 1

In Figure 6-13 the bipartite representation of facilities in the layers two and three of the designed structure is shown.

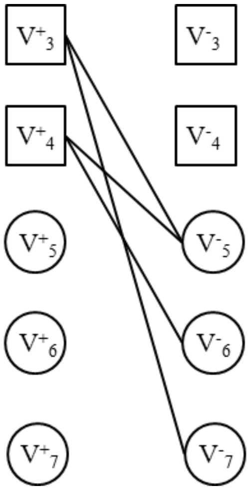


Figure 6-13 Bipartite representation of the second and third layers of the infrastructure network

The bi-partite representation of the designed structure can be used to determine the matched and unmatched nodes. In Figures 6-14, arcs in the red color are matched arcs, and the nodes connected to these arcs are matched nodes. The maximum matched is the one with the maximum number of matched nodes in a designed structure.

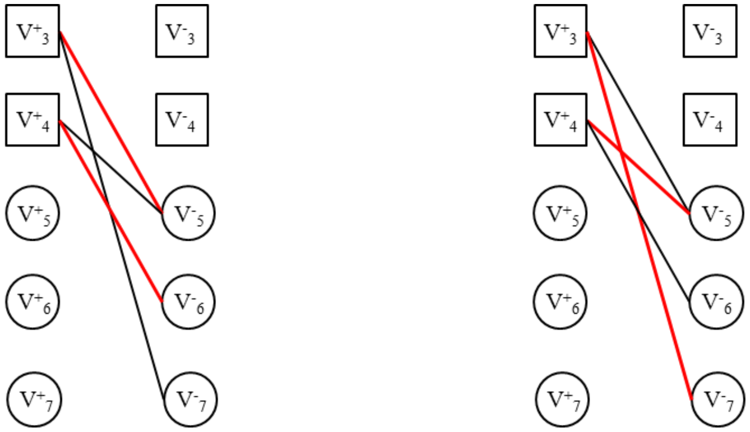
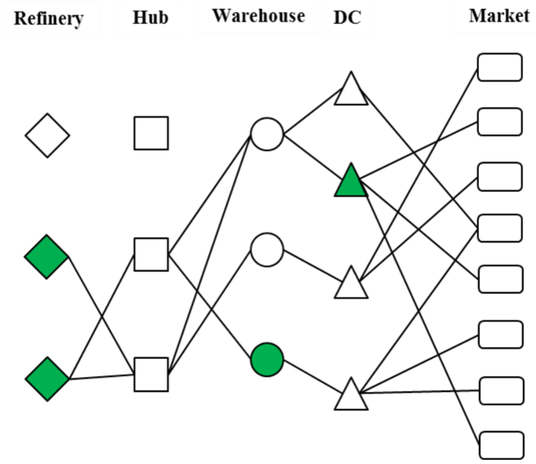


Figure 6-14 Two representations of matched arcs in the designed structure

Based on the result of the maximum matching, the location and number of driver nodes are determined and shown in Figure 6-15 in which green facilities are driver nodes.



Unmatched facilities are shown in green = Driver facilities (controllers) are shown in green

Figure 6-15 Location of driver nodes in the designed structure

Based on the results of the Lin's Theorem, only four driver nodes are located in the designed structure. However, from the infrastructure network perspective, more possibilities for the location and number of driver nodes are required. Therefore, four more possibilities for the location and number of drive facilities are defined, which with the original one (i.e., presented in Figure 6-15) form five control policies for the designed infrastructure network. These control policies and their representations are addressed as follows.

Control Policy 1: locate driver nodes on all unmatched nodes (see Figure 6-15)

Control Policy 2: locate driver nodes on all unmatched nodes and use auxiliary arcs if required (see Figure 6-16)

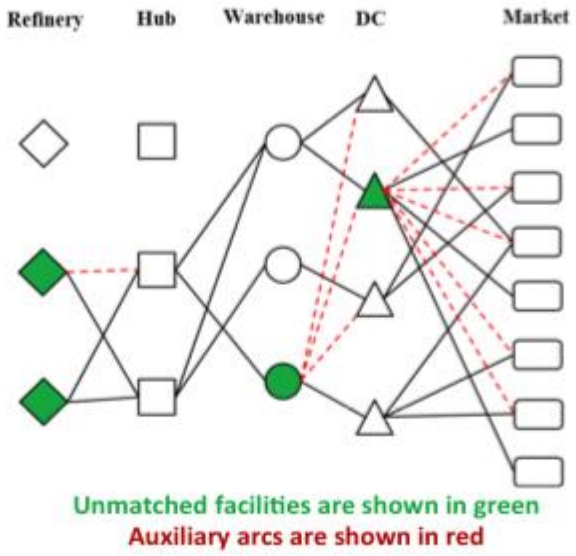


Figure 6-16 Illustration of driver nodes and auxiliary arcs for Control Policy 2

Control Policy 3: locate driver nodes on all unmatched nodes but each layer should have at least one driver node (see Figure 6-17)

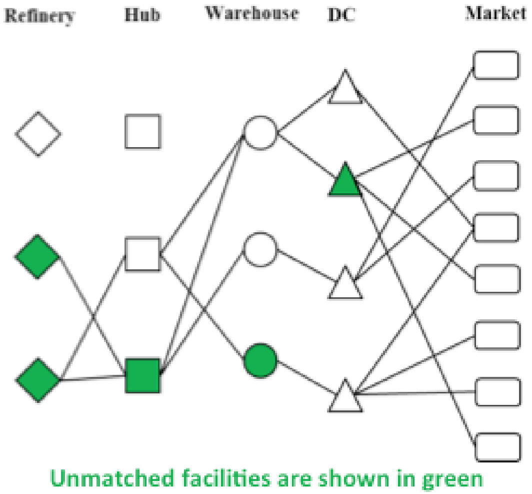


Figure 6-17 Illustration of driver nodes for Control Policy 3

Control Policy 4: locate one driver node on each layer of the network (see Figure 6-18)

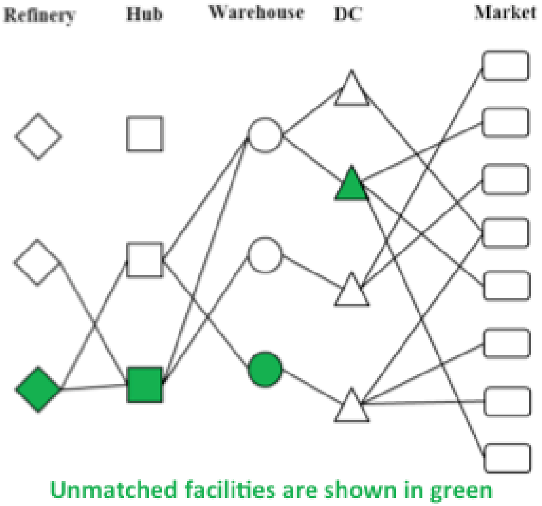


Figure 6-18 Illustration of driver nodes in Control Policy 4

Control Policy 5: locate one driver node on each layer of the network and add auxiliary transportation arcs (see Figure 6-19)

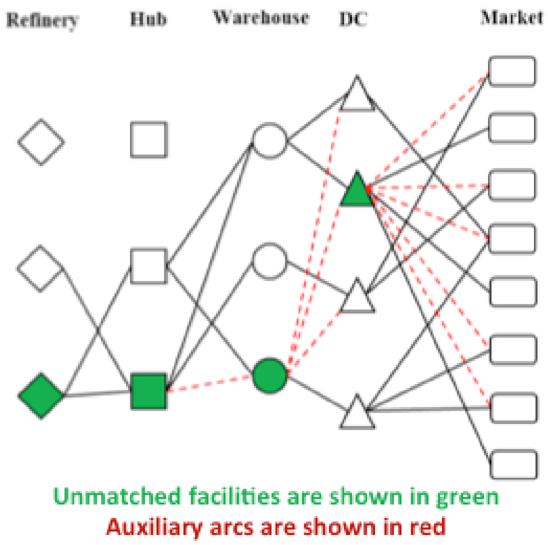


Figure 6-19 Illustration of driver nodes and auxiliary arcs in Control Policy 5

These control policies, which determine the location and number of driver nodes, are outputs of the Stage 2 of the RCIN method. Each of these control policies is a resilience strategy that can be applied for the designed structure from Stage 1. In next section, the infrastructure network is redesigned from the operational perspective.

6.5 STAGE 3 OF THE RCIN METHOD: OPERATIONAL DESIGN OF THE RESILIENT AND STRUCTURALLY CONTROLLABLE INFRASTRUCTURE NETWORK OF THE PETROLEUM INDUSTRY

Stage 3 of the proposed RCIN method is explained in details in Section 4.6. The word formulation and mathematical model for operational decisions and dynamical design of resilient and controllable infrastructure networks are presented in Section 4.6. Two goals are considered: (1) minimize the re-planning in the designed infrastructure network; in other words, the deviation between the disrupted supply chain (considered in

Stage 3) and the steady state supply chain (considered in Stage 1) should be minimized in regard to the service level, and (2) minimize the cost of controllability; in other words, the cost of resilience strategies. The first goal is interesting since in the literature, the cost of re-planning the whole network, while a disruption is happening in one facility, is not considered. The output of this method in Stage 3 is to determine the required flexible production or inventory capacity at refineries, hubs or warehouses after a disruption happens. The detail of the third stage of the RCIN method is explained in Section 4.6.

The two considered resilience measures in evaluating the control policies are the control cost and the deviation in the service level. In the control cost goal, minimizing the cost of fortifying driver nodes and having extra transportation arcs is considered. In the deviation goal, minimizing the deviation in the service level between the service level from Stage 1 and when disruptions happen and control policies are determined in Stage 3 are considered. The comparison between different control policies is shown in Figure 6-20.

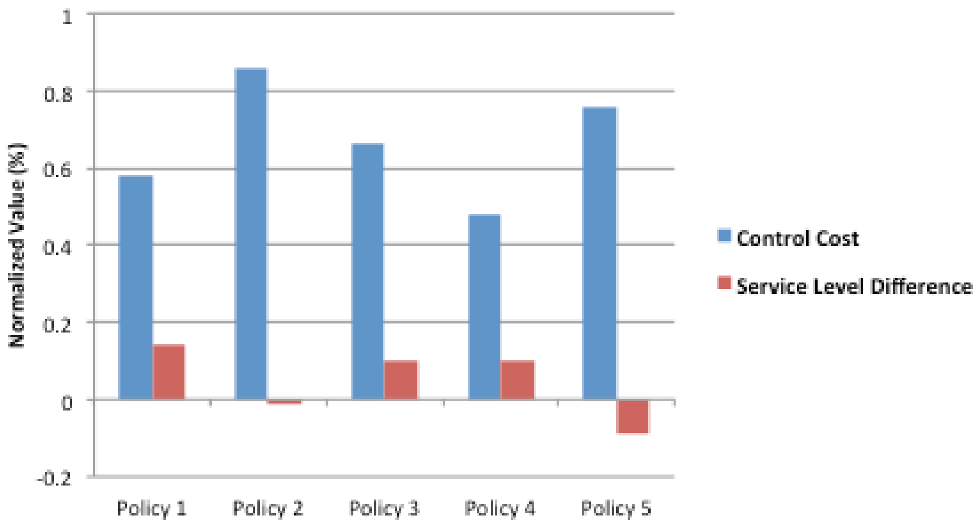


Figure 6-20 Trade-off among different control policies in Stage 3

As is shown in Figure 6-20, control policies 2 and 5 could increase the service level although disruptions happen on the infrastructure network. Although the service level is improved for both control policies 2 and 5, the control cost is increased as well. Based on the preferences of the infrastructure network designers either improving the service level (or keeping the same service level before disruptions happen) or decreasing the control cost can be emphasized in recovering disrupted infrastructure networks.

In the previous sections, only structural disruptions are considered. In next section, both the supply and demand uncertainty is considered and explained.

6.6 SUPPLY AND DEMAND UNCERTAINTY IN THE RCIN METHOD

In the proposed RCIN method, occurrence of disruptions is considered in Stage 3. Disruptions are considered as external risk factors, which the possibility of their occurrences cannot be prevented. However, uncertainty is an internal risk factor, which can be managed. In this dissertation, in addition to the occurrence of disruptions, the occurrence of supply and demand uncertainty is considered as a scenario-based stochastic programming approach. Five uncertainty scenarios are defined as follows with the same occurrence probabilities.

Uncertainty Scenario 1: supply side uncertainty in Refinery 2 that decreases its production capacity to 50%.

Uncertainty Scenario 2: supply side uncertainty in Hub 2 that decreases its production capacity to 50%.

Uncertainty Scenario 3: demand side uncertainty in markets that increases the demand by 10%.

Uncertainty Scenario 4: demand side uncertainty in markets that increases the demand by 20%.

Uncertainty Scenario 5: demand side uncertainty in markets that decreases the demand by 10%.

The probability of occurrence these five uncertainty scenarios are considered equal to 20%. Two situations are considered: when the first control policy (i.e., see Section 6.5 for Control Policy 1) is considered as the recovery scenario; when none of the control policies are applied. The results for the service level is shown in Figure 6-21.

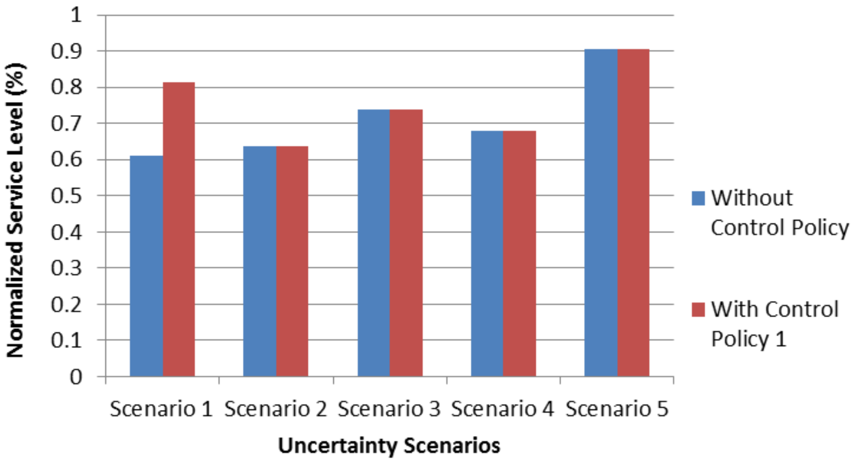


Figure 6-21 The impact of uncertainty scenarios on the service level

As is shown in Figure 6-21, if Uncertainty Scenario 1 occurs on Refinery 2, the production capacity of the infrastructure network will decrease into 6000 products and the service level will decrease into 61%. However, using the Control Policy 1 will help in reaching to the initial service level (i.e., 81%), especially because that Refinery 2 is a driver node. On the other hand, because no driver node is selected in the second layer, as is shown in Uncertainty Scenario 2, using the Control Policy 1 cannot make any difference in managing the supply uncertainty on Hub 2.

From the cost perspective, two conclusions are derived. First, regarding the value of control cost for these five uncertainty scenarios, as is shown in Figure 6.20, the control cost is same for all uncertainty scenarios. In other words, from the structure perspective in order to make a network structurally controllable a one-time cost should be spent for the network. Therefore, the control cost for all these five uncertainty scenarios is same (see Figure 6.20 for the result). Second, the only factor which may cause a difference in the value of total cost function is the operating cost of the network. The ratio of the control cost in compare with the operating cost can be much higher. Therefore, considering the cost with and without the Control policy 1 for these five uncertainty scenarios demonstrates that using control policies for a short-term decision making time frame usually are not economically acceptable. The reason for this conclusion is that the cost when control policies have been used are much higher than the time control policies have not been used. Therefore, analyzing the cost of control policies in the decision making process should be considered as the strategic decision (long-term decision making).

In this section, only five uncertainty scenarios on both supply and demand uncertainty are considered, and by using the scenario-based stochastic programming more uncertainty scenarios can be also analyzed. However, there is opportunity in improving the way that uncertainty is considered in the RCIN method explained in detail in Chapter 7 based on Trafalis and Gilbert (2006) and Choi and co-authors (2008). In next section, the exploration of the solution space through using ternary plots is presented.

6.7 EXPLORATION OF THE SOLUTION SPACE IN THE RCIN METHOD

As is shown in Figure 6-2, exploration of the solution space is considered in the proposed RCIN method. Especially because models are incomplete and inaccurate, exploration of the solution is required. Therefore, the ternary plot is used to explore the solution space through considering the trade-off among three goals such as tardiness, cost and service level in the first stage of the RCIN method. Ternary plots are created to show the interdependence among goals (e.g., tardiness, cost and service level), and to understand possible compromises among individual goals. These plots can help a policy maker/designer visually explore possible opportunities for the resilient and structurally controllable design of infrastructure networks under disruption. Using ternary plots helps to decrease the time required to provide results of all possible weight sets (see Section 6.3) in the decision making process for policy makers/designers and allows the rapid, convenient exploration of various alternative configurations. In other words, instead of solving the proposed method for all possible weight sets which requires a high computational cost and time, ternary plots can be created with a few sample points.

In Figure 6-22, the visualization of the normalized value of the service level for the considered infrastructure network is shown. As indicated in Figure 6-22, the red color indicates the highest normalized value of the service level (the value equals to one) and the blue color shows the lowest normalized value of the service level (the value equals zero). The intent for the service level in designing infrastructure networks is maximizing the service level or equivalently the red area in the triangle. Each side of the triangle and numbers on it show one of goals and its weights. As is shown in Figure 6-22, at any point in the interior of the triangle, the value of the weights for each goal is determined by finding the intersection of lines drawn parallel to the gridlines.

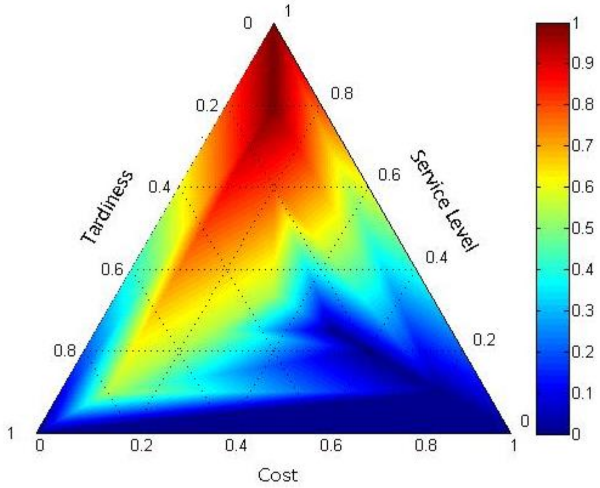


Figure 6-22 Visualization of the normalize value of the service level

In Figure 6-23, the visualization of the normalized value of the tardiness for the considered infrastructure network is shown. As indicated in Figure 6-23, the red color indicates the highest normalized value of the tardiness (the value equals to one) and the blue color shows the lowest normalized value of the tardiness (the value equals zero). The intent for the tardiness in designing infrastructure networks is minimizing the tardiness or equivalently the blue area in the triangle. Each side of the triangle and numbers on it show one of goals and its weights. As is shown in Figure 6-23, at any point in the interior of the triangle, the value of the weights for each goal is determined by finding the intersection of lines drawn parallel to the gridlines.

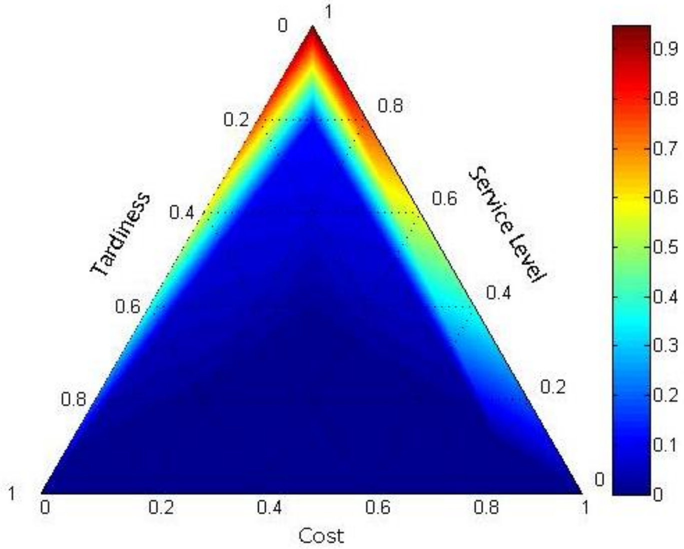


Figure 6-23 Visualization of the normalized value of the tardiness

In Figure 6-24, the visualization of the normalized value of the cost for the considered infrastructure network is shown. As indicated in Figure 6-24, the red color indicates the highest normalized value of the cost (the value equals to one) and the blue color shows the lowest normalized value of the cost (the value equals zero). The intent for the cost in designing infrastructure networks is minimizing the cost or equivalently the blue area in the triangle. Each side of the triangle and numbers on it show one of goals and its weights. As is shown in Figure 6-24, at any point in the interior of the triangle, the value of the weights for each goal is determined by finding the intersection of lines drawn parallel to the gridlines.

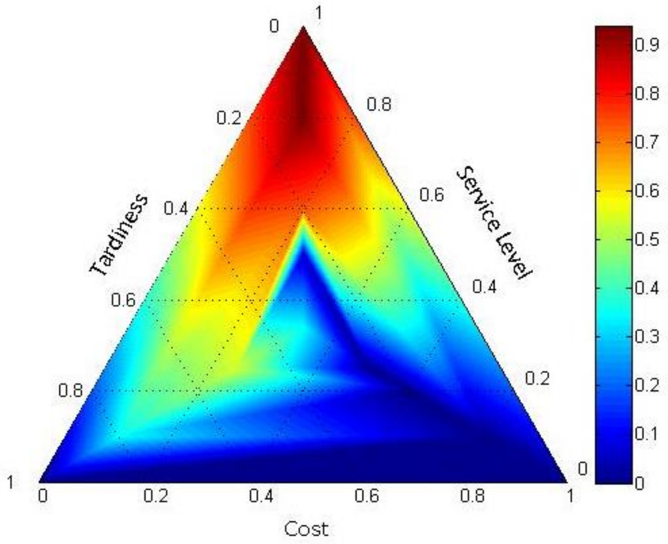


Figure 6-24 Visualization of the normalized value of cost

In this section, the exploration of the solution space is performed through using the Ternary plots. In next section, the empirical performance validation of the work is addressed.

6.8 EMPIRICAL PERFORMANCE VALIDATION

In this chapter, the RCIN method and exploration of the solution space are demonstrated based on the example of designing a resilient and structurally controllable infrastructure network of the petroleum industry. In this section, the usefulness of the RCIN method is argued via validating Hypotheses 2, 3, and 4, which is the empirical performance validation in the validation square shown in 6-26.

Task 1: Validate that using the Lin's Theorem and Minimum Input Theorem in determining the location and minimum number of driver nodes discussed in Section 4.5

help in structural controllability of a disrupted infrastructure network. This task is the demonstration for validating Hypothesis 3 discussed in Section 1.5.

***Result 1*:** In order to design a structurally controllable infrastructure network, the Lin's theorem and minimum input theorem are applied. Both these two theorems are considered in the second stage of the CRSM method. Through using these theorems, the location and minimum number of driver nodes are determined, shown and discussed in Section 6.4.

***Task 2*:** Validate that using the tardiness, service level, and control cost as resilience measures can help in evaluating the resilience discussed in Sections 6.3 and 6.5. This task is the demonstration for validating Hypothesis 2 in Section 1.5.

Results 2: Using the multi-objectives approach for Stages 1 and 3 of the proposed RCIN method help in evaluating the resilience in a disrupted infrastructure network. In Stage 1, tardiness, service level and total cost is used which the focus of the service level and tardiness is on meeting the demand of customers on time. In Stage 3, the control cost and the deviation between the service level after and before the occurrence of disruptions are considered as resilience measures. The results are shown in Sections 6.3 and 6.5.

Task 3: Validate that using flexible production capacity, flexible inventory capacity and back-up inventory are effective restoration strategies for mitigating the risk of disruptions discussed in Section 6.5. This task is the demonstration for validating Hypothesis 4 in Section 1.5.

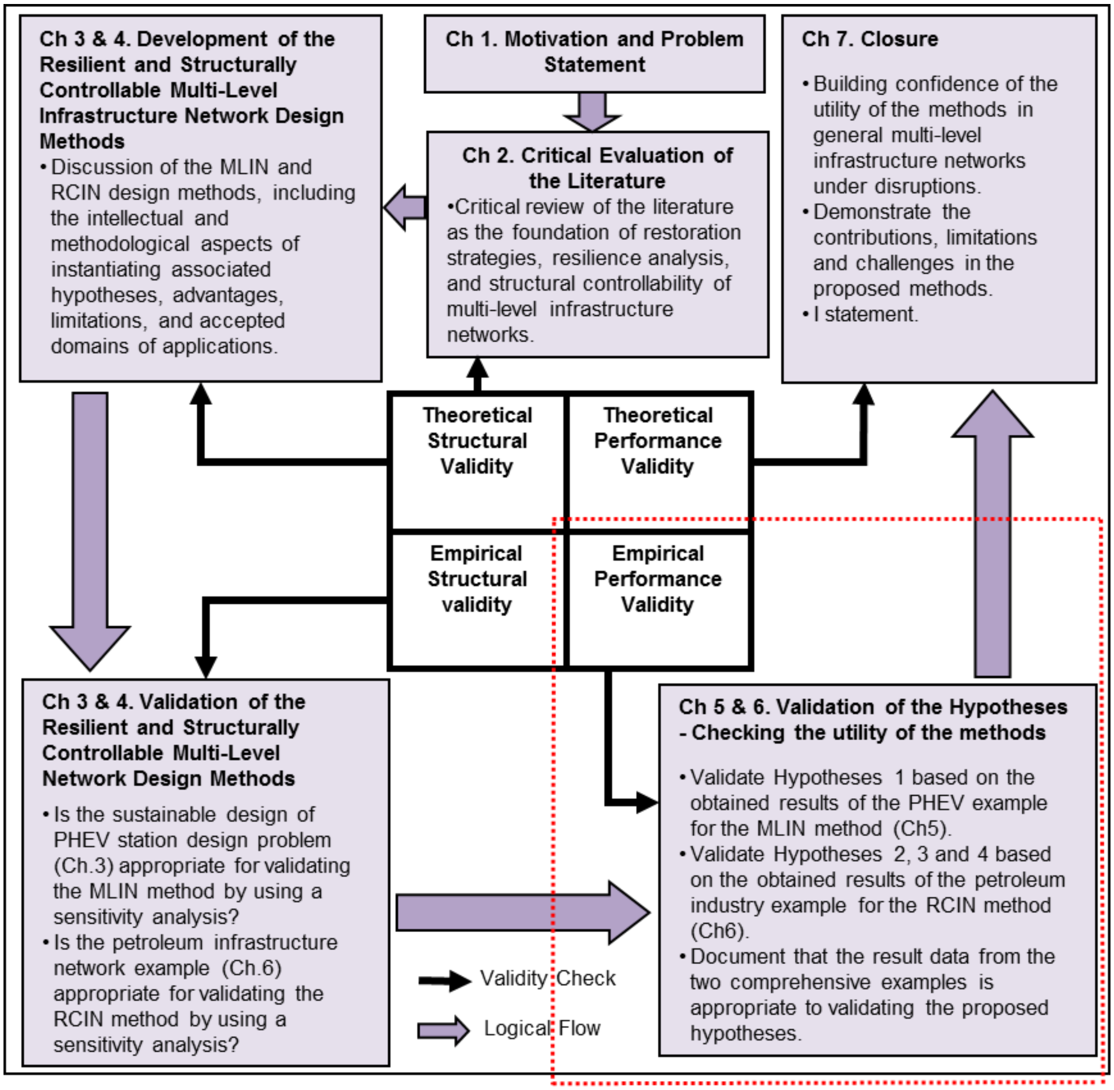


Figure 6-25 Validation strategy of the dissertation

Results 3: Three restoration strategies are defined and applied for a disrupted infrastructure network as are shown in Sections 6-3 to 6-5. For disrupted refineries and hubs in the infrastructure network, the flexible restoration strategy is applied. For disrupted warehouses in the infrastructure network, flexible inventory capacity is applied, and for disrupted distribution centers back-up inventory is applied.

All these results indicate the advantages of using the RCIN method. In summary, managing disruptions and mitigating the risk of disruptions are important in designing and operating infrastructure networks. Applying structural controllability in infrastructure networks can help in order to manage disruption, decrease the recovery time and increase the resilience, which is considered in the proposed RCIN method.

6.9 CHAPTER SYNOPSIS

In this chapter the usefulness of the RCIN method is validated (Empirical Performance Validation) with an example of the petroleum infrastructure network considering disruptions that is validated as an appropriate example (Empirical Structure Validation).

In Section 6.1, an introduction and the problem statement of designing resilient and controllable infrastructure networks, and an overview of the proposed RCIN method are presented. The purpose and capability of the design problem are discussed. It is argued that why the petroleum infrastructure network example is an appropriate example for validating the RCIN method (Empirical Performance Validation). In addition, three tasks for validating the functionality of the RCIN method based on this example are planned.

In Section 6.2, the RCIN method is reviewed and explained in the context of the example of the petroleum industry. In Section 6.3, the first stage of the RCIN method (i.e., strategic design of the infrastructure network) is applied for the petroleum example and all results are discussed. In Section 6.4, the example of the petroleum industry is used, and results for all five-control policies are discussed for it. In Section 6.5, the results of the operational stage of the RCIN method for the petroleum example are discussed. The focus in this dissertation is mainly on disruption management; however, both the supply and demand uncertainties are considered as well and addressed in Section 6.6. In Section 6.7, the exploration of the solution space for the petroleum example is explained, and finally in Section 6.8, Empirical Performance Validation of the RCIN method via the petroleum example is performed.

In the next chapter, a summary of the proposed methods, research questions, limitation and future directions are discussed.

CHAPTER 7 CLOSURE

The problem that is considered in this dissertation is on applying structural controllability in designing a resilient multi-level infrastructure network in the face of disruptions. In addition, selection of appropriate post-disruption and pre-disruption restoration strategies is part of the problem while considering the trade-off between effectiveness and redundancy in resilience analysis of disrupted infrastructure networks. The main contributions are the two proposed methods, multi-level infrastructure network (MLIN) and resilient and structurally controllable infrastructure network (RCIN) methods.

In this chapter, a summary of the problem statement, research questions, contributions, proposed methods, and achieved results are presented in Section 7.1. In section 7.2, my contributions in this dissertation are explicitly explained and justified. Quadrant four of the validation square, theoretical performance validation, is explained in Section 7.3, and limitations and challenges in this work are addressed in Section 7.4. *I Statement* is presented in Section 7.5. The *I statement* has two parts: in the first part, I address my future research direction, and in the second part I address the expansion of one of my research ideas related to the interconnected infrastructure networks.

7.1 SUMMARY OF THIS DISSERTATION

In this dissertation, designing a resilient and structurally controllable multi-level infrastructure network under disruptions is considered. The considered problem statement is as follows:

Applying structural controllability in order to design a resilient multi-level infrastructure network in the face of disruptions with selection of appropriate restoration strategies and consideration of effectiveness and redundancy in resilience analysis.

As discussed and explained in Sections 1.2 and 1.3, the considered problem has four aspects shown in Figure 7-2. For the aforementioned problem, a requirement list is defined and explained in Section 1.3 (see Table 1-1). Based on the critical literature evaluation (see Section 1.4 and Chapter 2) and the requirement list, four research questions are defined.

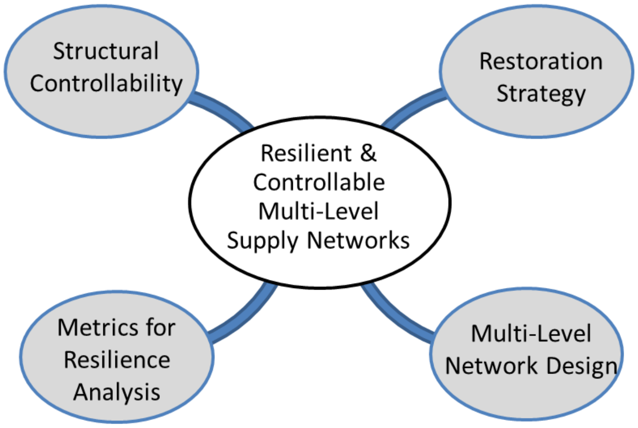


Figure 0-1 Four aspects of resilient and strcuturally controllable multi-level infrastructure networks under disruptions

The proposed research questions in this dissertation are as follows.

- What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?

- What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?
- What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?
- What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?

In order to answer to these four research questions, two methods are developed, named multi-level infrastructure network (MLIN) and resilient and structurally controllable infrastructure network (RCIN) methods. The MLIN method is explained in Section 7.2.1 briefly and in Chapter 3 in detail. The RCIN method is explained in Section 7.2.2 briefly and in Chapter 4 in detail. These two methods are the contributions in this dissertation.

Proposed methods are solved using two examples. The MLIN method is solved using an example of designing a bi-level network of electric charging stations for plug-in hybrid electric vehicles and its results is analyzed in Chapter 5. Some of the results of using the MLIN method for designing a bi-level network of electric charging stations for plug-in hybrid electric vehicles are as follows.

- Simulate operational or short term decisions in the level of nodes (i.e., charging stations) of the network using discrete-event simulation modeling for stochastic parameters (e.g., demand, waiting time, and service time);
- Formulate the strategic or long-term decisions in both levels of the network using the compromise Decision Support Problem (cDSP) construct;
- Estimate the operational decisions (i.e., especially decisions related to the node level) using surrogate modeling and incorporate it in the cDSP construct.

The results achieved by the MLIN method for the considered example fulfill the requirement of the multi-level aspect of the problem (see Section 1.3 or Table 7-1).

The RCIN method is solved using an example of designing a network of the petroleum industry under disruptions and its results is analyzed in Chapter 6. Some of the results of using the RCIN method for designing a resilient and structurally controllable network of the petroleum industry are as follows.

- Design a multi-product, multi-period petroleum industry infrastructure network considering redundancy and effectiveness using conflicting goals such as minimizing the strategic and operational cost, maximizing the service level and minimizing the tardiness or recovery time;
- Design a structurally controllable network using Lin’s theorem, and identify the location and number of driver nodes;
- Select the best restoration strategies among three possible strategies such as flexible production capacity, flexible inventory capacity and back-up inventory;

- Consider the cost of structural controllability (redundancy) and the difference in the service level between the disrupted state and the recovered state (effectiveness) as two measures of resilience analysis.

The results achieved by the RCIN method for the considered example fulfill the requirements of the structural controllability, restoration strategies and resilience analysis aspects of the problem (see Section 1.3 or Table 7-1).

In Figure 1-4, the connection between the two proposed methods, research questions and structure of the dissertation is shown. In next section, the main contributions in this dissertation along with the requirement list of the considered problem are addressed.

7.2 CONTRIBUTIONS OF THIS DISSERTATION

In order to answer to the research questions, two methods, the MLIN and RCIN methods, are proposed. Each of these methods are explained briefly in Sections 7.2.1 and 7.2.2, respectively. In Table 7-1, the connection between the four aspects of the problem, research questions, requirement list, contributions, and proposed methods is shown.

The first contribution is the MLIN method for the integrated design of both node-level decisions and network-level decisions. This contribution is related to the first aspect of the problem which is designing multi-level infrastructure network, and it is explained in detail in Chapter 3. In Section 7.2.1 a summary of the MLIN method is presented.

The second contribution is the RCIN method with focus on three aspects of the problem.

1) The first one is related the restoration strategy aspect. The proposed RCIN method support the selection of appropriate pre-disruption and post-disruption restoration strategies while disruptions happen. This is explained in Sections 4.6 and 6.5.
2) The second one is related to the resilience analysis aspect. The proposed RCIN method support the resilience analysis with considering the trade-off between redundancy and effectiveness. More specifically, these measures for the resilience analysis are defined: cost of designing and cost of controlling a network as the redundancy measure, and service level and tardiness (recovery time) as effectiveness measures. These measures are time-based measures and are used to calculate the resilience of infrastructure networks under disruptions. These measures are explained in Sections 4.4, 4.6, 6.3, and 6.5.
3) The third one is related to the structural controllability aspect of the problem. The proposed RCIN method support the determination of the location and number of driver nodes in a network. These driver nodes are used to apply the selected restoration strategies. This is explained in Sections 4.5, and 6.4.

Table 0-1 Mapping research questions, research hypotheses and key contributions

Aspect	Research Question	Research Hypothesis	Contribution	Detail of Contribution	Chapter
Multi-level network design	RQ1: What is a method to design a multi-level infrastructure network (e.g., node-level and network-level structures) considering both operational and strategic decisions?	Implement an integrated simulation model (for operational decisions in the node-level) and mathematical model (using the compromise Decision Support Problem) to design a multi-level network with conflicting goals.	Multi-level infrastructure network (MLIN) method	Integrated node-level and network-level decisions considering both operational and strategic decisions with conflicting design goals	Explained the MLIN method in Chapter 3, evaluated it in Chapter 5
Restoration strategies	RQ2: What is a method to design a resilient infrastructure network through selecting appropriate pre-disruption (e.g., facility fortification, backup inventory) and post-disruption (e.g., reconfiguration, flexible production and inventory capacity) restoration strategies?	Implement a method to select appropriate restoration strategies for possible occurrence of disruptions considering is dependent on anticipation, preparedness, adaptability, and recovery phases.	Resilient and structural controllability infrastructure network (RCIN) method	Selection of appropriate pre-disruption and post-disruption restoration strategies of a disrupted infrastructure network considering redundancy and effectiveness	Explained the RCIN method in Chapter 4, evaluated it in Chapter 6
Resilience analysis	RQ3: What is a method to evaluate network resilience as a function of time considering effectiveness and redundancy measures (e.g., service level and transportation time as effectiveness measures and control cost as redundancy measure)?	Implement a method that includes measures for analyzing resilience of disrupted networks while addressing redundancy and effectiveness.	Resilient and structural controllability infrastructure network (RCIN) method	Resilience analysis using time-based measures such as service level, recovery time and control cost considering redundancy and effectiveness	Explained the RCIN method in Chapter 4, evaluated it in Chapter 6
Structural controllability	RQ4: What is a method to determine the minimum number of driver nodes (i.e., driver nodes or controllers are required for controlling networks) to get structurally controllable infrastructure networks?	Implement a method occupied with maximum matching and minimum input theorem to find the minimum number of driver nodes to control a disrupted network in order to increase the resilience.	Resilient and structural controllability infrastructure network (RCIN) method	Location and minimum number of driver nodes in a disrupted network in order to restore the network by applying restoration strategies	Explained the RCIN method in Chapter 4, evaluated it in Chapter 6

7.2.1 Multi-Level Infrastructure Network (MLIN) Method

Designing multi-level infrastructure networks while operational (short-term) decisions and strategic (long-term) decisions are considered in the hierarchical structure are addressed in the MLIN method. In the proposed method, an integrated design for multi-level infrastructure networks is presented. The main idea is based on using surrogate models for operational decisions with short time scales in the node-level of infrastructure networks. In addition, the conflicts among the system goals are also considered in the MLIN method through applying the compromise Decision Support Problem (cDSP).

In this dissertation, The MLIN method is tailored for a two-level infrastructure network and named as a bi-level infrastructure network design. This method includes four steps, that is, the inputs, simulation model, surrogate model and the cDSP as illustrated in Figure 7-2. The conflicts among goals are considered in the proposed method, and the method explained as follows for a bi-level network structure.

Step (1) Overall Design Requirements: In this step assumptions for designing bi-level infrastructure networks with operational and strategic decisions are determined. In addition, values of input parameters and the system boundary are determined in this step. This step is explained with more detail in Section 3.4.

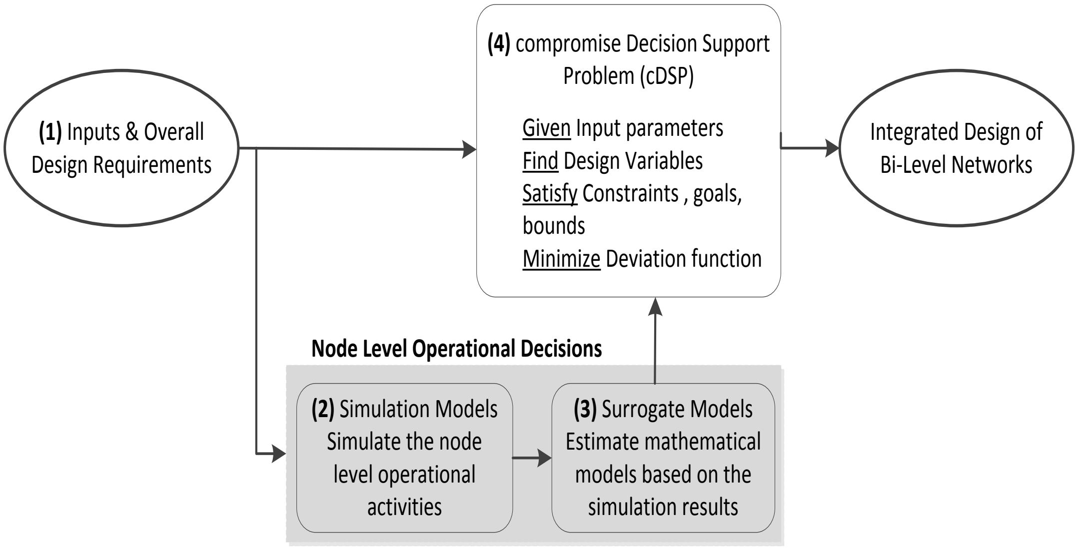


Figure 0-2 Multi-level infrastructure network (MLIN) method for bi-level structures

Step (2) Simulation Model: In this step, operations or entities in the lower level (node-level) are stimulated using simulation packages, algorithms or other similar approaches (e.g., queue models, etc.). Modeling the behavior of entities or operations in nodes of a network is required in this step. This step is explained in detail in Section 3.5.

Step (3) Surrogate Model: All operations with the short time scale can be simulated in the previous step. The focus in the previous step is mainly on operations in the lower level (node-level) of networks. In order to have an integrated design method for bi-level infrastructure networks, a one-stage, integrated mathematical model is required. To do so, the results of the simulation model from Step (2) are estimated by mathematical models using surrogate modeling. This step is explained in detail in Section 3.6.

Step (4) compromise DSP: In this step, the one-stage, integrated mathematical model for designing bi-level infrastructure networks considering conflicting system goals are presented. The compromise Decision Support Problem (cDSP) is used for modeling the bi-level infrastructure networks, especially because considering the conflicts among goals of the system is inevitable. This step is explained in more detail in Section 3.7.

7.2.2 Resilient and Structurally Controllable Infrastructure Network Method

Designing infrastructure networks involves determining the network configuration and the distribution of resources over the network. Basically, designing infrastructure networks includes two types of decisions: first, decisions on the location of facilities, connections between facilities, and their capacities (strategic decisions); and, second, assigning the demand to available facilities, and identifying production planning along the network (operational decisions).

In addition, designing infrastructure networks requires resilience as ‘the ability of a network to return to its original state or move to a new, more desirable state after being disturbed’. Using structural controllability as a feasible and convincing approach to mitigate the risk of disruptive events in infrastructure networks (control decisions) is proposed in this dissertation. Considering these three types of decisions, such as the strategic decisions, control decisions, and operational decisions, my proposed three-stage method for designing resilient and structurally controllable infrastructure networks (RCIN) is shown in Figure 7-3.

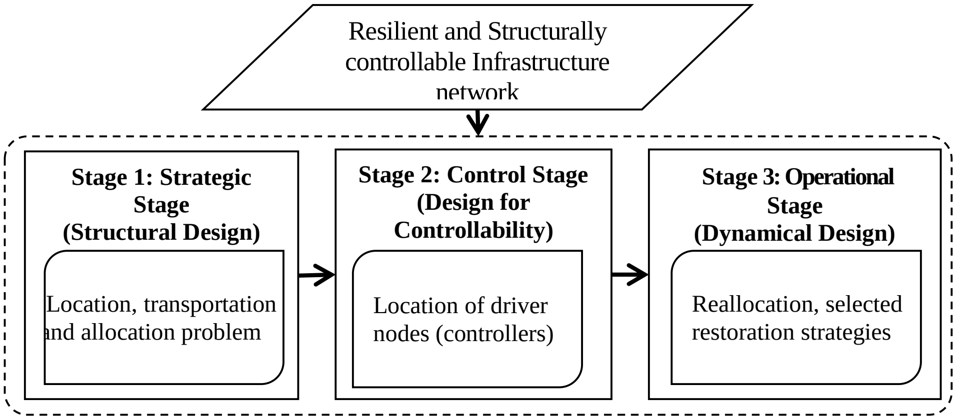


Figure 0-3 A three-stage method for the resilient and structurally controllable infrastructure network design

As is shown in Figure 7-3, the proposed RCIN method includes three stages, such as the strategic stage, control stage, and operational stage. Each of these stages is explained in detail in Sections 4.4 to 4.6.

7.3 THEORETICAL PERFORMANCE VALIDATION

As discussed in Section 1.7, the ability to produce useful results beyond the chosen example problems is considered in Quadrant 4 of the validation square. This requires a “leap of faith” which is eased by the process of building confidence. This involves two parts: 1) determining the characteristics of the example problems that make them representative of general classes of problems, and 2) other examples for using the proposed methods (i.e., usage scenarios). In next two sections, each of these two parts is explained.

7.3.1 Characteristics of the Example Problems

Based on the utility of the proposed methods (see Sections 7.2.1 and 7.2.2) and the requirement list (see Section 1.3) for the considered problem, the usefulness of the example problems for general classes of problems should be inferred for the Quadrant 4 of the Validation Square.

For empirical structural validation, it is argued in Sections 5.1 and 6.2 that the example problems are collectively representative of a general class of problems, defined by the following characteristics.

For the bi-level network of the PHEV charging example:

- There is hierarchical structure in an infrastructure network structure in which decisions in the higher level can affect the result of decisions in the lower levels.
- Input parameters have stochastic behavior/nature and formulating this stochastic behavior is difficult/not possible with the linear mathematical formulations.
- Decisions in each level of the structure are functions of operational/short-term and strategic/long-term decisions.
- The model is not complete and accurate, and the model cannot represent the whole characteristics of the system. Therefore, the optimum solution of the model is not necessarily the optimum solution of the system.
- In order to design the system, conflicts among the system goals need to be considered.

For the network of the petroleum industry example:

- When capacitated/uncapacitated facilities with different functions such as supply, inventory, distribution, and demand are considered in a multi-level infrastructure network.
- The model is not complete and accurate, and the model cannot represent the whole characteristics of the system. Therefore, an optimum solution of the model is not necessarily the optimum solution of the system.
- In order to design the system, conflicts among the system goals need to be considered.
- When disruptions on facilities and transportation arcs, or supply and demand uncertainty are considered in an infrastructure network.
- Different transportation modes and transportation times are considered in an infrastructure network.

This is intended to be a list of the signature properties of the examples for which the effectiveness of the MLIN and RCIN methods are demonstrated. It is demonstrated in this section and Section 5.1.2 and 6.1.1 that the MLIN and the RCIN methods are effective for the example problems with these characteristics. Therefore, there is reason to believe that the MLIN and the RCIN methods are effective for general classes of problems with these characteristics. Some of these properties and associated opportunities for future work are discussed in next section as usage scenarios for MLIN and RCIN methods.

7.3.2 Usage Scenarios and Research Directions from MLIN and RCIN Methods

In this section, I address several directions that this dissertation can be expanded. In some of them the focus is on the MLIN method, and in some others the focus is on the RCIN method. Since applying the structural controllability in infrastructure networks is a new research direction, I try to focus mainly on this aspect of my research. In this section, first a title of the idea is given, and then in one or two paragraphs the idea is explained.

Structural Controllability vs. Constructal Theory: constructal theory is a theory of the generation of design (configuration, pattern, geometry) in nature. According to this theory, natural design and the constructal theory unite all animate and inanimate systems. This theory is stated by Adrian Bejan in 1996 as follows: “for a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it.” Constructal is a word coined by Bejan, in order to describe the natural tendency of flow systems to generate and evolve structures that increase flow access (Hernandez, 2001).

The structural controllability theory is originally applied for the self-organized complex networks. The notion of the cactus structure in the controllable structures makes these two theories very similar with each other. One possibility is comparing both theories with each other and find out which theory provides better results for different assumptions or applications.

Since there are several applications for the constructal theory in the product design, the possibility of applying the structural controllability in the product design can be studied. In addition, constructal theory can be applied in planning the flow in infrastructure networks.

Structural controllability for material design: one of the brilliant applications for the structural controllability is in the material design, especially when propagation in the structure of a designed product is considered. For example, the heat or pressure transfer in a product can be analyzed through using structural controllability. In order to do this, the topology optimization can be used in which meshing products is considered using the finite elements methods. In this stage, the structural controllability can be used to consider the possibility of accessibility through some specific meshes; this can help in studying the stress and fragility in designed products.

Complex Network Analysis to Infrastructure networks: There is a rich literature on the network analysis techniques. These techniques can be applied in the area of the supply chain, and it can result in improving the design or re-design of networks. For example, most of infrastructure networks have the scale-free network structure. One of the characteristics of the scale-free networks is that they have few hubs (few nodes with high number of connected links) in their structure. This characteristic shows that if a random disruption happens on the structure of such infrastructure networks, few percentage of the demand will be lost in comparison with intentional attacks (terrorist attacks).

Queuing models to Infrastructure networks: One of the developments regarding the MLIN method is related to the modeling of the node-level decisions for a bi-level network structure. In the proposed MLIN method, the simulation model and surrogate modeling is used. However, when high number of scenarios should be considered in running the simulation model, the computational time will increase. In this situation, it is recommended to use the queue models for modeling the node-level decisions, especially when there is a closed form for a queue model.

7.4 Limitations and Challenges

In this section limitations of both the MLIN and RCIN methods, and some of my challenges in this dissertation are addressed.

7.4.1 Limitations of the MLIN and RCIN Methods

There are three limitations related to the proposed methods. The first limitation is that the MLIN method is solved for only a bi-level infrastructure network problem, and it is not solved for networks with more than two levels. Uncertainty parameters are not considered in the MLIN method, and finally robustness is not considered in both the MLIN and RCIN methods in this dissertation.

Limitation One in the MLIN Method: The multi-level infrastructure network is developed for multi-level networks. However, MLIN method is tailored and explained in detail for the bi-level infrastructure networks in Chapter 3. The method is solved using an example of PHEV charging stations with node-level and network-level decisions.

<u>*Limitation Two in the MLIN Method*</u>: Another limitation is that uncertain parameters are not considered in the MLIN method. There is uncertainty associated with some of parameters in multi-level infrastructure networks such as demand of products, and availability and capacity of suppliers. The possibility of considering uncertainty in the MLIN method should be considered. Considering uncertain parameters will necessitate the robust design of infrastructure networks addressed as the next limitation.

<u>*Limitation Three in the MLIN and RCIN Methods*</u>: As it is mentioned, uncertainty parameters are not considered in the MLIN method. However, as is addressed in Section 6.6, uncertainty parameters are considered in the RCIN method as a scenario-based stochastic programing approach. Considering uncertain parameters necessitates that robust design be considered as well. Since the cDSP construct is used in both MLIN and RCIN methods, considering uncertain parameters and robust design can be facilitated using the construct addressed in Table 7-2. The mathematical form of the cDSP for the robust design is based on the robust concept exploration method (RCEM) uses Error Margin Indices (EMIs) (Choi and co-authors, 2008).

Table 0-2 Mathematical form of the cDSP for RCEM-EMI

Given

n, number of system variables
p, number of equality constraints
q, number of inequality constraints
m, number of system goals
$g_i(\mathbf{x})$, constraint functions
$G_{i,}$, system goals
$A_i(\mathbf{x})$, performance functions
URLi and LRLi, performance requirements
$\Delta\mathbf{x}$, deviation of systems variables
EMItarget,i , EMI targets

Find

$\boldsymbol{\mu}_\mathbf{x}$ (mean of system variables)
d_i^-, d_i^+ (deviation variables)

Satisfy

System constraints:
$EMI_{constraint,i}(x)>=1$ *where* $i = 1,\ldots,q$
System goals:
$EMI_i(x)/EMI_{target,i} + d_i^- - d_i^+ = 1$ *where* $i = 1,\ldots,n$
Bounds:
$x_i^{min} \le x_i \le x_i^{max}$ *where* $i = 1,\ldots,n$
$d_i^-, d_i^+ \ge 0$ and $d_i^- \cdot d_i^+ = 0$ *where* $i=1,\ldots,m$

Minimize

$Z = [f_1(d_i^-,d_i^+), \ldots, f_k(d_i^-,d_i^+)]$ *Preemptive*
$Z = \Sigma W_i (d_i^- + d_i^+)\ \Sigma W_i=1,\ W_i >=0$ *Archimedean*

7.4.2 Challenges in Working on this Dissertation

I faced several challenges through working on my dissertation. In this section, I address two main technical challenges such as the computational complexity in solving the proposed MLIN method and the difficulties with my multi-disciplinary work. More description on these two challenges is addressed as follows.

I was challenged with the computational complexity: As it is addressed in Chapter 3, the proposed MLIN method can be applied for designing infrastructure networks with hierarchical structures. This method is applied for designing PHEV charging stations that its results are presented in Chapter 5. The considered problem for designing PHEV charging stations for 9 counties in Dallas-Fort Worth has some characteristics as follows:

- The network of charging stations is developed for nine counties
- The problem has three conflicting system goals
- The considered problem has 600 Boolean variables
- The considered problem has more than 500,000 continuous variables

The linear mathematical model is coded using Python and Gurobi, and solved on a PC with CPU 3.66 Hz and 8 GB RAM. After running the model for more than 144 hours, the gap to reach the solution is still 80%. I took different approaches in order to decrease the computational time and reach to the solution in a reasonable time. The taken approaches are as follows:

- Use model simplification: Instead of running the model for all 9 counties together, the model for each county is solved separately.
- Use approximation: for the large model, the Boolean variables are relaxed and solved as continuous variables.
- Use parallel computing: the parallel computing is used to decrease the computational time.
- Use super computer: The large model is solved using the super computer center at OU in order to decrease the computational time.

Using these approaches, the computational time of the model is decreased to 20 hours.

I was challenged with the multi-disciplinary work: My background is in operations research and supply chain. However, my work on both the PHEV project and the proposed RCIN method are multidisciplinary. In the PHEV project, I worked with two electrical engineers at University of Texas at Arlington, and I needed to have some knowledge about the renewable energy, and DC and AC charging technology.

The more challenging part of my work was related to the control theory. Since the control theory is a concept in electrical engineering, and the structural controllability is a concept from computer science and physical science, I had to increase my knowledge in these aspects. Therefore, I attended a control course in the School of Electrical and Computer Science Engineering, and I had one meeting per week for one and half year with Professor Thulasiraman at the School of Computer Science. Not just from the knowledge perspective, but also connecting the concept of the structural controllability with the infrastructure network was really challenging.

In the next section, I address some of directions for expanding the presented work in this dissertation as my "*I Statement*".

7.5 I Statement

The problem statement is introduced in Chapter 1, the research gap and research questions are justified in Chapter 3, the MLIN method is explained in Chapter 3 and solved using an example in Chapter 5, and the RCIN method is explained in Chapter 4 and solved using an example in Chapter 6. Finally, In Chapter 7, the work is summarized, research questions and developed methods are revisited, contributions are expressed, limitations and difficulties are mentioned, and it is shown that the presented work is generalizable for various applications. In this section, I address my vision for my future research directions in two subsections. In the first part, I address my future research direction for a time horizon of 3-5 years. Then, in the second part, I address initial thoughts of one of my potential research proposals.

7.5.1 My Future Research Directions

My future research direction is simply anchored in Figure 7-5. Three domains of my research focus are Infrastructure networks, transportation systems, and social/business/political systems. In order to support my research projects in these three domains, three areas of knowledge such as network analysis, data science, and risk management are applied. My work and contributions in this dissertation is a scaffold to build my future research dirction as is presented in this section. In this section, first, I briefly explain my research directions in three paragraphs, and then three knowledge area are explained.

Infrastructure Networks: Telecommunication, power grid and transportation networks are examples of *infrastructure networks*. Not only the performance of each of these infrastructure networks is dependent to the performance of other infrastructure networks (e.g., interconnection between the power grid and telecommunication networks), but also the operations and performances of most supply chains (e.g., governmental or private supply chains) are dependent on the operations and performances of the aforementioned infrastructure networks. Therefore, the interconnections and dependencies among connected infrastructure networks, and among infrastructure networks and supply chains should be considered. In addition to the interdependency among infrastructure networks, considering disruptions and uncertainties in designing and operating such networks is considered as my future research domains.

Transportation Systems: Transportation systems are as a complex, large-scale, integrated, and interdisciplinary systems. The transportation system is an interdisciplinary system since it interacts directly with the social, political, and economic aspects of contemporary society. In my future research direction, I consider transportation planning/re-planning of agile aviation and freight transportation systems (3-5 year plan), and intelligent transportation systems (5-7 year plan) under disruptions and uncertainties. Some of my specific interests in this area are related to the sustainable transportation systems, renewable energy in transportation systems (e.g., public transportation and electric cars), and planning and designing highways/roads for driverless vehicles.

Social/Business/Political Networks: Social/Business/Political Systems refer to a very vast area. My focus in this area is limited to 1) predicting emergent behaviors in social, business or political networks because of the occurrence of disruptions, and 2) consider the impact of social, business, and political networks in planning and designing of interconnected infrastructure networks.

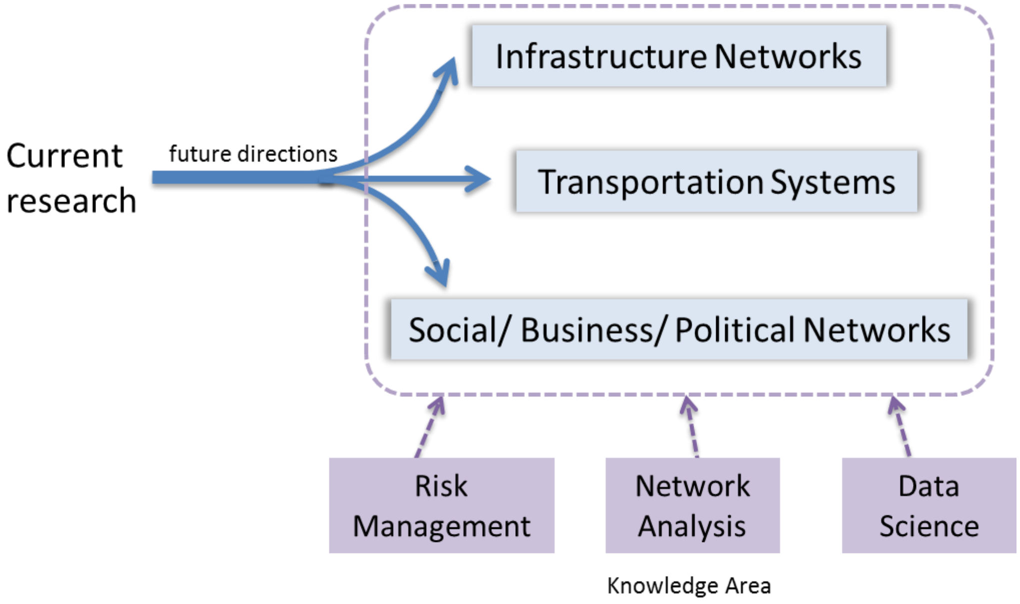


Figure 0-4 My future research direction

As is shown in Figure 7-5, network analysis, data science, and risk management are applied in order to tackle the aforementioned three research domains. Theories and models from graph theory and network science are considered as the network analysis knowledge area. Data analysis and visualization, machine learning, and data mining techniques are considered as the data science knowledge area.

Risk can be categorized as uncertainty or disruption. Uncertainty has an internal source and it can be controlled. Disruption has an external source and its occurrence is out of control. There are different approaches for risk management (i.e., managing uncertainties and disruptions). I consider resilience as the core of the risk management. Resilience has three components such as robustness, flexibility and controllability. All these four terms are defined in the glossary. In order to show the connection between these four terms, consider the following definition for resilient networks (see glossary for the complete list of definitions):

A **resilient** infrastructure network is one that is capable of effectively absorbing (**robustness**), adapting to (**flexibility**) or rapidly recovering from disruptive events, and returning to its original state or moving to a new state (**Controllability**) after being disrupted. Considering all these topics is required in order to achieve high resilience and manage risks.

In this section, an overview of my future research direction is addressed. In next section, I expand one of my ideas for a research proposal related to the first research domain, infrastructure networks.

7.5.2 Resilient Interconnected Infrastructure Systems and Supply Chains

In this section, my future research direction and the initial thoughts for my career proposal are addressed. First, the motivation and general problem statement are presented in the next paragraph. Then, it is followed by the frame of reference, research questions and closure.

In network-based systems, an Infrastructure system is defined as the set of interdependent systems that provide a reliable flow of products and services essential to the defense, economic and security of a country, the smooth functioning of government at all levels, and society as a whole. A supply chain consists of different entities that are connected by the physical flow of materials or products. The boundary of a supply chain is not necessarily limited to the boundary of one country. Therefore, the world trading agreements, and national and international regulations are involved in such international supply chains. Since the functioning of society depends heavily on energy, transportation, telecommunication, financial, and other infrastructures, resilience of infrastructure systems play an important role in the face of disruptions and uncertainties. In addition, the resilience of international and national supply chains depend heavily on the resilience of infrastructure systems.

Resilience is a property of a system that is capable of effectively overcoming disruptive events through absorbing, adapting to or rapidly recovering from disruptive events. Resilience emphasizes an assessment of the system’s ability to (1) *Anticipation* or anticipates and absorbs potential disruptions; (2) *Preparation* or develops adaptive means to accommodate changes within or around the system; (3) *Adaptation* or establish response behaviors aimed at either building the capacity to withstand the disruption or recover as quickly as possible after an impact.

Anticipating, preparing for and adapting to disruptions and uncertainties in infrastructure networks and supply chains are inevitable. Having access to all facilities and nodes in such networks (e.g., infrastructure networks and supply chains) via some specific nodes (controllers) is a *recovering* approach to *adapt* to disruptions and uncertainties named structural controllability. In addition, *preparing* the network to be controllable is essential before disruptions happen. In this research area, selecting efficient and effective restoration strategies based on the structural controllability are questioned while *a*) interconnections between infrastructure networks and supply chains, *b*) international and national regulations and trading agreements, and c) occurrence of disruptions and uncertainties are considered.

In the next section, the frame of reference is addressed, and then followed by research questions.

Frame of Reference

Telecommunication, power grid and transportation networks are examples of infrastructure networks. Not only the performance of each of these infrastructure networks is dependent to the performance of other infrastructure networks (e.g., interconnection between the power grid and telecommunication networks), but also the operations and performance of most supply chains are dependent on the operations and performance of the aforementioned infrastructure networks. Therefore, the interconnections and dependencies among connected infrastructure networks and supply chains should be considered.

One supply chain (e.g., Amazon, Walmart, eBay, etc.) may be connected to other supply chains all over the world (i.e., global supply chains). Shipping products or materials between international suppliers involve several international infrastructure networks (e.g., transportation and telecommunication networks). The international and national agreements, rules and regulations should be considered when designing such interconnected networks or applying recovery/restoration strategies.

From the structure perspective, connections and interconnections between supply chains and infrastructure networks can be formulated as a multi-layer interconnected network. Supply chains and infrastructure systems are usually shown with single-layer networks. However, one of the limitations of single-layer networks is their inability to represent relationship between supply chains and infrastructural systems. Interdependent Layered Networks (ILN) can be employed in modeling interconnected supply chains and infrastructure networks. The ILN composes of multiple networks in which each network is modeled as a layer. The logical relationship between supply chains and infrastructure systems can be shown via the ILN.

$\text{Min } \Sigma(c^i x^i + h^i y^i + r^i s^i)$

$\text{s.t}: A^i x^i + B^i y^i + C^i s^i = b^i$

i is the set of all network layers involved, and A^i, B^i, C^i are matrices based on the topology of each network. The connection between networks is shown by c^i, h^i, b^i, and r^i. the location decisions, the flow decisions, and the control policy (restoration strategy) are shown by x^i, y^i, and s^i.

Research Questions

The problem that is considered in this research thrust can be explained as follows: consider a global supply chain that may have suppliers, distribution centers or customers all over the world. The global supply chain is supported with several infrastructure networks such as the telecommunication, power grid and transportation networks. Not only the performance of these infrastructure networks can affect the performance of the global supply chain, but also the performance of global supply chains can affect the performance of the infrastructure networks. In other words, occurrence of disruptions and uncertainties in any of interconnected networks can affect the performance of other networks. Therefore, designing for a resilient supply chain, while its interconnections with other supply chains and infrastructure networks are considered, is critical. The following research questions are proposed.

a) Considering the interconnections between networks is important. The Interdependent Layered Networks modeling approach can be applied when multi-layer networks are connected with each other.

Research Question 1: How can the interconnected supply chains and infrastructure networks be modeled using a multi-level modeling approach (e.g. the Interdependent Layered Networks modeling approach)?

b) Communication between operating managers can help in anticipating, preparing and recovering networks from propagated disruptions and uncertainties.

Research Question 2: How can the communication between managers of infrastructure systems and supply chains impact the anticipating and preparing for propagated disruptions and uncertainties?

c) International and national regulations and protocols may restrict communications between network managers. Considering this restriction is important since it can affect the anticipation and preparation for propagated disruptions and uncertainties.

Research Question 3: How can the international and national regulations and protocols impact the anticipation and preparation for propagated disruptions and uncertainties among supply chains and infrastructure networks?

d) The structural controllability can be used to have access to all nodes in a network. In the centralized structural controllability, there is access from a supply chain to nodes in all other supply chains. In the decentralized structural controllability, each supply chain has access to its all nodes within itself. Both centralized and decentralized structural controllability can be used for recovering networks from disruptions and uncertainties.

Research Question 4: How can infrastructure networks and supply chains benefit from structural controllability in recovering a network from propagated disruptions and uncertainties?

In Section 7.4.3, I propose a multi-disciplinary research. This research is involved with various schools such as the industrial engineering, computer science, electrical engineering, civil engineering, and international relations, and each of these areas can add into the problem statement and assumptions of the proposed problem. This high-level picture (i.e., details are not addressed) of the project only shows the direction for my future research area and career proposal.

7.6 Closing Remarks

In this dissertation, two methods are proposed, named, multi-level infrastructure network (MLIN) and resilient and structurally controllable infrastructure network (RCIN) methods, with focus on managing disruptions on multi-level infrastructure networks.

A summary of the problem statement, research questions, contributions, proposed methods, and achieved results are presented in Section 7.1. In section 7.2, my contributions in this dissertation are explicitly explained and justified. Quadrant four of the validation square is explained in Section 7.3, and limitations and challenges in this work are addressed in Section 7.4. *I Statement* is presented in Section 7.5. My *I statement* has two parts: in the first part, I address my future research direction, and in the second part I address the expansion of one of my research ideas related to the interconnected infrastructure networks.

In the following two appendices, the codes for solution algorithms used in this dissertation in Chapters 5 and 6 are presented.

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Appendix A: SOLUTION ALGORITHM FOR MLIN METHOD

In this dissertation, designing the resilient and structurally controllable multi-level infrastructure networks under disruptions is considered. As it is explained in Section 5.1.4, the codes for the solution algorithm of the MLIN method is presented in Appendix A as follows.

```
# Amirhossein Khosrojerdi
# Step four of the MLIN method
# PHEV Project - Energy Policy Journal
# June 2015
# For 24 hours for one week (168 time periods)
# For Dallas county - This is a combination of the control and system design problems
# Wind, solar and power grid are considred as sources of energy and control decisions are associated with
the power grid and storage level
# Strategic decisions are related to the number of stands and capacity of the battery at each station
# Operational decisions is related to the interaction of energy between sources of energy

from gurobipy import *
m = Model('MLIN Mtheod - PHEV Energy Policy')

##################################data##############################
Tset= [0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24]

Gset = [0,1,2]

#Demand: %10 of the Dallas county demand in kWh
D= [7.016204981,14.64894818,47.84336613,101.8644452,326.6419507,795.4391195]
# Maximum wind in MWh
# h=
[398.55,306.08,1108.69,129.3,80.54,38.01,15.99,10.61,0.95,0,13.22,28.78,9.27,24.53]
# Maximum solar in Wh
k= [0,0,0,0,0,0,0,0,115.5,4394,13098.5,18612.5,22372,20064,17159.5,16503,10429.5]
# price of electricty
c= [24.39,22.88,21.15,20.74,21.45,21.96,25.09,24.81,24.44,25.53,26.78,28.96,31.79]
#environmental coefficient
e = 0.02
#environmental from electricty generation
Eelec = 3.04
#battery efficiency
ebat = 0.9
#discharging efficiency rate
edchar = 0.9
#charging rate battery wh should be 600
cr = 600
#discharge rate wh
dr = 75
```

```
#Discharge slot wh
drstand = 75
#capacity battery per module (equal to per stand) W should be 3600
CM = 3600
#cost for each stand $
cstand = 15000
#cost of battery $
cbat = 3000
#goal
G = [0,0,1]
#weights
W = [0.33,0.33,0.33]

###########################Variables##################################
# Y = {}
# Y = m.addVar(vtype=GRB.CONTINUOUS, name='Y')
X = {}
X = m.addVar(vtype=GRB.INTEGER, name='X')
MB = {}
for t in Tset:
	MB[t] = m.addVar(vtype=GRB.CONTINUOUS, name='MB_%s' % (t))
MS = {}
for t in Tset:
	MS[t] = m.addVar(vtype=GRB.CONTINUOUS, name='MS_%s' % (t))
N = {}
for t in Tset:
	N[t] = m.addVar(vtype=GRB.CONTINUOUS, name='N_%s' % (t))
O = {}
for t in Tset:
	O[t] = m.addVar(vtype=GRB.CONTINUOUS, name='O_%s' % (t))
R = {}
for t in Tset:
	R[t] = m.addVar(vtype=GRB.CONTINUOUS, name='R_%s' % (t))
Met = {}
for t in Tset:
	Met[t] = m.addVar(vtype = GRB.CONTINUOUS, name = 'Met Demand_%s'%(t))

Q = {}
for t in Tset:
	Q[t] = m.addVar(vtype=GRB.CONTINUOUS, name='Q_%s' % (t))
QT = {}
QT = m.addVar(vtype=GRB.CONTINUOUS, name='TotalinBattery')
DevN = {}
for i in Gset:
	DevN[i] = m.addVar(vtype=GRB.CONTINUOUS, name='DevN_%s' % (i))
DevP = {}
for i in Gset:
	DevP[i] = m.addVar(vtype=GRB.CONTINUOUS, name='DevP_%s' % (i))
obj = {}
for i in Gset:
	obj[i] = m.addVar(vtype=GRB.CONTINUOUS, name='Obj_%s' % (i))
Ren = {}
```

```
for i in Tset:
        Ren[i] = m.addVar(vtype=GRB.CONTINUOUS, name='Ren_%s' % (i))
Sell = {}
Sell = m.addVar(vtype=GRB.CONTINUOUS, name='Sell')
Buy = {}
Buy = m.addVar(vtype=GRB.CONTINUOUS, name='Buy')
Wind = {}
Wind = m.addVar(vtype=GRB.CONTINUOUS, name='Wind')
Solar = {}
Solar = m.addVar(vtype=GRB.CONTINUOUS, name='Solar')
Einf = {}
Einf = m.addVar(vtype=GRB.CONTINUOUS, name='Einf')
Es = {}
Es = m.addVar(vtype=GRB.CONTINUOUS, name='Es')

################################Update#################################
m.update()
###############################Constraints##############################
#Const (1):  Level of electricity in the battery
# for t in TTset:
        # m.addConstr(Q[t] == ebat*Q[t-1] + MB[t] + N[t] + O[t] - (R[t] + MS[t])/edchar, 'eleclevel_%s'
% (t))

# m.addConstr(Q[0] == MB[0] + N[0] + O[0] - (R[0] + MS[0]), 'eleclevel_%s' % (t))

for t in TTset:
        m.addConstr(Q[t] == ebat*Q[t-1] + MB[t] + N[t] + O[t] - (R[t]+MS[t])/edchar, 'eleclevel_%s' %
(t))

m.addConstr(Q[0] == MB[0] + N[0] + O[0] - (R[0]+MS[0])/edchar, 'eleclevel_%s' % (t))

#Const (2): Charging rate
for t in Tset:
        m.addConstr(MB[t] + N[t] + O[t] <= X * cr, 'charging-rate_%s' % (t))
#Const (3): discharge rate
# for t in Tset:
        # m.addConstr(MS[t] + R[t] <= edchar * dr * X, 'discharg-rate_%s' % (t))

#Const (4): discharge stand
for t in Tset:
        m.addConstr(R[t]+MS[t] <= edchar * X * drstand, 'discharg-stand_%s' % (t))

#Const (5): wind available
for t in Tset:
        m.addConstr(N[t] <= h[t], 'AvailableWind_%s' % (t))

#Const (6): solar available
for t in Tset:
        m.addConstr(O[t] <= 0.001 * k[t], 'AvailableSolar_%s' % (t))

#Const (7): Battery capacity
for t in Tset:
```

```
	m.addConstr(Q[t] <= CM * X, 'capacity-Battery_%s' % (t))

#Constr (8): Demand
for t in Tset:
	m.addConstr(R[t] <=  D[t], 'demand_%s' % (t))

#Help Constraints
for t in Tset:
	m.addConstr(Buy == quicksum(MB[t] for t in Tset), 'Buy')

for t in Tset:
	m.addConstr(Sell == quicksum(MS[t] for t in Tset), 'Sell')

for t in Tset:
	m.addConstr(Wind == quicksum(N[t] for t in Tset), 'Wind')

for t in Tset:
	m.addConstr(Solar == quicksum(O[t] for t in Tset), 'Solar')

#m.addConstr(X == 7)
m.addConstr(Q[167] == 0)
#m.addConstr(Solar == 0)
#m.addConstr(Wind == 0)
# for t in Tset:
	# m.addConstr(MB[t] == 0)
# m.addConstr(DevN[0] == 0)
# m.addConstr(DevP[0] == 0)
# m.addConstr(DevN[1] == 0)
# m.addConstr(DevP[2] == 0)
# m.addConstr(Buy >= Sell)
# m.addConstr(Buy <= quicksum(D[t] for t in Tset))

m.addConstr(QT == quicksum(Q[t] for t in Tset))

for t in Tset:
	m.addConstr(Met[t] == R[t] / D[t] , 'Met')

for t in Tset:
	m.addConstr(Ren[t] == O[t] + N[t] , 'Ren')

m.addConstr(Einf == e * 2 * (X)/0.8/2)
m.addConstr(Es == quicksum(Eelec * MB[t] for t in Tset)/271700/2)

#################################Goals#################################
#Goal 1
# m.addConstr(obj[0] == (((cstand+cbat) * X)/360000 + quicksum(c[t] * (MB[t] - MS[t]) for t in
Tset)/754716)/2, 'obj0')
m.addConstr(obj[0] == (((cstand+cbat) * X)/360000 + quicksum(c[t] * (MB[t]-MS[t]) for t in
Tset)/2827944)/2, 'obj0')
m.addConstr(G[0] - obj[0] == DevN[0] - DevP[0],'goal1')
```

```
# m.addConstr(G[0] - (((cstand+cbat * X)/360000 + quicksum(c[t] * (MB[t] - MS[t]) for t in
Tset)/154716)/2) == DevN[0] - DevP[0],'goal1')

# m.addConstr(obj1[0] == (((cstand+cbat * X)/360000 + quicksum(c[t] * MB[t] for t in Tset)/949203)/2))
# m.addConstr(obj2[0] == (quicksum(c[t] * MS[t] for t in Tset)/794487)/2)

#Goal 2
# m.addConstr(obj[1] == ((e * 2 * (X))/0.8 + quicksum(Eelec * MB[t] for t in Tset)/271700)/2, 'obj1')
m.addConstr(obj[1] == ( quicksum(Eelec * MB[t] for t in Tset)/271700), 'obj1')

m.addConstr(G[1] - obj[1] == DevN[1] - DevP[1],'goal2')

#Goal 3
m.addConstr(obj[2] == (quicksum(R[t] * (1/(D[t])) for t in Tset))/168, 'obj2')
m.addConstr(G[2] - obj[2] == DevN[2] - DevP[2],'goal2')
#################################Update###############################
m.update()
###############################Objective#################################objective
function
m.setObjective(W[0]*(DevP[0]+DevN[0]) + W[1]*(DevP[1]+DevN[1])+ W[2]*(DevP[2]+DevN[2]),
GRB.MINIMIZE)
m.optimize()
m.update()
##########################Results in Screen##########################
if m.status == GRB.OPTIMAL:
    for t in TTTset:
        with open("C:\Users\SRL2\Dropbox\Results\MB.txt", "a") as text_file:
                text_file.write("MB: %s"%MB[t])
if m.status == GRB.OPTIMAL:
    for t in TTTset:
        with open("C:\Users\SRL2\Dropbox\Results\MS.txt", "a") as text_file:
                text_file.write("MS: %s"%MS[t])
if m.status == GRB.OPTIMAL:
    for t in TTTset:
        with open("C:\Users\SRL2\Dropbox\Results\Ren.txt", "a") as text_file:
                text_file.write("Ren: %s"%Ren[t])

if m.status == GRB.OPTIMAL:
    for t in TTTset:
        with open("C:\Users\SRL2\Dropbox\Results\W.txt", "a") as text_file:
                text_file.write("N: %s"%N[t])
```

Appendix B: SOLUTION ALGORITHM FOR RCIN METHOD

In this dissertation, designing the resilient and structurally controllable multi-level infrastructure networks under disruptions is considered. As it is explained in Section 6.1.3, the codes for the solution algorithm of the RCIN method is presented in Appendix B as follows.

The code for the strategic stage is presented:

```
#Amirhossein Khosrojerdi

from gurobipy import *
m = Model('RCIN1')
##################################data##################################
##################################sets##################################
iset = [0,1,2]
jset = [0,1,2]
kset = [0,1,2]
lset = [0,1,2,3]
mset = [0,1,2,3,4,5,6,7]
#parameters
w1 = 0.2, w2 = 0.2,w3 = 0.6
#demand in 8 markets
d = [1765, 1200, 1100, 1200, 1365, 400, 2000, 800]
#transportation time between different layers of the supply chain
#transportation time between refineries and hubs in hours
tij = [128,15,20,128,15,15,128,15,15]
#transportation time between hubs and warehouses in hours
tjk = [114,157,5,6,37,71,2.5,31,121]
#transportation time between warehouses and DCs in hours
tkl = [142,10,100,114,171,42,57,157,100,117,188,5]
#transportation time between DCs to markets in hours
tlm= [200,200,200,37,200,100,200,200,200,16,200,200,15,200,200,22,37,200,13,200]
 # for REFINERY
# capacity of refineries
capr = [12000, 12000, 12000]
#blending time at refinery
tr = [10, 10, 10]
#cost of opening a refinery
cfr = [1000, 1000, 1000]
#cost per component at refineires
cvr = [0.15, 0.15, 0.15]
#for HUB
#capacity hub
caph = [4000, 3500, 4500]
#production time at hub
```

```
th = [4, 6, 4]
#cost of opening a hub
cfh = [750, 750, 750]
#cost per component at hubs
cvh = [0.4, 0.4, 0.4]

#for WAREHOUSE
#capacity warehouse
capw = [4000,4000,5500]
#average store time for products at a warehouse
tw = [10, 24, 12]
#fixed cost for opening warehouses
cfw = [500, 500, 500]

#for DCs
capd = [2000,4000,3000,4000]
cfd = [200,200,200,200]

##############################Variables###############################
X = {}
for i in iset:
	for j in jset:
		X[i,j] = m.addVar(vtype=GRB.CONTINUOUS, name='X_%s_%s' % (i,j))

Y = {}
for j in jset:
	for k in kset:
		Y[j,k] = m.addVar(vtype=GRB.CONTINUOUS, name='Y_%s_%s' % (j,k))

W = {}
for k in kset:
	for l in lset:
		W[k,l] = m.addVar(vtype=GRB.CONTINUOUS, name='W_%s_%s' % (k,l))

V = {}
for l in lset:
	for e in mset:
		V[l,e] = m.addVar(vtype=GRB.CONTINUOUS, name='V_%s_%s' % (l,e))

MI = {}
for i in iset:
	for j in jset:
		MI[i,j] = m.addVar(vtype=GRB.BINARY, name='MI_%s_%s' % (i,j))

GA = {}
for j in jset:
	for k in kset:
		GA[j,k] = m.addVar(vtype=GRB.BINARY, name='GA_%s_%s' % (j,k))

BE = {}
for k in kset:
	for l in lset:
```

```
                BE[k,l] = m.addVar(vtype=GRB.BINARY, name='BE_%s_%s' % (k,l))

AL = {}
for l in lset:
        for e in mset:
                AL[l,e] = m.addVar(vtype=GRB.BINARY, name='GA_%s_%s' % (l,e))

U = {}
for i in iset:
        U[i] = m.addVar(vtype=GRB.BINARY, name='U_%s' % (i))

O = {}
for j in jset:
        O[j] = m.addVar(vtype=GRB.BINARY, name='O_%s' % (j))

G = {}
for k in jset:
        G[k] = m.addVar(vtype=GRB.BINARY, name='G_%s' % (k))

F = {}
for l in lset:
        F[l] = m.addVar(vtype=GRB.BINARY, name='F_%s' % (l))

TIJ = {}
TIJ = m.addVar(vtype = GRB.CONTINUOUS, name = 'TIJ')

TJK = {}
TJK = m.addVar(vtype = GRB.CONTINUOUS, name = 'TJK')

TKL = {}
TKL = m.addVar(vtype = GRB.CONTINUOUS, name = 'TKL')

TLM = {}
TLM = m.addVar(vtype = GRB.CONTINUOUS, name = 'TLM')

TR = {}
TR = m.addVar(vtype = GRB.CONTINUOUS, name = 'TR')

TH = {}
TH = m.addVar(vtype = GRB.CONTINUOUS, name = 'TH')

TW = {}
TW = m.addVar(vtype = GRB.CONTINUOUS, name = 'TW')

TMAX = {}
TMAX = m.addVar(vtype = GRB.CONTINUOUS, name = 'TMAX')

TardinessA = {}
TardinessA = m.addVar(vtype = GRB.CONTINUOUS, lb=-2000, name = 'TardinessA')

Tardiness = {}
Tardiness = m.addVar(vtype = GRB.CONTINUOUS, name = 'Tardiness')
```

```
ServiceLevel = {}
ServiceLevel = m.addVar(vtype = GRB.CONTINUOUS, name = 'ServiceLevel')

Cost = {}
Cost = m.addVar(vtype = GRB.CONTINUOUS, name = 'Cost')

##################################Update##############################
m.update()
################################Constraints###########################
#Const (1): demand of markets
for e in mset:
        m.addConstr(quicksum(V[l,e] for l in lset) <= d[e], 'demand_%s' % (e))

#network flow constraints
#const(2): on DCs
for l in lset:
        m.addConstr(quicksum(W[k,l] for k in kset) == quicksum(V[l,e] for e in mset), 'flowinDCs_%s'
% (l))
#const(3): on warehouses
for k in kset:
        m.addConstr(quicksum(Y[j,k] for j in jset) == quicksum(W[k,l] for l in lset), 'flow in
warehouses_%s' % (k))
#const(4): on hubs
for j in jset:
        m.addConstr(quicksum(X[i,j] for i in iset) == quicksum(Y[j,k] for k in kset), 'flow in hubs_%s'
% (j))
#####capacity constraints
#capacity at refineries
for i in iset:
                m.addConstr(quicksum(3*X[i,j] for j in jset) <= U[i] * capr[i], 'capacity refinery_%s' %
(i))
#capacity at hubs
for j in jset:
        m.addConstr(quicksum(Y[j,k] for k in kset) <= O[j] * caph[j], 'capacity hub_%s' % (j))
#capacity at warehouse
for k in kset:
                m.addConstr(quicksum(W[k,l] for l in lset) <= G[k] * capw[k], 'capacity
warehouse_%s' % (k))
#capacity at distribution centers
# for l in lset:
#       m.addConstr(quicksum(V[l,e] for e in mset) <= F[l] * capd[l], 'capacity DC_%s' % (l))
#####Structural and Arc constraints
#for refinery and hubs
for i in iset:
        for j in jset:
                m.addConstr(X[i,j] <= 4000 * MI[i,j], 'structure-Refinery-Hub_%s_%s' % (i,j))
#for hubs and warehouses
for j in jset:
        for k in kset:
                m.addConstr(Y[j,k] <=  4000 * GA[j,k], 'structure-Hub-Warehouse_%s_%s' % (j,k))
#for warehouse and DCs
for k in kset:
```

```
        for l in lset:
                m.addConstr(W[k,l] <= 4000 * BE[k,l], 'structure-warehouse-DC_%s_%s' % (k,l))
#for DCs and markets
for l in lset:
        for e in mset:
                m.addConstr(V[l,e] <= 4000 * AL[l,e], 'structure-DC-Market_%s_%s' % (l,e))
#for tardiness
m.addConstr(TIJ ==
128*X[0,0]+15*X[0,1]+20*X[0,2]+128*X[1,0]+15*X[1,1]+15*X[1,2]+128*X[2,0]+15*X[2,1]+15*X[2,
2], 'TIJ')
m.addConstr(TJK ==
114*Y[0,0]+157*Y[0,1]+5*Y[0,2]+6*Y[1,0]+37*Y[1,1]+71*Y[1,2]+2.5*Y[2,0]+31*Y[2,1]+121*Y[2,2
],'TJK')
m.addConstr(TKL ==
142*W[0,0]+10*W[0,1]+100*W[0,2]+114*W[0,3]+171*W[1,0]+42*W[1,1]+57*W[1,2]+157*W[1,3]+1
00*W[2,0]+117*W[2,1]+188*W[2,2]+5*W[2,3], 'TKL')
m.addConstr(TLM ==
200*V[0,0]+200*V[0,1]+200*V[0,2]+37*V[0,3]+200*V[0,4]+100*V[0,5]+200*V[0,6]+200*V[0,7]+20
0*V[1,0]+16*V[1,1]+200*V[1,2]+
200*V[1,3]+15*V[1,4]+200*V[1,5]+200*V[1,6]+22*V[1,7]+37*V[2,0]+200*V[2,1]+13*V[2,2]+200*V
[2,3]+
200*V[2,4]+200*V[2,5]+200*V[2,6]+200*V[2,7]+200*V[3,0]+200*V[3,1]+200*V[3,2]+128*V[3,3]+2
00*V[3,4]+12*V[3,5]+5*V[3,6]+200*V[3,7], 'TLM')
m.addConstr(TR ==
3*(10*(X[0,0]+X[0,1]+X[0,2]+X[1,0]+X[1,1]+X[1,2]+X[2,0]+X[2,1]+X[2,2])),'TR')
m.addConstr(TH ==
4*(Y[0,0]+Y[0,1]+Y[0,2])+6*(Y[1,0]+Y[1,1]+Y[1,2])+4*(Y[2,0]+Y[2,1]+Y[2,2]),'TH')
m.addConstr(TW ==
10*(W[0,0]+W[0,1]+W[0,2]+W[0,3])+24*(W[1,0]+W[1,1]+W[1,2]+W[1,3])+12*(W[2,0]+W[2,1]+W[2,
2]+W[2,3]),'TW')
m.addConstr(TMAX ==
120*(V[0,0]+V[0,1]+V[0,2]+V[0,3]+V[0,4]+V[0,5]+V[0,6]+V[0,7]+V[1,0]+V[1,1]+V[1,2]+V[1,3]+V[1
,4]+V[1,5]+V[1,6]+V[1,7]+V[2,0]+V[2,1]
+V[2,2]+V[2,3]+V[2,4]+V[2,5]+V[2,6]+V[2,7]+V[3,0]+V[3,1]+V[3,2]+V[3,3]+V[3,4]+V[3,5]+V[3,6]+
V[3,7]), 'TMAX')
m.addConstr( TardinessA == TIJ+TJK+TKL+TLM+TR+TH+TW-TMAX, 'LATENESS')
m.addConstr( Tardiness >= TardinessA, 'TARDINESS')
#for cost
m.addConstr(Cost == quicksum(quicksum(0.15*3*X[i,j] for i in iset)for j in jset) +
quicksum(quicksum(0.4*Y[j,k] for j in jset)for k in kset)
+1000*(U[0]+U[1]+U[2])+750*(O[0]+O[1]+O[2])+500*(G[0]+G[1]+G[2])+200*(F[0]+F[1]+F[2]+F[3])
)
#for service level
m.addConstr(ServiceLevel == quicksum(quicksum(V[l,e]/d[e] for l in lset) for e in mset))
##########################################Update#########################
m.update()
########################################Objective#################################
#objective function
m.setObjective(w1 * Tardiness/4316030 + w2 * Cost/15905 - w3 * ServiceLevel/8, GRB.MINIMIZE)
#m.setObjective(-TardinessA, GRB.MINIMIZE)
m.optimize()
m.update()
```

```
#####################################################Resultsif m.status == GRB.OPTIMAL:
    for i in iset:
        for j in jset:
            print X[i,j]
if m.status == GRB.OPTIMAL:
    for j in jset:
        for k in kset:
            print Y[j,k]
if m.status == GRB.OPTIMAL:
    for k in kset:
        for l in lset:
            print W[k,l]
if m.status == GRB.OPTIMAL:
    for l in lset:
        for e in mset:
            print V[l,e]
if m.status == GRB.OPTIMAL:
    print ServiceLevel
    print Cost
    print Tardiness
```

The code for the operational stage while the control structure is presented:

```
# Amirhossein Khosrojerdi
# Stage 3 of the RCIN method
from gurobipy import *
m = Model('RCIN2-for weights 0.6-0.2-0.2')
#####################################data#######################################
#sets
iset = [0,1,2]
jset = [0,1,2]
kset = [0,1,2]
lset = [0,1,2,3]
mset = [0,1,2,3,4,5,6,7]
nset = [0,1,2,3,4,5,6,7,8,9,10]
nnset = [1,2,3,4,5,6,7,8,9,10]
sset = [0,1,2,3,4,5,6,7,8,9,10]
ijset = [0,1,2,3,4,5]
jkset = [0,1,2,3,4,5]
klset = [0,1,2,3,4,5,6,7,8,9,10,11]
lmset = [0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31]
#parameters
##################### parameters related to disruptions
ps = [0.028, 0.028, 0.114,0.114,0.028, 0.114,0.114, 0.114,0.028,0.114,0.114]
dr1 = [1,0,0,0,0,0,0,0,0,0,0]
dr2 = [0,1,0,0,0,0,0,0,0,0,0]

dh1 = [0,0,1,0,0,0,0,0,0,0,0]
dh2 = [0,0,0,1,0,0,0,0,0,0,0]

dw0 = [0,0,0,0,1,0,0,0,0,0,0]
dw1 = [0,0,0,0,0,1,0,0,0,0,0]
dw2 = [0,0,0,0,0,0,1,0,0,0,0]
```

```
dd0 = [0,0,0,0,0,0,0,1,0,0,0]
dd1 = [0,0,0,0,0,0,0,0,1,0,0]
dd2 = [0,0,0,0,0,0,0,0,0,1,0]
dd3 = [0,0,0,0,0,0,0,0,0,0,1]

cu0 = 0
cu1 = 1
cu2 = 1
co0 = 0
co1 = 0
co2 = 0
cg0 = 1
cg1 = 0
cg2 = 0
cz0 = 0
cz1 = 1
cz2 = 0
cz3 = 0
######################### from Level 3 - operational decisions under disruptions
#capacity related to flexible production capacity in refineries
capfi = [0,400,800,1200,1600,2000,2400,2800,3200,3600,4000]
#capacity related to flexible production capacity in hubs
capom = [0,400,800,1200,1600,2000,2400,2800,3200,3600,4000]
#capacity related to flexible inventory capacity at warehouses
capte = [0,400,800,1200,1600,2000,2400,2800,3200,3600,4000]
#capacity related to backup inventory at DCs
capal = [0,100,200,300,400,500,600,700,800,900,100]
#it comes from level 1
ServiceLevel = 0.709
######################### related to the cost
#cost of flexible production capacity at refineries
cfi = 250
#cost of flexible production capacity at hubs
com = 200
#cost of flexible inventory capacity at warehouses
cte = 80
#cost of backup inventory at DCs
cal = 160
#cost of having control refinery
cfr = 4000
#cost of having control hub
cfh = 3500
#cost of having control warehouse
cfw = 1000
#cost of having control DC
cfd = 1000
#cost of having a control link between refinery and hub
carh = 25
#cost of having a control link between hub and warehouse
cahw = 20
#cost of having a control link between warehouse and DC
cawd = 15
```

```
#cost of having a control link between DC and market
cadm = 10
###############################Variables################################
XN = {}
for i in iset:
        for j in jset:
                for s in sset:
                        XN[i,j,s] = m.addVar(vtype=GRB.CONTINUOUS, name='XN_%s_%s_%s' %
(i,j,s))
XP = {}
for i in iset:
        for j in jset:
                for s in sset:
                        XP[i,j,s] = m.addVar(vtype=GRB.CONTINUOUS, name='XP_%s_%s_%s' %
(i,j,s))
YN = {}
for j in jset:
        for k in kset:
                for s in sset:
                        YN[j,k,s] = m.addVar(vtype=GRB.CONTINUOUS, name='YN_%s_%s_%s' %
(j,k,s))
YP = {}
for j in jset:
        for k in kset:
                for s in sset:
                        YP[j,k,s] = m.addVar(vtype=GRB.CONTINUOUS, name='YP_%s_%s_%s' %
(j,k,s))

CY = {}
for j in jset:
        for k in kset:
                for s in sset:
                        CY[j,k,s] = m.addVar(vtype=GRB.CONTINUOUS, name='CY_%s_%s_%s' %
(j,k,s))

WN = {}
for k in kset:
        for l in lset:
                for s in sset:
                        WN[k,l,s] = m.addVar(vtype=GRB.CONTINUOUS, name='WN_%s_%s_%s'
% (k,l,s))

WP = {}
for k in kset:
        for l in lset:
                for s in sset:
                        WP[k,l,s] = m.addVar(vtype=GRB.CONTINUOUS, name='WP_%s_%s_%s'
% (k,l,s))
CW = {}
for k in kset:
        for l in lset:
                for s in sset:
```

```
            CW[k,l,s] = m.addVar(vtype=GRB.CONTINUOUS, name='CW_%s_%s_%s' % (k,l,s))
VN = {}
for l in lset:
    for e in mset:
        for s in sset:
            VN[l,e,s] = m.addVar(vtype=GRB.CONTINUOUS, name='VN_%s_%s_%s' % (l,e,s))

VP = {}
for l in lset:
    for e in mset:
        for s in sset:
            VP[l,e,s] = m.addVar(vtype=GRB.CONTINUOUS, name='VP_%s_%s_%s' % (l,e,s))
FI = {}
for n in nset:
    for i in iset:
        FI[i,n] = m.addVar(vtype=GRB.BINARY, name = 'FI_%s_%s' % (i,n))
OM = {}
for n in nset:
    for j in jset:
        OM[j,n] = m.addVar(vtype=GRB.BINARY, name = 'OM_%s_%s' % (j,n))
TE = {}
for n in nset:
    for k in kset:
        TE[k,n] = m.addVar(vtype=GRB.BINARY, name = 'TE_%s_%s' % (k,n))
AL = {}
for n in nset:
    for l in lset:
        AL[l,n] = m.addVar(vtype=GRB.BINARY, name = 'AL_%s_%s' % (l,n))
RePlanning = {}
RePlanning = m.addVar(vtype=GRB.CONTINUOUS, name = 'RePlanning')
CostControl = {}
CostControl = m.addVar(vtype = GRB.CONTINUOUS,name = 'CostControl')
CostControlFlex = {}
CostControlFlex = m.addVar(vtype = GRB.CONTINUOUS,name = 'CostControlFlex')
CostControlFacility = {}
CostControlFacility = m.addVar(vtype = GRB.CONTINUOUS,name = 'CostControlFacility')
CostControlArc = {}
CostControlArc = m.addVar(vtype = GRB.CONTINUOUS,name = 'CostControlArc')
Lose = {}
Lose = m.addVar(vtype = GRB.CONTINUOUS,name = 'Lose')
Add = {}
Add = m.addVar(vtype = GRB.CONTINUOUS,name = 'Add')
ServiceDiff = {}
for s in sset:
    ServiceDiff[s] = m.addVar(vtype=GRB.CONTINUOUS, lb=-10, name = 'ServiceDiff_%s' % (s))
ServiceDif = {}
ServiceDif = m.addVar(vtype = GRB.CONTINUOUS, name = 'ServiceDif')
```

```
##############################Update################################
m.update()
############################Constraints###############################
#demand constraints
for s in sset:
        m.addConstr(1765 + VP[2,0,s] - VN[2,0,s] <= 1765)
for s in sset:
        m.addConstr(1200 + VP[1,1,s] - VN[1,1,s] <= 1200)
for s in sset:
        m.addConstr(1100 + VP[2,2,s] - VN[2,2,s] <= 1100)
for s in sset:
        m.addConstr(1200 + VP[0,3,s] - VN[0,3,s] + VP[3,3,s] - VN[3,3,s] <= 1200)
for s in sset:
        m.addConstr(1365 + VP[1,4,s] - VN[1,4,s] <= 1365)
for s in sset:
        m.addConstr(400 + VP[3,5,s] - VN[3,5,s] <= 400)
for s in sset:
        m.addConstr(170 + VP[3,6,s] - VN[3,6,s] <= 2000)
for s in sset:
        m.addConstr(800 + VP[1,7,s] - VN[1,7,s] <= 800)
#Network flow constraints
#20
for s in sset:
        m.addConstr(635 + WP[0,0,s] - WN[0,0,s] == 635 + VP[0,3,s] - VN[0,3,s])
for s in sset:
        m.addConstr(3365 + WP[0,1,s] - WN[0,1,s] == 3365 + VP[1,1,s] - VN[1,1,s] + VP[1,4,s] -
VN[1,4,s] + VP[1,7,s] - VN[1,7,s])
for s in sset:
        m.addConstr(2865 + WP[1,2,s] - WN[1,2,s] == 2865 + VP[2,0,s] - VN[2,0,s] + VP[2,2,s] -
VN[2,2,s])
for s in sset:
        m.addConstr(1135 + WP[2,3,s] - WN[2,3,s] == 1135 + VP[3,3,s] - VN[3,3,s] + VP[3,5,s] -
VN[3,5,s] + VP[3,6,s] - VN[3,6,s])
#21
for s in sset:
        m.addConstr(4000 + YP[1,0,s] - YN[1,0,s] + YP[2,0,s] - YN[2,0,s] == 4000 + WP[0,0,s] -
WN[0,0,s] + WP[0,1,s] - WN[0,1,s])
for s in sset:
        m.addConstr(2865 + YP[2,1,s] - YN[2,1,s] == 2865 + WP[1,2,s] - WN[1,2,s])
for s in sset:
        m.addConstr(1135 + YP[1,2,s] - YN[1,2,s] == 1135 + WP[2,3,s] - WN[2,3,s])
#22
for s in sset:
        m.addConstr(3500 + XP[2,1,s] - XN[2,1,s] == 3500 + YP[1,0,s] - YN[1,0,s] + YP[1,2,s] -
YN[1,2,s])
for s in sset:
        m.addConstr(4500 + XP[1,2,s] - XN[1,2,s] + XP[2,2,s] - XN[2,2,s] == 4500 + YP[2,0,s] -
YN[2,0,s] + YP[2,1,s] - YN[2,1,s])
#Capacity Constraints
#23
for s in sset:
```

```
        m.addConstr(4000 + XP[1,2,s] - XN[1,2,s] <= (4000 + quicksum(capfi[n] * FI[1,n] for n in
nset)) * (1-dr1[s]))
for s in sset:
        m.addConstr(4000 + XP[2,1,s] - XN[2,1,s] + XP[2,2,s] - XN[2,2,s] <= (4000 +
quicksum(capfi[n] * FI[2,n] for n in nset)) * (1-dr2[s]))
#24
for s in sset:
        m.addConstr(3500 + YP[1,0,s] - YN[1,0,s] + YP[1,2,s] - YN[1,2,s] <= (3500 +
quicksum(capom[n] * OM[1,n] for n in nset)) * (1-dh1[s]))
for s in sset:
        m.addConstr(4500 + YP[2,0,s] - YN[2,0,s] + YP[2,1,s] - YN[2,1,s] <= (4500 +
quicksum(capom[n] * OM[2,n] for n in nset)) * (1-dh2[s]))
#25
for s in sset:
        m.addConstr( 4000 + WP[0,0,s] - WN[0,0,s] + WP[0,1,s] - WN[0,1,s] <= (4000 +
quicksum(capte[n] * TE[0,n] for n in nset)) * (1-dw0[s]))
for s in sset:
        m.addConstr( 2865 + WP[1,2,s] - WN[1,2,s] <= (4000 + quicksum(capte[n] * TE[1,n] for n in
nset)) * (1-dw1[s]))
for s in sset:
        m.addConstr( 1135 + WP[2,3,s] - WN[2,3,s] <= (4000 + quicksum(capte[n] * TE[2,n] for n in
nset)) * (1-dw2[s]))

#26
for s in sset:
        m.addConstr(635 + VP[0,3,s] - VN[0,3,s] <= (4000 + quicksum(capal[n] * AL[0,n] for n in
nset))* (1-dd0[s]))

for s in sset:
        m.addConstr(3365 + VP[1,1,s] - VN[1,1,s] + VP[1,4,s] - VN[1,4,s] + VP[1,7,s] - VN[1,7,s] <=
(4000 + quicksum(capal[n] * AL[1,n] for n in nset)) * (1-dd1[s]))

for s in sset:
        m.addConstr(2865 + VP[2,0,s] - VN[2,0,s] + VP[2,2,s] - VN[2,2,s] <=(4000 +
quicksum(capal[n] * AL[2,n] for n in nset)) * (1-dd2[s]))

for s in sset:
        m.addConstr(1135 + VP[3,3,s] - VN[3,3,s] + VP[3,5,s] - VN[3,5,s] + VP[3,6,s] - VN[3,6,s]
<=(4000 + quicksum(capal[n] * AL[3,n] for n in nset)) * (1-dd3[s]))

# constraint for variables
#27
for s in sset:
        m.addConstr(XP[1,2,s] <= 4000 * (1-dr1[s]) * (1-dh2[s]))
for s in sset:
        m.addConstr(XN[1,2,s] <= 4000)
for s in sset:
        m.addConstr(XP[2,1,s] <= 4000 * (1-dr2[s]) * (1-dh1[s]))
for s in sset:
        m.addConstr(XN[2,1,s] <= 3500)
for s in sset:
        m.addConstr(XP[2,2,s] <= 4000 * (1-dr2[s]) * (1-dh2[s]))
```

```
for s in sset:
        m.addConstr(XN[2,2,s] <= 500)
#29
for s in sset:
        m.addConstr(YP[1,0,s] <= 4000 * (1-dh1[s]) * (1-dw0[s]))
for s in sset:
        m.addConstr(YN[1,0,s] <= 2365)
for s in sset:
        m.addConstr(YP[1,2,s] <= 4000 * (1-dh1[s]) * (1-dw2[s]))
for s in sset:
        m.addConstr(YN[1,2,s] <= 1135)
for s in sset:
        m.addConstr(YP[2,0,s] <= 4000 * (1-dh2[s]) * (1-dw0[s]))
for s in sset:
        m.addConstr(YN[2,0,s] <= 1635)
for s in sset:
        m.addConstr(YP[2,1,s] <= 4000 * (1-dh2[s]) * (1-dw1[s]))
for s in sset:
        m.addConstr(YP[2,1,s] <= 2865)

#31
for s in sset:
        m.addConstr(WP[0,0,s] <= 4000 * (1-dw0[s]) * (1-dd0[s]))
for s in sset:
        m.addConstr(WN[0,0,s] <= 635)
for s in sset:
        m.addConstr(WP[0,1,s] <= 4000 * (1-dw0[s]) * (1-dd1[s]))
for s in sset:
        m.addConstr(WN[0,1,s] <= 3365)
for s in sset:
        m.addConstr(WP[1,2,s] <= 4000 * (1-dw1[s]) * (1-dd2[s]))
for s in sset:
        m.addConstr(WN[1,2,s] <= 2865)
for s in sset:
        m.addConstr(WP[2,3,s] <= 4000 * (1-dw2[s]) * (1-dd3[s]))
for s in sset:
        m.addConstr(WN[2,3,s] <= 1135)
#33
for s in sset:
        m.addConstr(VP[0,3,s] <= 4000 * (1-dd0[s]))
for s in sset:
        m.addConstr(VN[0,3,s] <= 635 )
for s in sset:
        m.addConstr(VP[1,1,s] <= 4000 * (1-dd1[s]))
for s in sset:
        m.addConstr(VN[1,1,s] <= 1200)
for s in sset:
        m.addConstr(VP[1,4,s] <= 4000 * (1-dd1[s]))
for s in sset:
        m.addConstr(VN[1,4,s] <= 1365)
for s in sset:
        m.addConstr(VP[1,7,s] <= 4000 * (1-dd1[s]))
```

```
for s in sset:
        m.addConstr(VN[1,7,s] <= 800)
for s in sset:
        m.addConstr(VP[2,0,s] <= 4000 * (1-dd2[s]))
for s in sset:
        m.addConstr(VN[2,0,s] <= 1765)
for s in sset:
        m.addConstr(VP[2,2,s] <= 4000 *(1-dd2[s]))
for s in sset:
        m.addConstr(VN[2,2,s] <= 1100)
for s in sset:
        m.addConstr(VP[3,3,s] <= 4000 * (1-dd3[s]))
for s in sset:
        m.addConstr(VN[3,3,s] <= 565)
for s in sset:
        m.addConstr(VP[3,5,s] <= 4000 * 1-dd3[s])
for s in sset:
        m.addConstr(VN[3,5,s] <= 400)
for s in sset:
        m.addConstr(VP[3,6,s] <= 4000 * (1-dd3[s]))
for s in sset:
        m.addConstr(VN[3,6,s] <= 170)
#flexible production and inventory facility
#35
m.addConstr(quicksum(FI[0,n] for n in nnset) <= cu0)
m.addConstr(quicksum(FI[1,n] for n in nnset) <= cu1)
m.addConstr(quicksum(FI[2,n] for n in nnset) <= cu2)
#36
m.addConstr(quicksum(OM[0,n] for n in nnset) <= co0)
m.addConstr(quicksum(OM[1,n] for n in nnset) <= co1)
m.addConstr(quicksum(OM[2,n] for n in nnset) <= co2)
#37
m.addConstr(quicksum(TE[0,n] for n in nnset) <= cg0)
m.addConstr(quicksum(TE[1,n] for n in nnset) <= cg1)
m.addConstr(quicksum(TE[2,n] for n in nnset) <= cg2)
#38
m.addConstr(quicksum(AL[0,n] for n in nnset) <= cz0)
m.addConstr(quicksum(AL[1,n] for n in nnset) <= cz1)
m.addConstr(quicksum(AL[2,n] for n in nnset) <= cz2)
m.addConstr(quicksum(AL[3,n] for n in nnset) <= cz3)
#39
m.addConstr(quicksum(FI[0,n] for n in nset) == 1)
m.addConstr(quicksum(FI[1,n] for n in nset) == 1)
m.addConstr(quicksum(FI[2,n] for n in nset) == 1)
#40
m.addConstr(quicksum(OM[0,n] for n in nset) == 1)
m.addConstr(quicksum(OM[1,n] for n in nset) == 1)
m.addConstr(quicksum(OM[2,n] for n in nset) == 1)
#41
m.addConstr(quicksum(TE[0,n] for n in nset) == 1)
m.addConstr(quicksum(TE[1,n] for n in nset) == 1)
m.addConstr(quicksum(TE[2,n] for n in nset) == 1)
```

```
#42
m.addConstr(quicksum(AL[0,n] for n in nset) == 1)
m.addConstr(quicksum(AL[1,n] for n in nset) == 1)
m.addConstr(quicksum(AL[2,n] for n in nset) == 1)
m.addConstr(quicksum(AL[3,n] for n in nset) == 1)
#m.addConstr((VP[0,3,s] + VP[21,s >=ServiceLevel)
m.addConstr(Add == quicksum(quicksum(quicksum(VP[l,e,s] for l in lset)for e in mset)for s in sset))
m.addConstr(Lose == quicksum(quicksum(quicksum(VN[l,e,s] for l in lset)for e in mset)for s in sset))
#for objectives
#Cost
m.addConstr(CostControlFacility ==
(2500*(cu0+cu1+cu2)+2000*(co0+co1+co2)+1000*(cg0+cg1+cg2)+900*(cz0+cz1+cz2+cz3))/6900)
m.addConstr(CostControlArc == 250*(0)+200*(0)+150*(0)+10*(0))
m.addConstr(CostControlFlex == (250*(quicksum(quicksum(FI[i,n]*capfi[n] for n in nset)for i in iset))
+ 200*(quicksum(quicksum(OM[j,n]*capom[n] for n in nset)for j in
jset))+80*(quicksum(quicksum(TE[k,n]*capte[n] for n in nset)for k in
kset))+160*(quicksum(quicksum(AL[l,n]*capal[n] for n in nset)for l in lset)))/1480000)
m.addConstr(CostControl == CostControlFacility + CostControlArc + CostControlFlex)
#service level
for s in sset:
            m.addConstr(ServiceDiff[s] == ServiceLevel - (((1765 + VP[2,0,s] - VN[2,0,s])/1765)+((1200
+ VP[1,1,s] - VN[1,1,s])/1200)+
            ((1100 + VP[2,2,s] - VN[2,2,s])/1100)+((1200 + VP[0,3,s] - VN[0,3,s] + VP[3,3,s] -
VN[3,3,s])/1200)+
            ((1365 + VP[1,4,s] - VN[1,4,s])/1365)+((400 + VP[3,5,s] - VN[3,5,s])/400)+((170 + VP[3,6,s]
- VN[3,6,s])/2000)+
            ((800 + VP[1,7,s] - VN[1,7,s])/800))/8)

m.addConstr(ServiceDif == quicksum(ServiceDiff[s] for s in sset))
############################Update####################################
m.update()
##########################Objective#####################################
#objective function
m.setObjective(0.5 * (CostControl - 6900)/4280000 + 0.5 * (ServiceDif)/11, GRB.MINIMIZE)
#m.setObjective(0.5 * (CostControl - 6900)/4280000 , GRB.MINIMIZE)
m.optimize()
m.update()
```