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OPTIMIZING THE PLANNING OF BUILDING RENOVATION PROJECTS

BY

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DISSERTATION

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ABSTRACT

A large number of the buildings in the United States are aging and in urgent need of renovation to improve their operational, economic, social, and environmental performance. To address this, building renovation projects in the United States have been increasing in recent years. A significant volume of this building renovation work focuses on leased buildings and hotel properties as they represent a substantial percentage of all existing buildings. This type of building renovation projects presents planners with significant challenges because they need to consider and minimize the disruptive impact of renovation activities on building operations and revenues during the planned work.

The main goal of this study is to present the development of novel models for optimizing the planning of building renovation projects that are capable of analyzing and minimizing the disruptive impact of renovation activities on the revenues of leased buildings and hotels. To achieve this goal, the research objectives of this study are to develop: (1) a novel model for optimizing the planning of leased building renovation projects that enables building owners to minimize total renovation cost including rental income losses; (2) an innovative model for optimizing the planning of renovation work in leased buildings that enables contractors working under Integrated Project Delivery method to maximize their reward sharing while minimizing total renovation cost; and (3) a novel model for optimizing the planning of hotel renovation projects that enables hotel owners to maximize their revenues during renovation work while minimizing project cost. The performance of the developed models was analyzed using real-life case studies. The results of this analysis illustrated the novel and unique capabilities of the developed models to (i) generate feasible renovation plans that fully comply with all practical constraints including the availability dates of leased units and hotel floors, (ii) quantify and minimize revenue losses of

leased buildings and hotels during renovation work, (iii) reduce total renovation cost, and (iv) maximize net profits of both owners and contractors.

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CHAPTER 1: INTRODUCTION

1.1 Overview and Problem Statement

The total number of buildings in the United States was reported to be approximately 111 million buildings in 2017 (U.S. Census Bureau 2019 and Potter 2020). The Institute for Building Efficiency (2014) reported that 70% of buildings in the United States are aging and in urgent need of renovation to improve their operational, economic, social, and environmental performance. To address this, building renovation projects in the United States have been increasing in recent years (Jeunesse 2019). A significant volume of this building renovation work focuses on leased buildings and hotel properties as they represent a substantial percentage of all existing buildings. For example, the total number of leased units and hotels in the United States were reported to be approximately 54 million units and 50 thousand hotels, respectively (AHLA 2021; EIA 2020; U.S. Census Bureau 2019).

This type of building renovation projects presents planners with significant challenges because they need to consider and minimize the disruptive impact of renovation activities on building operations and revenues during the planned work. For example, renovations of leased buildings often cause substantial reduction in their annual rental income as they require occupants to leave units during renovation work (Park 2017). Similarly, renovations of hotels often lead to temporary reduction in their revenues due to the partial closure of hotel floors during renovation work (Meerendonk 2014). Accordingly, the renovation of leased buildings and hotels present owners and renovation contractors with new and significant challenges including how to optimize the planning of renovation work to enable (1) owners of leased buildings to minimize total renovation cost including rental income loss during renovation work; (2) contractors working under Integrated Project Delivery (IPD) method to maximize their reward sharing while

minimizing total renovation cost; and (3) hotel owners to maximize revenues during renovation work while minimizing project cost, as shown in Figure 1.1. The following sections provide a concise discussion of these three challenges confronting building owners and contractors working on renovation projects.

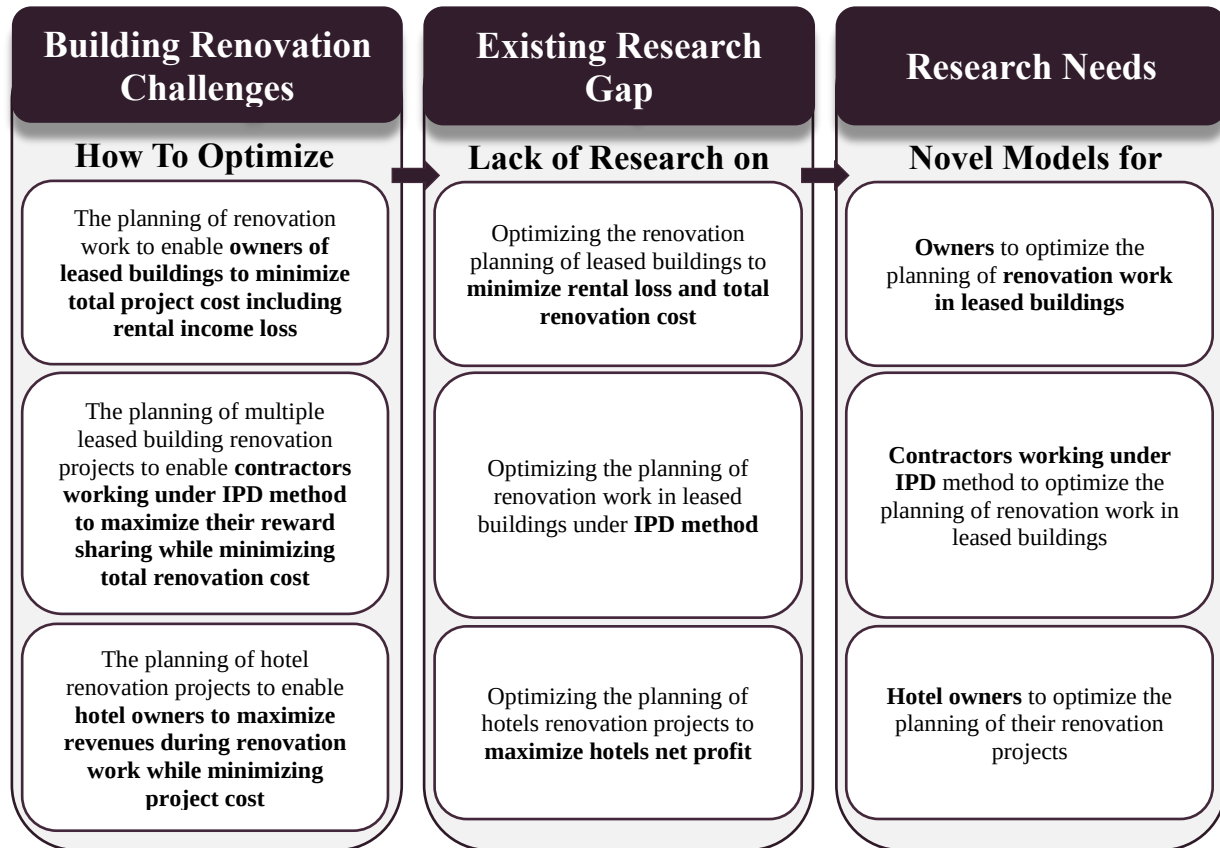


Figure 1.1. Planning of building renovation projects challenges and research needs

1.1.1 Owners of leased buildings optimizing the planning of renovation work

Optimizing the planning of renovation work in leased buildings confronts owners with a number of practical challenges including how to (1) consider and comply with the important planning constraint of units' availability dates; (2) account for total rental income loss during renovation work; and (3) identify optimal project start date and unit renovation sequence that minimize total renovation cost, as shown in Figure 1.2. First, each unit in a leased building often

has a different availability date that should be considered during the planning of renovation activities, where renovation crews are not allowed to start the work before that availability date. For example, schedule (A) in Figure 1.2 is infeasible because it plans the start of activity A in units 2 and 3 (A_2 & A_3) before the units' availability dates. Second, optimizing the renovation planning of leased building needs to consider the important cost component of rental income loss that is directly affected by the renovation period of each unit, as shown in Figure 1.2. Third, the planning optimization of leased building renovation projects needs to identify an optimal project start date and unit renovation sequence due to their significant impact on the total renovation cost especially when leased units have different availability dates and varying monthly rent rates.

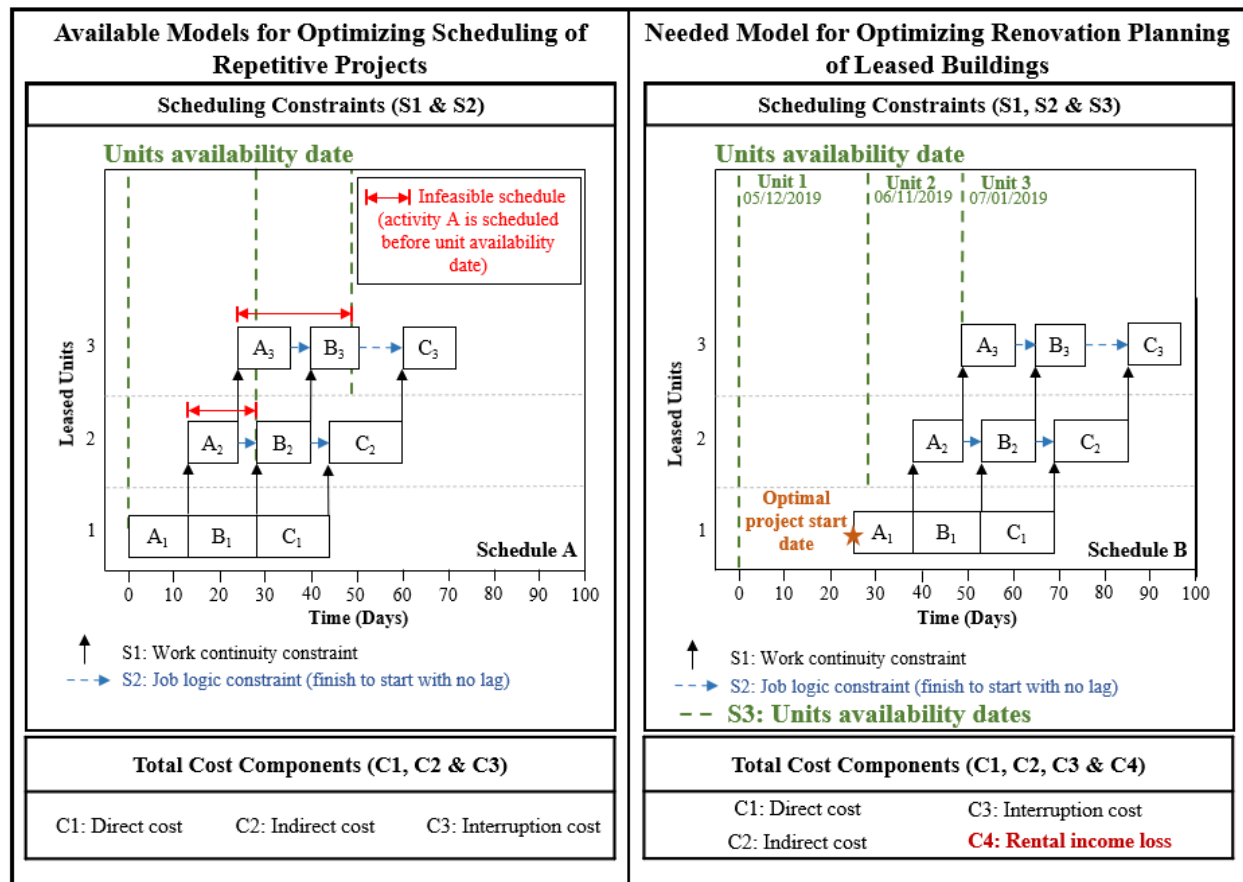


Figure 1.2. Limitation of existing models related to the planning of leased building renovation project

1.1.2 Renovation contractors working under IPD optimizing the planning of renovation work

Renovation contractors working under IPD method need to optimize the planning of renovation work when dealing with multiple leased building projects in order to maximize contractors reward sharing while minimizing total renovation cost. The application of the IPD method in the planning of renovation projects in leased buildings often confronts contractors with a number of challenges, including how to (1) minimize total renovation cost while maximizing IPD reward sharing achieved by the early finish of leased units before their specified target completion dates; (2) identify optimal scheduling decisions including crew deployment date for all activities, renovation order of all leased units, and number of assigned crews for each activity in all units; and (3) develop practical and feasible renovation plans that comply with the availability dates of all renovated units based on their lease end dates and availability of renovation crews, as shown in Figure 1.3. First, contractors in an IPD contract need to minimize total renovation cost while expediting the completion of all renovated units to maximize their IPD reward sharing based on the specified IPD contractual agreement. To achieve that, construction planners need to consider the important trade-off that often exists between total renovation cost and IPD reward sharing, as shown in Figure 1.3. For example, a construction planner may select renovation schedule of case (A) in Figure 1.3 that provides (1) lower total renovation cost due to its lower crew idle and indirect costs, and (2) lower IPD reward sharing due to its higher late completion penalty cost and lower shared lease income savings. On the other hand, the construction planner may select renovation schedule of case (B) in Figure 1.3 that provides (1) higher total renovation cost due to its higher crew idle and indirect costs, and (2) higher IPD reward sharing due to its higher shared lease income savings compared to case (A). Accordingly, the impact of renovation

scheduling decisions on total renovation cost and IPD reward sharing needs to be carefully analyzed and optimized to maximize the overall contractor's profitability.

Second, optimizing the planning of leased buildings renovation work needs to identify a number of optimal decisions including crew deployment date for all activities, renovation order of all leased units, and number of assigned crews for each activity in all leased units due to their significant impact on total renovation cost and IPD reward sharing especially when units have different lease end dates and varying monthly lease rates, as shown in Figure 1.3. For example, the impact of the crew deployment date decision variable on total renovation cost and IPD reward sharing is illustrated in Figure 1.3. In case (A) in Figure 1.3, A1,1 and B1,1 crews can be deployed on days 4 and 7, respectively to minimize total renovation cost by reducing crew idle cost and project indirect cost, as shown in Figure 1.3. On the other hand, A1,1 and B1,1 crews can be deployed earlier on days 0 and 3, respectively to maximize total IPD reward sharing by expediting the delivery of all leased units before their target completion date, as shown in case (B) in Figure 1.3. Similarly, the remaining two decision variables of renovation order of leased units, and number of assigned crews for each activity have a significant impact on both the total renovation cost and IPD reward sharing.

Third, developing a plan for renovation work in leased buildings needs to comply with a number of practical constraints, including the availability dates of all renovated units based on their lease end dates and the availability of renovation crews. For example, plans in case (A) and case (B) in Figure 1.3 comply with the availability dates of all four renovated units because they plan the start date of activity A1,1; A1,2; A2,1; and A2,2 on or after their lease end dates. Similarly, the availability of renovation crews constraint needs to fully comply with to ensure the practicality

of the generated renovation plan. Accordingly, the planning of renovation work under IPD method needs to be carefully analyzed and optimized to address the aforementioned three challenges.

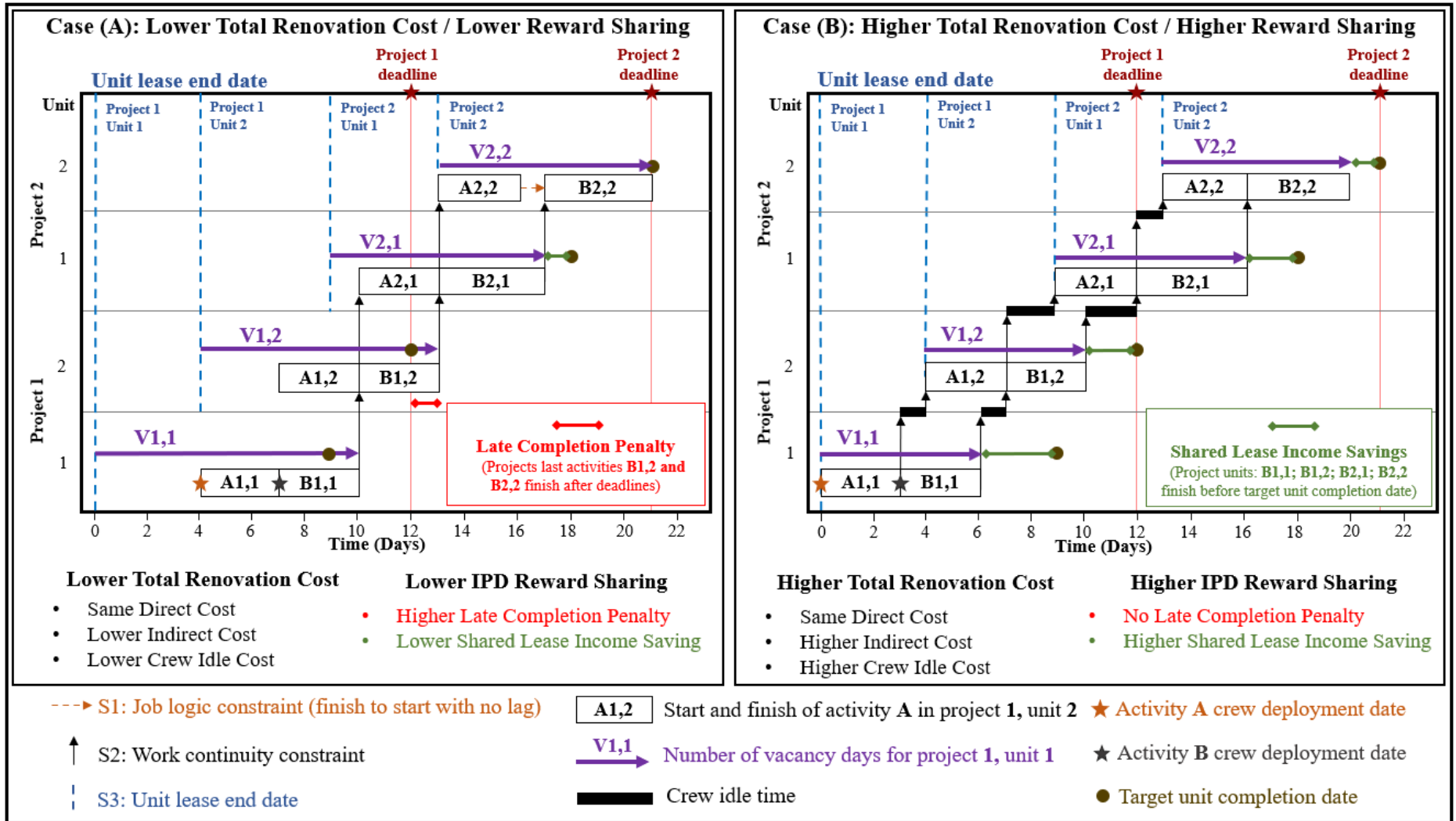


Figure 1.3. Impact of total renovation cost and IPD risk and reward sharing structure in renovation planning

1.1.3 Hotel Owners optimizing the planning of renovation work

Hotel owners need to carefully analyze and optimize renovation decisions to maximize the revenues of hotels during renovation work while minimizing their renovation cost. This presents renovation planners of hotel renovation projects with a number of planning challenges, including how to identify (1) which hotels to be renovated during a fiscal year based on an allocated renovation budget; (2) optimal floor renovation start date in each hotel; (3) optimal use of overtime hours and number of assigned crews for each renovation activity; and (4) optimal floor renovation order in each hotel, as shown in Figure 1.4. First, renovation planners need to prioritize which hotels to be renovated during a fiscal year based on the allocated renovation budget. For example, a planner with an allocated renovation budget of \$2.3 million for an upcoming fiscal year needs to prioritize which hotels to be renovated from a set of five competing hotels that have varying annual revenues and renovation cost. This allocated \$2.3 million budget cannot cover the renovation cost of all five hotels in the upcoming fiscal year and therefore the planner needs to select a subset of these five hotels to renovate and another subset to defer to future fiscal years. This decision needs to be optimized to maximize the net profit of all five hotels during the upcoming fiscal year. This can be achieved by carefully analyzing the impact of a number of important factors, including daily hotel revenue of each floor, peak seasons, and total renovation cost.

Second, planners need to analyze and optimize the impact of floor renovation start date decision on total hotel profitability, as shown in Figure 1.4 (A and B). For example, a renovation planner may select the earliest start date for each floor, as shown in the original plan in Figure 1.4 (A). Alternatively, the planner may delay the renovation start date in selected floors to minimize floor closures and hotel revenue losses during high peak seasons, as shown in Figure 1.4 (B). These two renovation plan examples in Figure 1.4 illustrate that renovation plan (B) provides higher hotel

revenues than those of the original plan (A); however, it requires higher renovation cost due to work disruption suffered by the crews assigned to activities A and B that were only allowed to resume their work after the end of high peak seasons, as shown in Figure 1.4. This highlights the need to carefully consider and optimize the selection of floor renovation start dates to maximize hotel net profit.

Third, planners need to study and optimize the impact of overtime hours use for each renovation activity on total hotel profitability. For example, the impact of the use of overtime hours decision variable on hotel revenue and renovation cost is demonstrated in Figure 1.4 (A and C). A renovation planner may select working regular working hours or adding overtime hours for the renovation crews of activities A and B, as shown in Figure 1.4 (A and C), respectively. In this example, utilizing overtime hours provides higher hotel revenues than working regular working hours only because it minimizes floor closures during peak seasons, as shown in Figure 1.4 (A and C). On the other hand, utilizing overtime hours requires higher renovation cost due to the higher premiums paid for overtime hours. This demonstrates the need to carefully consider and optimize overtime hours use for each renovation activity to maximize hotel net profit. It should be noted, the selection of number of renovation crews decision has a similar impact on hotel net profit as the use of overtime hours decision.

Fourth, optimizing the planning of hotels renovation projects needs to identify an optimal floor renovation order that maximizes hotel net profit. For example, a renovation planner may select an ascending floor renovation order starting with floor 1, moving to floor 2, then floor 3, and ending with floor 4, as shown in the original renovation plan in Figure 1.4 (A). Alternatively, the planner can select a descending floor order starting by renovating floor 4 first, then floor 3, moving to floor 2, and ending by floor 1 to minimize the closures of floors with high daily revenues

such as floor 4 during high peak seasons, as shown in Figure 1.4 (D). This highlights the need to carefully consider and optimize the decision of floor renovation order to maximize hotel profitability. Accordingly, the planning of hotel renovation projects needs to be carefully analyzed and optimized to address the aforementioned related four challenges.

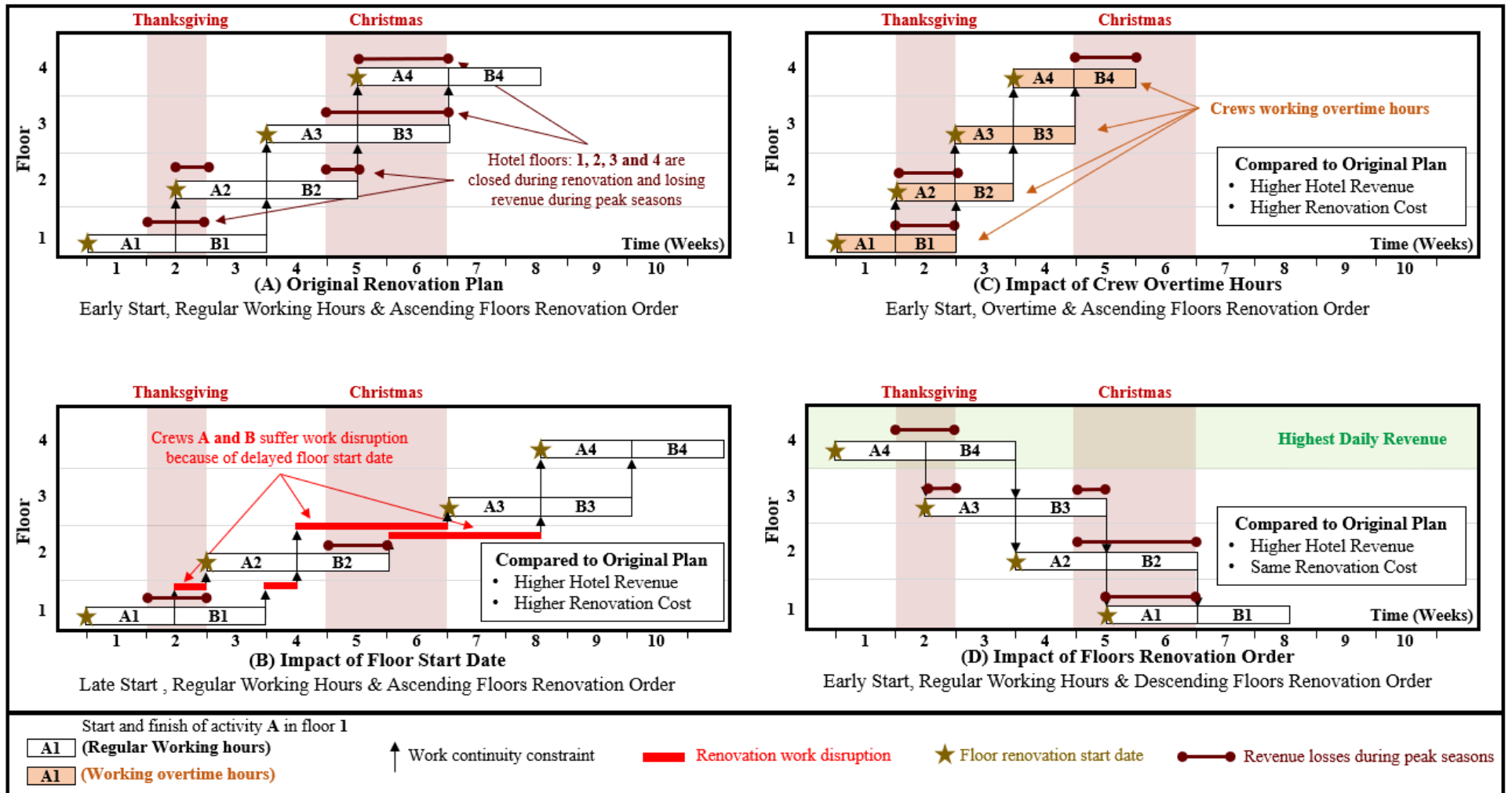


Figure 1.4. Impact of renovation planning decisions on hotel revenue and cost

A number of research studies have been conducted to analyze and optimize the planning of building renovation projects. These studies focused on (1) improving the planning of renovation work in existing buildings (Abdallah et al. 2015; Bucoń and Tomczak 2016; Chantrelle et al. 2011; Cho and Kim 2021; Farahani et al. 2018; Fiedler 1987; Galiotto et al. 2015; Grussing et al. 2014; Jensen and Maslesa 2015; Lee 2011; Liu 2017; Park 2017; Shiue et al. 2019; Wayne and Irvvig 1988; Yee et al. 2013); (2) optimizing the scheduling of repetitive construction projects (Altuwaim and El-Rayes 2018a; b; Bakry et al. 2014; El-Rayes 2001; Fan and Lin 2007; Fan et al. 2012; Hassan and El-Rayes 2019; Hegazy et al. 2007; Hyari and El-Rayes 2005; Hyari et al. 2009; Ipsilandis 2007; Jaskowski and Biruk 2020; Liu and Wang 2007; Long and Ohsato 2009; Monghasemi and Abdallah 2021; Russell et al. 1988; Salama and Moselhi 2019); (3) improving the use of Integrated Project Delivery (IPD) method in construction projects (El Asmar et al. 2013; Elghaish et al. 2020; Engebo et al. 2020; Ghassemi and Becerik-Gerber 2011; Kent and Becerik-Gerber 2010; Lahdenperä 2012; Mahdi and Alreshaid 2005; Muryadi and Christensen, Clayton M., Bower 1994; Pishdad-Bozorgi and Srivastava 2018; Su et al. 2021); and (4) investigating the impact of renovation on hotels performance (Bloom 2012; Echarri et al. 2017; Hassanien 2006, 2007; Hassanien and Baum 2002; Hassanien and Losekoot 2002; Ihsan and Alshibani 2018; Nanu et al. 2020; Penner 1996; Turner and Hesford 2019). Despite the significant contributions of these studies on the planning of renovation projects, there has been no reported research that addressed the aforementioned three main challenges, as shown in Figure 1.1. To this end, this study will explore and develop three novel optimization models to address these challenges.

1.2 Research Objectives

The primary goal of this research study is to develop novel models for optimizing the planning of renovation projects of leased buildings and hotels to overcome the aforementioned

challenges. To accomplish this goal, the research objectives and research questions of this study are summarized as follows:

Objective One: Conduct a comprehensive literature review on the latest research on (1) improving the planning of renovation work in existing buildings; (2) improving the sustainability in existing buildings; (3) prioritization of existing building renovation projects; (4) change order in renovation project; (5) optimizing the scheduling of repetitive construction projects; and (6) limitations of existing models and research needs.

Research Questions: (a) What are the latest research studies on renovating projects?; (b) What are the capabilities and limitations of existing techniques in renovating existing buildings?; (c) What are the latest repetitive scheduling techniques for renovation projects?; (d) What are the main objectives of the available repetitive scheduling optimization models?; and (f) What are the latest models for prioritizing existing building renovation projects?.

Objective Two: Develop a novel model for optimizing the planning of leased building renovation projects that enables owners of leased buildings to minimize total renovation cost including rental income losses.

Research Questions: (a) What are the decision variables and constraints that need to be considered and optimized in this optimization problem?; (b) How to formulate an optimization objective function that minimizes the total project cost for renovating leased buildings?; and (c) How to evaluate the performance of the developed optimization model?.

Objective Three: Develop an innovative model for optimizing the planning of renovation work in leased buildings that enables contractors working under IPD method to maximize their reward sharing while minimizing total renovation cost.

Research Questions: (a) What are the decision variables and constraints that need to be considered to represent the optimal renovation plan of multiple leased buildings projects?; (b) How to formulate an optimization model to generate an optimal renovation plan that maximize contractor's IPD reward sharing while minimizing total renovation cost; (c) What is the most feasible optimization technique that can be utilized to develop the model?; and (d) How to evaluate the performance of the developed optimization model?.

Objective Four: Develop an original optimization model for planning of hotel renovation projects that enables hotel owners to maximize their revenues during renovation work while minimizing project cost.

Research Questions: (1) How to select which hotels to be renovated during any fiscal year from a set of competing hotels to maximize total revenue of all hotels while minimizing total renovation cost that comply with allocated renovation budget; (2) How to analyze and optimize the impact of renovation start date on maximizing hotels profitability; (3) How to optimize the significant impact of the renovation planning decisions of number and size of assigned renovation crews to maximize hotels revenue while minimizing their renovation cost; (4) What is the optimal floors renovation order that maximize hotels profitability; and (5) How to evaluate the performance of the developed optimization model?.

1.3 Research Methodology

To achieve the aforementioned research objectives, a detailed research methodology is established, as shown in Figure 1.5. The developed methodology consists of four tasks that are designed to: (1) conduct comprehensive literature review on the latest research on building renovation projects; (2) develop a novel model for optimizing the planning of leased building renovation projects that enables owners of leased buildings to minimize total renovation cost

including rental income losses; (3) develop an innovative model for optimizing the planning of renovation work in leased buildings that enables contractors working under IPD method to maximize their reward sharing while minimizing total renovation cost; and (4) develop a novel optimization model for planning of hotel renovation projects that enables hotel owners to maximize their revenues during renovation work while minimizing project cost.

Task 1: Conduct a Comprehensive Literature Review

The objective of this task is to conduct a comprehensive literature review and investigate the latest research developments in the planning of building renovation projects to establish baseline knowledge of existing research and practices. The following subtasks detail the components of this research task:

- 1.1** Review the latest research developments in the planning of building renovation projects.
- 1.2** Investigate the latest research on improving the planning of renovation work in existing buildings.
- 1.3** Review available literature on prioritizing building renovation projects.
- 1.4** Investigate the latest research on repetitive construction scheduling.
- 1.5** Explore effective optimization techniques for the planning of renovation projects.

Task 2: Develop Planning Model for the Renovation of Leased Buildings

This task will focus on developing a novel model for optimizing the planning of renovation work in leased buildings that enables owners to minimize total renovation cost including rental income losses. To accomplish this research task, the task is divided into four sub-tasks:

- 2.1** Formulate the model including its decision variables, objective function, and constraints.
- 2.2** Implement the optimization model computations using Genetic Algorithms (GA).

2.3 Evaluate the performance of the developed model and demonstrate its capabilities using an application example of renovating a leased building.

Task 3: Develop Planning Model for the Renovation Work of Leased Buildings Under IPD method

This task will focus on developing an innovative model for optimizing the planning of renovation work in leased buildings that enables contractors working under IPD method to maximize their reward sharing while minimizing total renovation cost. To accomplish this research task, the task is divided into four sub-tasks:

3.1 Identify all relevant decision variables that affect renovation cost and IPD reward sharing in leased building renovation projects.

3.2 Formulate optimization objective function to minimize total renovation cost while maximizing IPD reward sharing.

3.3 Model all relevant constraints to ensure the practicality of the model.

3.4 Execute the computations of the optimization model.

3.5 Analyze a case study to evaluate and refine the performance of the optimization model.

Task 4: Develop Renovation Planning Model for hotel projects

This task will focus on developing a novel optimization model for planning of hotel renovation projects that enables hotel owners to maximize their revenues during renovation work while minimizing project cost. To accomplish this research task, the task is divided into four sub-tasks:

4.1 Formulate the model including its decision variables, objective function, and constraints.

4.2 Implement the optimization model computations using Genetic Algorithms (GA).

4.3 Evaluate and improve the performance of developed renovation planning model using an application example of three hotels.

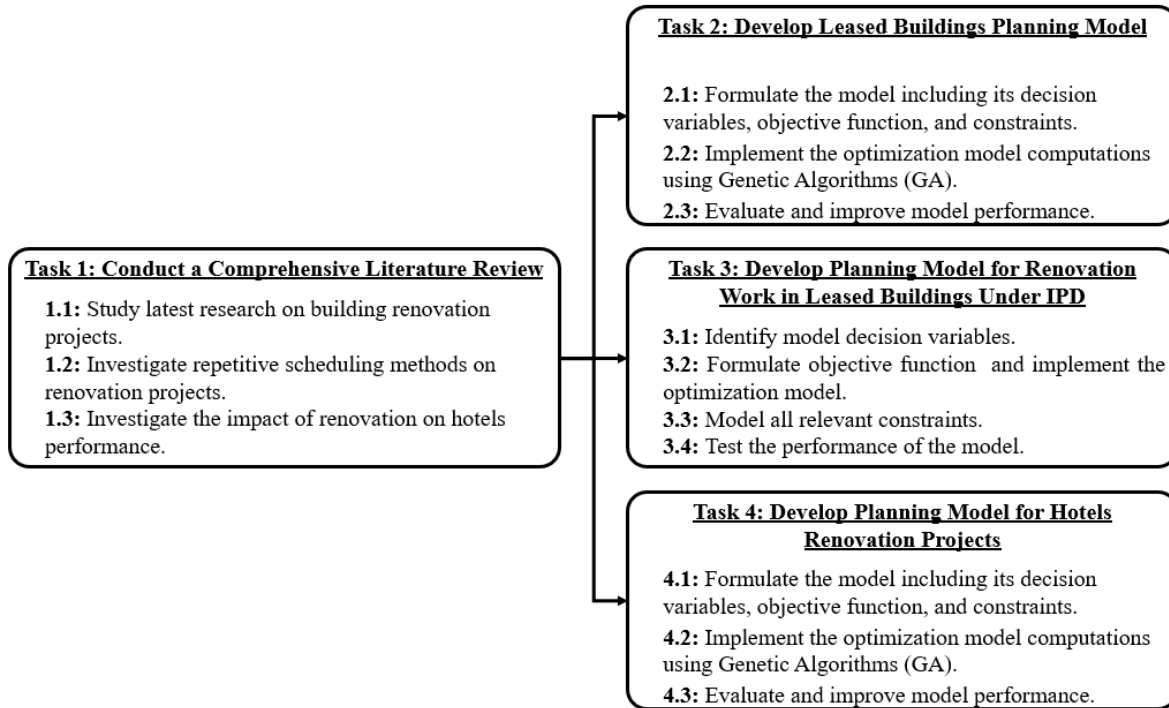


Figure 1.5. Research Methodology

1.4 Research Significance

This research study is expected to provide significant research contributions that will lead to broad and profound impacts on leased buildings and hotels renovation projects. These impacts include providing leased building and hotel owners and contractors with (1) practical scheduling tool for optimizing the planning of leased buildings renovation projects that enables owners of leased buildings to minimize total renovation cost including rental income losses; (2) optimization tool that assist contractors working under IPD method in optimizing the planning of renovation work in leased buildings to maximize contractor's reward sharing while minimizing total renovation cost; and (3) optimization model that helps hotel owners in the planning of their renovation projects in order to maximize hotels revenue during renovation work while minimizing project cost.

1.5 Report Organization

The organization of this report along with its relation to main research objectives, is discussed as follow:

Chapter 2 explores the latest literature in the planning and scheduling of renovation projects in order to establish baseline knowledge. It presents a comprehensive literature review of the latest research on (1) improving the planning of renovation work in existing buildings; (2) optimizing the scheduling of repetitive construction projects; (3) prioritization of existing building renovation projects.

Chapter 3 presents the development of a novel planning optimization model for leased building renovation project that enables leased building owners to minimize total renovation cost. This chapter evaluates the performance of the proposed planning model using a real-life case study of a residential renovation project and demonstrate the capabilities of the formulated model.

Chapter 4 describes the development of an innovative model for optimizing the planning of renovation work in leased buildings that enables contractors working under IPD method to maximize their reward sharing while minimizing total renovation cost. This model is developed in three main phases: optimization, renovation planning, and performance evaluation phases. A real-life case study of three renovation projects is analyzed to illustrate the use of this model and demonstrate its capabilities.

Chapter 5 presents the development of a novel optimization model for planning of hotel renovation projects that enables hotel owners to maximize their revenues during renovation work while minimizing project cost. An application example of three hotels is analyzed in this chapter to illustrate the use of the developed model and evaluate its performance.

Chapter 6 presents the conclusion, main contributions, and future research work.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The Institute for Building Efficiency (2014) reported that 70% of the existing buildings in the United States are aging and in need of renovation. To address this, the renovation of these buildings in the United States has been increasing in recent years (Jeunesse 2019). A significant volume of this building renovation work focuses on leased buildings and hotel properties as they represent a substantial percentage of all existing buildings. For example, the total number of leased units and hotels in the United States were reported to be approximately 54 million units and 50 thousand hotels, respectively (AHLA 2021; EIA 2020; U.S. Census Bureau 2019).

The renovation of leased buildings and hotels presents planners with significant challenges because planners need to consider and minimize the disruptive impact of building renovation activities on reducing building annual income during the planned work. Accordingly, there is a significant amount of research studies conducted to improve building renovation and remodeling processes which focused on (a) improving the planning of renovation work in existing buildings, and (b) optimizing the scheduling of repetitive construction projects. The following sections of this chapter present the findings of a comprehensive literature review that is organized as follow (1) improving the planning of renovation work in existing buildings; (2) improving the sustainability in existing buildings; (3) prioritization of building renovation projects; (4) change order in renovation project; (5) optimizing the scheduling of repetitive construction projects; and (6) limitations of existing models and research needs.

2.2 Existing Building Renovation

The construction industry has historically had significant environmental, social, as well as economic impacts on society (Zuo and Zhao 2014). Most buildings traditionally reflect the

mentioned impacts during their lifecycle. Such a building also never considered the aspects of renovation and refurbishment to conform to the changing needs of the users and various activities satisfying human being's requirements, providing new employment opportunities, and supporting the national economy. Wu et al. (2006) agreed that the ancient buildings, which were initially constructed with poor designs and given little renovation/maintenance, normally deteriorated much faster as compared to those that received regular tune-up. Some objectives of the historical building renovations included improving ventilation, increasing noise control, enhancing lighting conditions, and improving ventilation and air quality within the premise. Although the building and construction industry has a rich history concerning renovation and maintenance mechanisms, more emphasis was hardly put on sustained building renovation, where buildings are redesigned and upgraded to improve their environmental and energy performance besides addressing the essential wear and tear features.

On the other hand, Abdellatif and Othman (2006) stated that today's building technologies are progressing rapidly, and buildings became more complex and sophisticated; thus, their structural conditions and impacts on the environment, society, as well as economy are more significant. However, the authors' observation can be challenged because of the new constraints, such as efficient resource usage and low environmental impact, all of which influence the innovation needs, demand complete innovative and sustainable solutions. The emerging aspects of leased building renovation projects processes observe sustainability features, which have become a valuable pillar in developing building projects, especially in the low-income building projects. Therefore, sustainability is a new architectural requirement supporting the aspects of renovation, refurbishment, and maintenance of buildings. Emerging buildings achieve sustainability when they maintain qualities, meet clients' needs, remain cost-effective in both short

and long runs, maintain high quality, sustain the indoor environment, remain cheaper to maintain, and also user-friendly (Lombard 2017). Most contemporary buildings have considered the aspects of renovation and maintenance aspects to ensure sustainability and market relevance.

Dwaikat (2017) asserted that the building industry in today's world consumes large amounts of material and energy. Nevertheless, the EPIQR model was developed to evaluate the conditions of existing leased buildings before conducting renovation. Gómez-Soberón et al. (2018) argued that the model could help developers and designers to reduce the negative impact of housing subdivision projects, especially in the advanced economies. It also predicts the energy usage for leased buildings because building components have a varying lifespan. From another lens, it is arguable that longevity and the infill systems of a building should be given adequate maintenance in accordance with the ever-changing needs of users. For instance, infill systems, such as mechanical equipment, electrical systems, and interior installation, can last for only 3 to 20 years, while the building structure and the exterior systems can stand for 60 years. Overall, the modern building techniques allow building owners to conduct renovations for the infill systems without making changes to the building's structure to meet the dynamics of the housing market. Janjua, Sarker, and Biswas (2019) noted that environmental factors typically cause buildings to deteriorate over time. The resultant wear and tear often affect the physical structure, strength, aesthetic appeal, and market value of the buildings. For this reason, building owners and construction firms usually seek to renovate their buildings to remain in a usable state. Some practices that can be adopted to improve the usability of buildings include rehabilitation, reconstruction, maintenance, and renovation. Rehabilitation involves those activities that enhance the lifespan of a building, and it involves minimal or significant changes to preserve the original

building features. Reconstruction involves demolishing an old building in an area and replacing it with a new structure with novel features and amenities.

On the other hand, maintenance describes the regular repairs done in some parts of a building to maintain its operation life. Renovation involves improving a building's condition by replacing some parts or entire sections of the building. It involves making modifications and remodeling various parts of the original structure (Li et al. 2007). The literature concurs that the effects of environmental factors on buildings and the functional changes of premises due to dynamic economic needs necessitate the application of renovation and other architectural strategies to raise the relevance, strength, safety, and performance of the concerned structures.

Nevertheless, sustainable renovation of buildings can be achieved by rehabilitating unused buildings and upgrading existing buildings to improve their service value. Huang et al. (2011) asserted that with considerations for sustainability, the renovation of deteriorated buildings should focus more on reducing energy consumption, enhancing energy efficiency, and improving overall service value. Before pursuing renovation, the first step should involve conducting an assessment of the current condition of the building (Lombard 2017). Thus, rehabilitation can be used to upgrade existing buildings to improve their service value. Most authors in the construction industry concurred that the external and internal environments or buildings could also be upgraded through periodic renovations. Besides, renovations can be conducted in buildings to achieve other objectives. For instance, renovations can be conducted in a building to attract new occupants or tenants, include modern accommodations, or enhance the overall value of existing buildings (Gómez-Soberón 2018). Renovations for buildings should be conducted in a manner that preserves their utility to occupants. The schedules for renovations and periodic maintenance should not cause severe disruptions to the economic utility of the building. Sustainable renovation creates an

opportunity for building owners to adopt cost-effective measures, improve the environmental soundness of the premises, and ensure resource-efficiency. A topological representation of these main terms with partial overlaps among them, as shown in Figure 2.1.

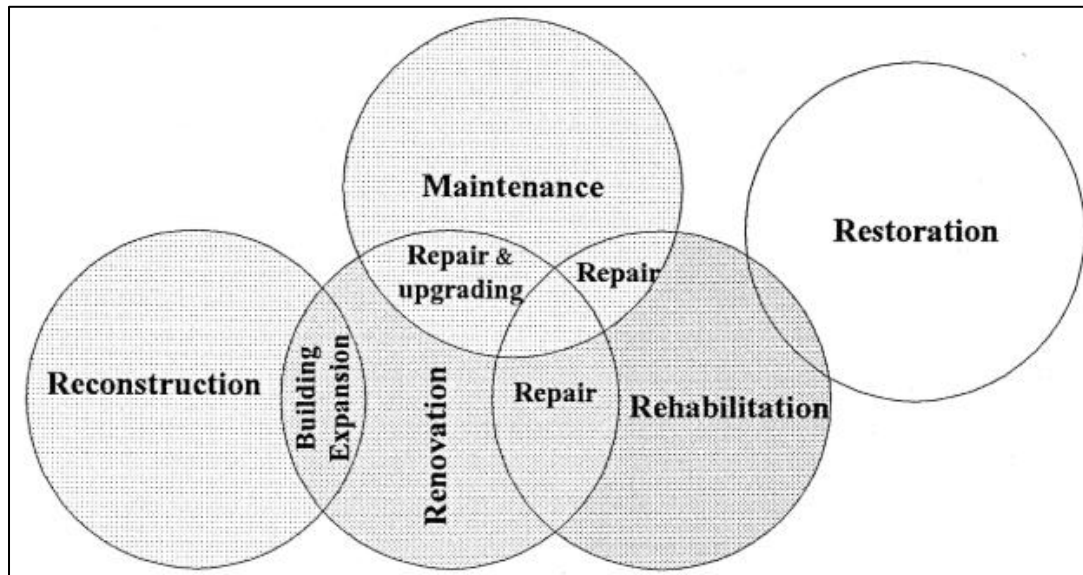


Figure 2.1. Terminology for the upgrading of constructed Buildings (Rosenfeld and Shohet 1999)

Before the renovation of a leased building, three main steps should be done as follow: (1) building status determinations, (2) renovation strategies, and (3) renovation measures (Abdul Hamid et al. 2018). Figure 2.2 illustrates the overall steps in a renovation project.

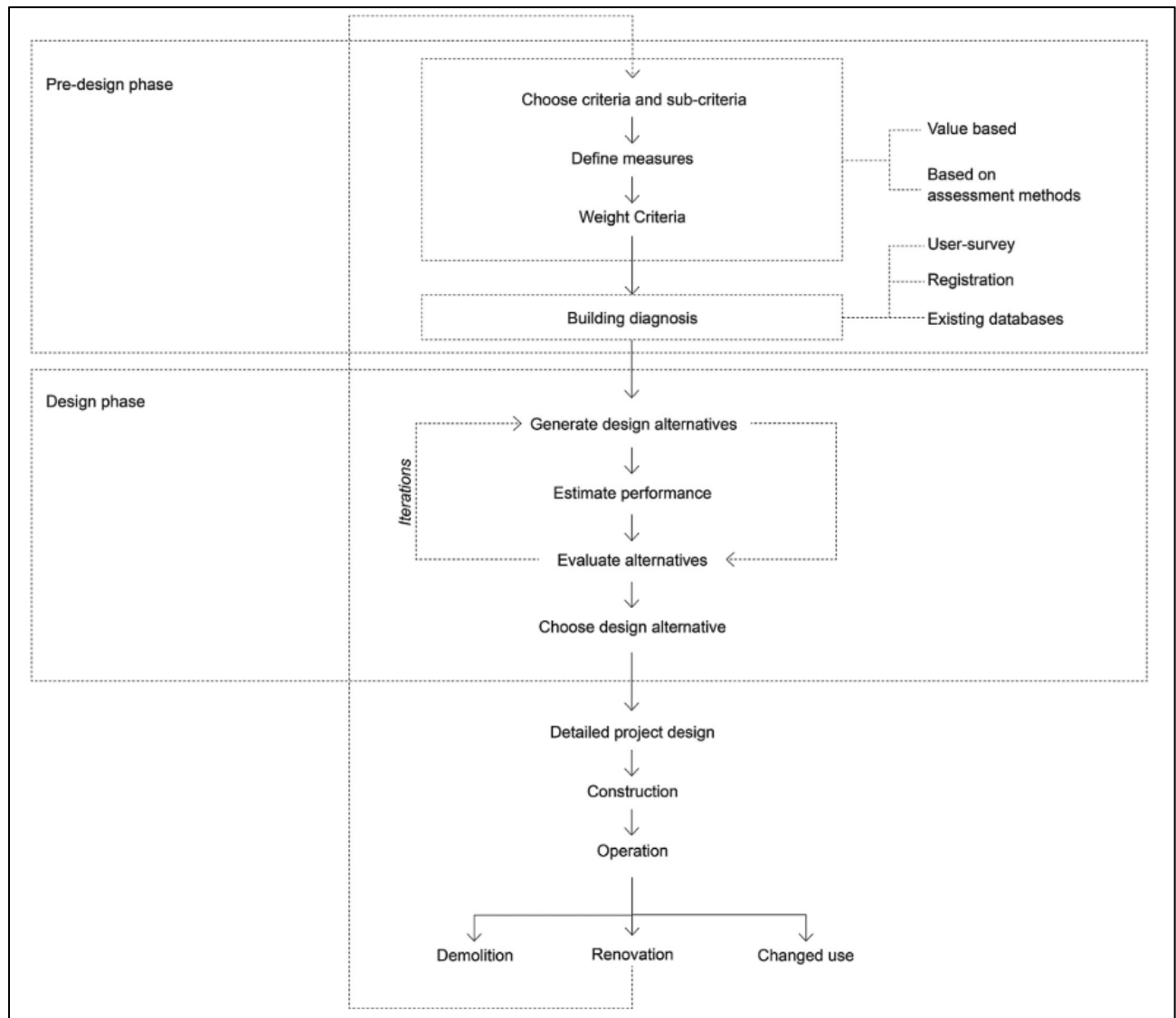


Figure 2.2. The building renovation process (Nielsen et al. 2016)

2.3 Sustainability in Buildings Improvement

Renovation of buildings is increasingly being influenced by sustainability concerns, such as social advancement, environmental deterioration, and community engagement. According to Zuo and Zhen-Yu (2014), these factors inform the push for sustainable construction and renovation of buildings. Sustainable buildings focus on ecological preservation and support the goal of resource conservation. Lawania and Prabir (2015) agreed that just like other industries that improve societal wellbeing and encourage economic growth, the construction sector significantly

contributes to the depletion of environmental resources and increased emission of greenhouse gases. The building construction sector contributes 30% of total annual greenhouse emissions in the world (Dean et al. 2016). The construction sector also contributes more than \$8.8 trillion in growth in the global economy (Janjua et al. 2019). It utilizes a third of global resources and produces almost 40% of all solid wastes. Every year, the construction sector consumes energy-intensive materials, glass, aluminum, cement, plastic, steel, wood, and water. By 2040, the estimated consumption of operational energy and global energy around the world would be 32% and 21% respectively. This growth will be fueled by the rising rates of urbanization in non-OECD countries. However, more research needs to be done to establish how sustainability in leased buildings improvement can be achieved without incurring more costs in the renovation aspects.

Smart building concepts, sustainable building, and green building can help in reducing greenhouse emissions through the building sector. Evangelista et al. (2018) reiterated that one standard approach for evaluating the environmental and economic impact of buildings is the Life Cycle Assessment. This approach uses economic, environmental, and social measures to evaluate the sustainability of buildings (Pillai et al. 2019). The projects use sustainability indicators to make such measures and set optimal performance criteria. Such measures are then weighed against the average service life of the buildings. Even though buildings are basic needs for humans, they also contribute significantly to environmental degradation, cause resource depletion, and promote pollution (De Luca et al. 2017). For this reason, construction firms now endeavor to pursue the sustainable development of buildings that meet environmental, economic, and social standards. Sustainable buildings follow a design philosophy that promotes efficient allocation of resources, lowers any adverse effects on human dignity and wellbeing, and ensures cost-efficiency.

2.3.1 Historical Perspective

Proper management of construction projects is guided by the need for efficient utilization of materials, cost-cutting without compromising quality, labor charges, and construction equipment. According to Abdellatif and Othman (2006), the decision-makers strive to enforce cost control to promote labor productivity and increase the efficiency of materials used. In concurrence, Alanne (2004) noted that material handling function might require cost reduction in elements such as procurement, field servicing, and inventory. In the construction sector, labor productivity is defined as output per labor hour. Quite often, the labor hours commonly contribute a large part of construction costs. Notably, the management can easily influence the number of labor hours as opposed to material costs. Building owners and contractors are generally concerned about labor productivity at work sites. Thus, they may use different systems to measure labor productivity.

In recent decades, innovative methods and new equipment have brought wholesale changes in the construction sector. Those organizations that fail to adjust to these changes have been forced to drop mainstream construction activities. For instance, the current demands in the construction sector require construction firms to develop sustainable buildings. Building owners who seek to renovate their buildings demand to hire construction contractors with demonstrated competence for constructing sustainable buildings (Alann 2004). Even though the materials and techniques used for constructing sustainable buildings have not changed much as compared to the early years in the 20th century, many construction firms have embraced significant mechanical and technological advances to support their productivity. They also have a new focus on sustainability than ever before.

2.4 Building Renovation Prioritization

According to Abdellatif and Othman (2006), clients and end-users of low-income building projects complain that their accommodations are not designed to match their requirements or meet their expectations. However, building designers believe that their designs have carefully considered the specific needs of clients, accommodating all specified requirements. Regrettably, the problem often emerges due to misunderstanding between the designers, who have a comprehensive and technical understanding of the building designs, and the final users who hardly communicate or provide feedback about the new needs of the building structure. Nevertheless, the renovation of buildings is usually informed by clear long-term strategies, the priority needs for deferred renovation, and the identified needs for renovation. Huang et al. (2019) stated that stating the renovation step requires prior planning to understand the past needs of the deteriorating building, the current backlog of renovation work that should be accomplished, and the future renovation needs. Therefore, the planning aspect involves reviewing the current status of leased buildings to determine any need for renovation or repair and the creation of long-term schedules for maintenance to prevent deterioration of the building.

Renovation needs for buildings keep changing depending on the age of buildings, the changing needs of users, and the emergence of new building technologies. For this reason, building owners may be forced to conduct renovation to address other factors beyond the essential wear and tear. For instance, old buildings can be renovated to address wear and tear, achieve sustainability, and improve their energy performance. To achieve these objectives, the first step to determine the renovation needs for buildings is to conduct a facility assessment. The process can be conducted formally by performing conditions analysis and inventory evaluation for specific building components. The step enables the building owner to know the status of the facility,

understand its repair and improvement needs, plan for capital renewal projects, and develop a plan to address issues of deferred renovation.

Secondly, an audit of a building's condition can be performed to obtain accurate measures of its upgrade needs (Gómez-Soberón 2018). The audit result will identify future needs for renovation, allow the building owners to schedule upcoming renovations, and prioritize some renovation projects over others. The audit process for buildings includes an initial design step for the audit tasks, followed by data collection, creation of upgrade schedules and cost estimates, and presentation of findings. Thus, it is crucial to do an audit of the renovation needs of a building for matters prioritization.

2.4.1 Facility Condition Index

Facility Condition Index describes an equation that weighs the value of deferred maintenance costs for a building against the current replacement value that the builder will pay if he/she chooses to construct a new one. Dwaikat (2017) stated that the audit report also provides baseline information that construction firms and building owners use to compare the conditions of different buildings for renovation and maintenance purposes. The audit report forms a basis for budgeting the costs of maintenance and renovation. A Facility Condition Index can then be developed from the audit report of the building to guide the future maintenance of the buildings.

2.4.2 Life Cycle Costing

Upon completion of the facility audit, the long-term costs of the building can be managed and monitored through the Life Cycle Costing program. Under this method, the building owner can evaluate the capital renewal costs, upgrade costs, and preventive maintenance costs of the building during its lifetime (Mihindu and Yusuf 2008). The process measures the costs of the building and all equipment in it, without including its occupant costs or energy use. The assessment

provides information for prioritizing imminent maintenance needs, budgeting for the identified needs, and planning for future renovation needs. The process also eliminates the uncertainty in budgeting for building renovation tasks, addresses the problem of renovation, and makes definite long-term plans for renovation. For this reason, Life Cycle Costing provides a proactive tool to manage the renovation process for buildings. It also sets comprehensive schedules for repairs and maintenance (Dwaikat, 2018). Overall, it is advisable to do life cycle costing for a building to understand the needs and possible viability of the prospected innovation.

2.5 Change Orders in Renovation Projects

Renovation and maintenance projects are so sophisticated and cannot be compared to new projects. In new construction projects, all parties can involve from the beginning of the conceptional design stage to control change orders during the execution phase. However, it is not the case in renovation and maintenance projects since these renovations have more aspects to consider, such as unforeseen conditions. Therefore, change orders in renovation projects are often costly from those for new construction projects. Unforeseen conditions change orders; for example, they can be more costly than once in maintenance and renovation projects due to usual undetailed study. Shrestha et al. (2018) stated that more types of change orders have a significant effect on cost and schedule overruns of renovation projects. Few studies have been conducted to investigate the effect of change orders in cost and time overrun during renovation projects. One of the main advantages of investigating such a correlation is to support decision-makers and renovation project planners to use a valid change order management process to control these overruns. This section is subcategorized into two parts: (1) what are the definitions of a change order, and (2) change orders related to renovation and maintenance projects.

2.5.1 Change Order Definitions

During any construction project execution phase, there are a number of factors that encounter for affecting the planning performance of the project. Change orders are considered as one of the most factors that play a significant role in the performance of the project. A change order can be defined as “a change order is a charge for work not included in a contract’s scope of work.” (Shrestha et al. , 2018). However, change orders not always result in costly and timely rework; it might reduce some unnecessary work that was mentioned in the scope of work. Jackson (2004) summarized that change order is “once the contract is signed, both parties must live with the terms of the contract, and any flaws, errors, or omissions in the plans and specs will result in a change order.” Khalafallah et al. (2019) stated that “a change order is issued to introduce a design change during the design phase and/or a construction change during the construction phase.” All aforementioned definitions are only considering change orders that are related to new construction projects. However, for maintenance and renovation projects, there are situations such as unforeseen conditions that can lead to change orders for urgent work that was not expected during the conceptional design stage.

2.5.2 Change Orders Related to Renovation and Maintenance Projects

A number of studies have be conducted to analyze the effect of change orders towards project cost. Shrestha et al. (2017) conducted a comprehensive study of the effects of change orders on the increase in the cost. Authors analyzed more than road maintenance projects to evaluate the relationship of change order values with project size and schedule. They found that renovation and maintenance change orders have caused an increase in the total cost of the project by 13%. Three main types of change orders are related to renovation projects. Shrestha et al. (2018) summarized them into change orders related to (1) unforeseen conditions change orders; (2) owner-initiated

change orders; and (3) design-related change orders. This study showed that change related to unforeseen conditions had the most significant effect on cost increase, followed by design-related change orders.

2.6 Repetitive Construction Scheduling Methods

Traditional scheduling methods have been advanced since 1940. Two of these well-known methods are the Gantt chart and network scheduling techniques. Such traditional techniques are used extensively in the construction field; however, they cannot be used for repetitive construction activities for a couple of reasons. Applying traditional scheduling methods for repetitive construction lead to the production of a massive and complex network of tasks that are sophisticated to understand. Briefly, planning and scheduling methods for construction projects can be divided into two groups; (1) time-driven methods such as critical path method (CPM) and Gantt chart – traditional scheduling techniques, and (2) resource-driven methods like repetitive scheduling method (RSM). Altuwaim & El-Rayes (2018) stated that utilizing traditional scheduling methods for repetitive construction projects are inefficient since their incapability of maintaining resources work continuity (Russell and Wong 1993; Hegazy and Wassef 2001; and Altuwaim & El-Rayes 2018), as shown in Figure 2.3. Therefore, many studies have been conducted to overcome these limitations of time-driven techniques in repetitive construction projects. These studies have developed models that can be classified as resource-driven scheduling models that are capable of achieving work continuity in repetitive activities while minimizing crews interruptions time. These resources-driven scheduling methods can be divided into two main groups: (1) deterministic scheduling models such as line of balance (LOB), and linear scheduling method (LSM); and (2) stochastic scheduling models such as probability-based scheduling models, and Project Evaluation and Review Technique (PERT) models.

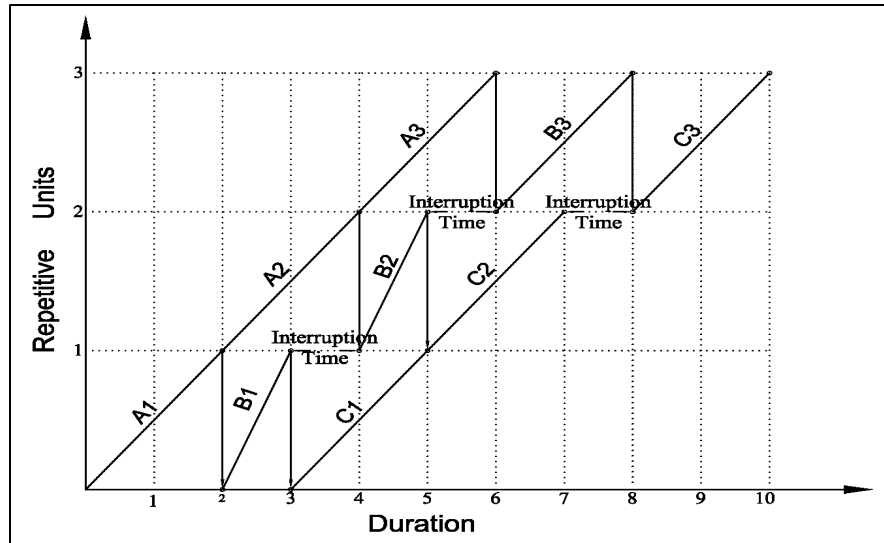


Figure 2.3. Time-Driven Scheduling for repetitive activities Representation

2.6.1 Line of Balance (LOB)

The U.S Navy developed Line Of Balance (LOB) scheduling technique in the early 1940s. Lumsden (1968) stated that LOB was primarily developed to control and schedule industrial manufacturing operations. In 1960, The UK Construction industry leaders utilized LOB technique, by National Building Agency of the UK (Yang & Ioannou 2004). The LOB only has the ability to schedule typical repetitive activities since it was developed, assuming that each repetitive activity has a constant output rate. LOB is a graphical technique that reflects the repetitive construction project schedule in a two dimensions diagram (an X-Y Axis), where the X-Axis highlights the duration and the Y-Axis represents the repetitive units, as shown in Figure 2.4. All activities are inclined represented as a bar for each activity, where the duration of each activity is reflected by the width of the bar, while the slope of the bar reflects the production rate of that activity. Moreover, the diagram shows the total project duration as well as the start and finish duration for each unit.

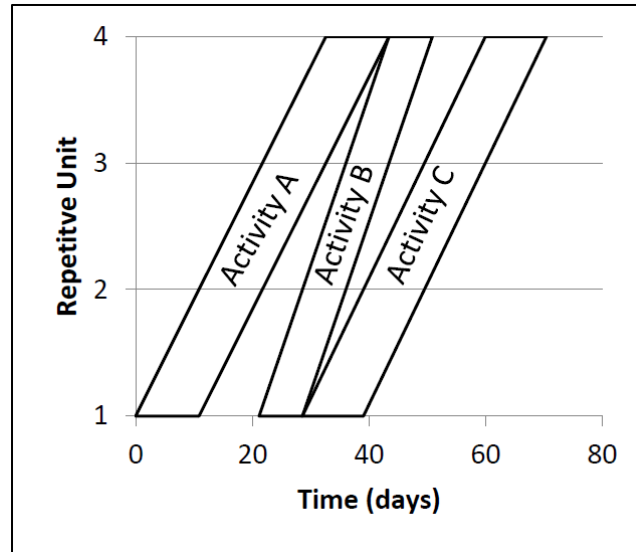


Figure 2.4. Line of Balance (LOB) representation (Altuwaim, 2018)

LOB scheduling method helps planners to (1) minimize crews interruption by regulating the rate of production of each repetitive activity; (2) improve demonstration of the whole project duration; (3) providing micro-scale scheduling by monitoring all repetitive activities; (3) improve the process of selecting the optimal crews that maximize work continuity; and (4) adjust resources to meet the required production rate (Lutz and Halpin 1992; Mattila and Abraham 1998; and Srisuwanrat 2009). Many studies have been conducted to develop LOB scheduling technique while maintaining the central concepts of the method. A new way of presenting the LOB diagram was developed, which deals with the difficulty of showing two activities with the same production rates (Hegazy et al. 1993). The model was designed to avoid overlapping among concurrent activities by producing two diagrams, one shows the critical path activities, while the second graph shows other activities. Additionally, Altuwaim (2018) stated that utilizing different colors and line patterns in the LOB diagram would enhance the activities presentation as well as the project schedule.

Furthermore, many scholars have conducted studies to develop more mathematical expressions and approaches for LOB rather than graphical presentations. Identifying the start and

finish dates for each repetitive activity at each unit was developed by (Al Sarrig 1990). Thabet and Beliveau (1994) studied the impact of workspace availability for each activity before the start date. The model was developed to measure the availability of workspace, and its capacity for the activity or not. If the workspace capacity is enough for the activity, then the model will consider that activity to start on that date. Otherwise, alternatives will be considered to avoid a lack in the workspace, such as decrease the crew production rates.

On the other hand, many studies have criticized LOB for two main reasons: (1) Srisuwanrat (2009) stated that non-typical repetitive activities could not be presented by LOB since the central core concept of LOB is to have constant production rates for each activity; and (2) crews learning curve is not considered by LOB, where such repetitive activities enhance workers' ability to increase productivity rates (Bakry 2014).

2.6.2 Linear Scheduling Method

The Linear Scheduling Method (LSM) was developed to overcome the LOB limitations for presenting nontypical repetitive activities as well as typical repetitive activities (Slinger 1980). LSM and LOB have similarity in presenting repetitive construction schedule in graphical presentation as well as maintaining work continuity. Despite these similarities, in LSM activities are presented as a line with a slope, while LOB presents activities as a format of the bar. Moreover, LSM reflects the production rate (line slope) for each repetitive activity in each unit (Bakry 2014). LSM is a graphical technique that reflects the repetitive construction project schedule in a two dimensions diagram (an X-Y Axis), where the X-Axis highlights the repetitive units, and the Y-Axis represents each repetitive activity with its duration as shown in Figure 2.5. A line presents each repetitive activity with different slope based on the production rate where production rate may vary from one unit to another.

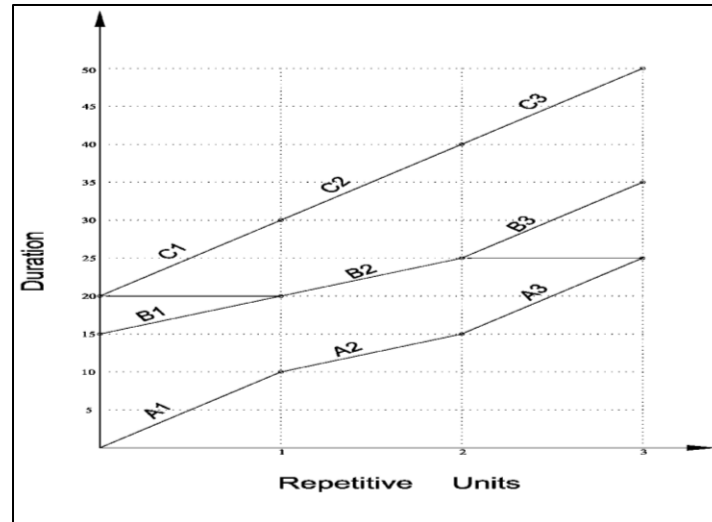


Figure 2.5. Linear Scheduling Method (LSM) Representation

Many models have been developed to minimize repetitive project duration by considering interruptions (Selinger 1980; Russell and Wong 1993; El-Rayes and Moselhi 2001; Altuwaim & El-Rayes 2018). Altuwaim & El-Rayes (2018) developed a scheduling model that simultaneously minimizes project duration, crew work interruptions, and interruption costs. The model calculated the early start for each repetitive activity as well as consider work continuity and total float. Additionally, Long and Ohsato (2009) developed an LSM model that has the capability of maximizing work continuity for all resources while minimizing project duration. This model identifies the start and finish dates of all repetitive activities in each unit with considering interruption cost for each crew.

2.6.3 Repetitive Construction Scheduling Optimization

Many constraints are associated with optimizing repetitive construction project schedules such as work continuity. Many optimization models have been developed and used for a couple of purposes: (1) minimize Total project duration; (2) minimize total project cost; and (3) minimize interruption time and cost in construction resources. The main challenge that scholars were tackling was identifying optimal crew for each activity that minimizes both project time and cost.

In traditional construction projects, planners try to minimize the duration of critical activities to minimize total project duration. However, in repetitive projects, this technique cannot be used to achieve minimal project duration since it will affect work continuity which leads to an increase in the total project cost (direct and indirect costs).

To overcome this, planners should consider all possibilities of crew alternatives to find the optimal combination that achieves minimal project duration and cost. El-Rayes 1997 stated that a number of possibilities for resources in construction projects are ZQ , where Z is the number of crews in each activity while Q is the number of repetitive activities. Planners should consider Z^Q combinations to select the optimal crew formation. A repetitive construction project, for example, consists of 10 activities, and each one of these activities can be performed by one of five possible crews, then the number of possible combinations is ($5^{10} = 9.7 \times 10^6$) combination. This way of selecting the fittest crew formation is unfeasible and unpractical (Bakery 2014).

One of the repetitive construction projects is trying to select the fitness resource that can minimize interruption time and cost for each repetitive activity. El-Rayes and Moselhi (2001), stated that allowing such interruption might reduce the total project duration. All possibilities of the optimal length of work interruption between two related activities can be obtained by utilizing this mathematical Equation 2.1.

$$Y^{((S * (E - 1)))} \quad (2.1)$$

Where:

Y = The maximum allowed period of work interruption between any two sequential units.

S = Number of activities.

E = The number of repetitive units in the project.

For instance, a repetitive construction project, for example, consists of 10 activities, and each one of these activities can be performed by one of five possible crews. Each activity consists

of 5 units and the maximum allowed interruption between repetitive units is 4 days, then the number of possible combinations of interruption is $(4^{((10 * (5 - 1))))) = 4^{40}$ combinations. Therefore, to determine the optimal resource utilization and interruption for each activity, $5^{10} \times 4^{40}$ combinations should be considered. This way of selecting the fittest crew formation is unfeasible and unpractical.

These repetitive scheduling challenges have been investigated heavily for the past four decades. Many optimization models have been developed to overcome these limitations (Cooper and Cooper 1981; El-Rayes 1997; Bakery 2014; and Altuwaim & El-Rayes 2018). These models have utilized different optimization techniques, such as genetic algorithms (GAs), linear programming, and dynamic programming.

2.6.4 Genetic Algorithm

In 1975, John Hollan was exploring the processes of the naturally working systems, and he developed an optimization algorithm tool that utilized such natural systems called Genetic algorithms (GA). Genetic algorithms (GA) mimic the evolutionary process in nature. The genetic algorithms operating principles are as follows: (1) create a population of individual solutions (chromosomes); (2) for each individual within the chromosomes, compute the objective function(s); (3) assign a fitness value to each individual based upon the objective function(s); (4) Crossover is performed for creating new individuals out of the selected individuals; (5) The algorithm will be terminated if the conditions are satisfied, and this happens by repeat steps 2-4 until termination. Many types of optimization problems such as static, dynamic, linear, nonlinear, and continuous were solved by utilizing GA approaches.

For construction engineering optimization problems, Genetic algorithm is reported to be the most optimization tool that has been used to tackle these construction problems including (1)

minimizing total cost and time of repetitive projects (El-Rayes 1997; Bakery 2014; Altuwaim & El-Rayes 2018; and Hassan & El-Rayes, 2019); and (2) sustainability optimization models (Hyari and El-Rayes 2006; Abdallah, Khaled El-Rayes, & Liu, 2015; and Karatas & El-Rayes, 2016).

2.7 Research Needs

This chapter provided a comprehensive review of existing buildings renovation projects. This detailed literature review will establish baseline knowledge of latest research on (1) improving the planning of renovation work in existing buildings; (2) improving the sustainability in existing buildings; (3) prioritization of building renovation projects; (4) change order in renovation project; (5) optimizing the scheduling of repetitive construction projects; and (6) limitations of existing models and research needs.

This review revealed that there is a pressing need for novel optimization models for the planning renovation projects that are capable of : (1) planning of leased building renovation projects that enables owners of leased buildings to minimize total renovation cost including rental income losses; (2) planning of renovation work in leased buildings that enables contractors to maximize their reward sharing while minimizing total renovation cost; and (3) planning of hotel renovation projects that enables hotel owners to maximize their revenues during renovation work while minimizing their renovation cost. Moreover, this chapter studied and analyzed the capabilities and limitations of available models for optimizing the planning of building renovation projects.

CHAPTER 3: OPTIMIZING THE RENOVATION PLANNING OF LEASED BUILDINGS TO MINIMIZE TOTAL PROJECT COST

3.1 Introduction

This chapter presents the development of a novel planning optimization model for leased building renovation projects that enables building owners to identify an optimal project start date (t), crew formation (x_i) for each renovation activity (i), and unit renovation sequence (u) that minimize total renovation cost including rental income losses. The computations of the developed model are performed in three main modules, as shown in Figure 3.1: (1) optimization module that searches for and identifies an optimal renovation schedule that minimizes total renovation cost; (2) scheduling module that calculates the start date, finish date, and total interruption duration for each activity (i) in all units that are planned to be renovated; and (3) cost module that computes expected total renovation cost for each generated solution in the optimization module. The following sections describe the development and computations of these modules:

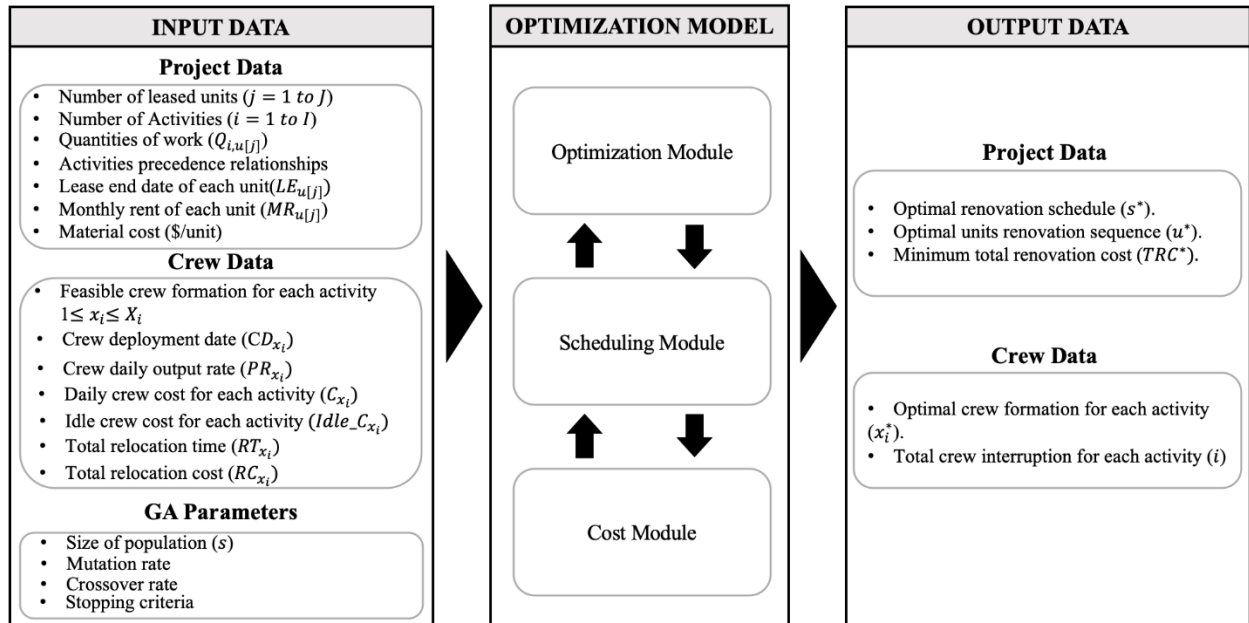


Figure 3.1. Model development for repetitive leased building renovation projects

3.2 Optimization Module

The primary purpose of this module is to search for and identify an optimal project start date (t), unit renovation sequence (u), and crew formation (x_i) for each renovation activity (i) that minimize total renovation cost. The optimization module is developed in three main phases (see Figure 3.2) that are designed to (1) model all relevant decision variables; (2) formulate the optimization objective function of minimizing total renovation cost; and (3) execute the computations of the optimization model. The following subsections provide a concise description of these development phases of the optimization module.

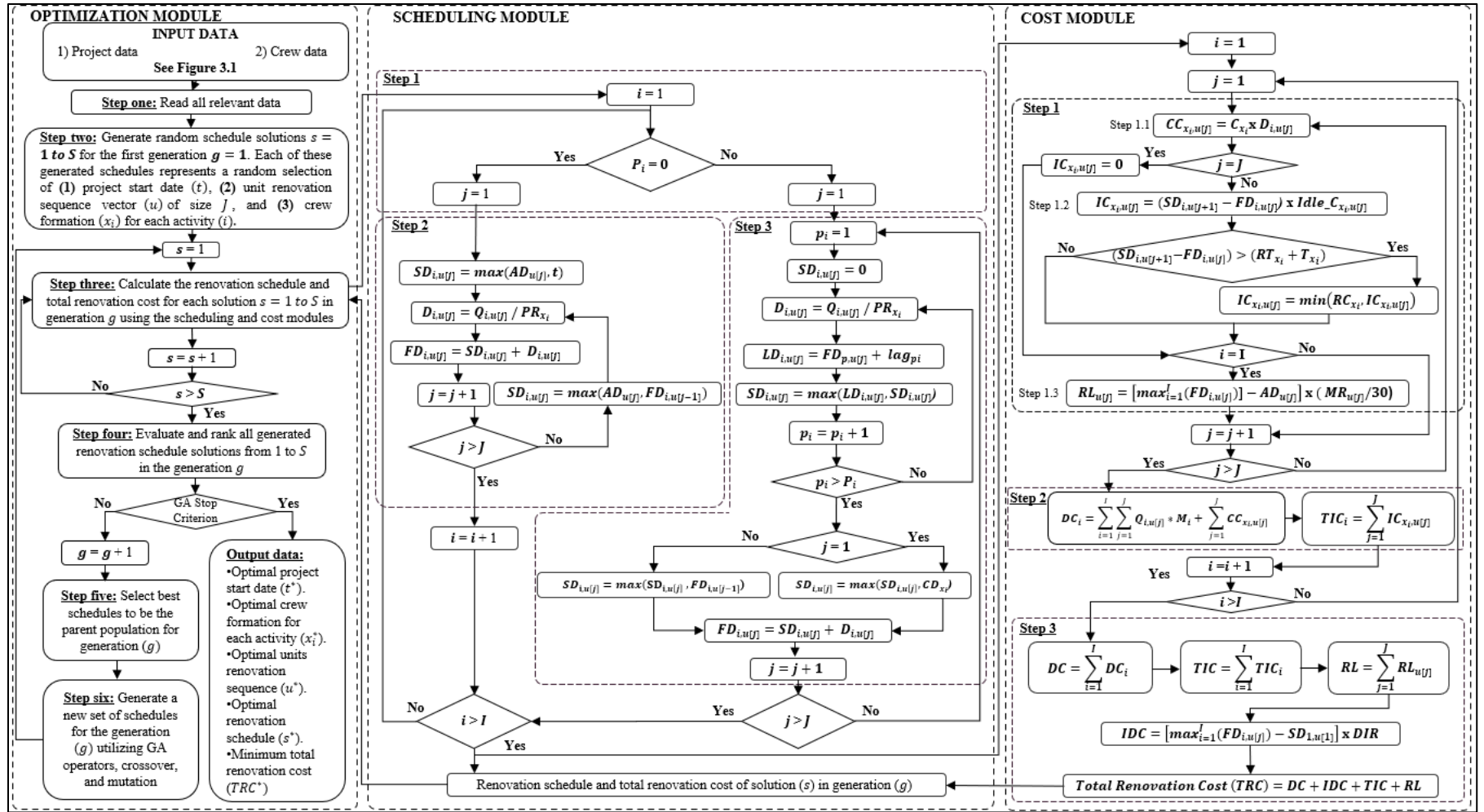


Figure 3.2. Optimization model computations

Phase 1: Decision Variables

The purpose of this phase is to identify all possible decision variables that affect the total renovation cost of leased buildings. Accordingly, the identified decision variables in this model are: (1) project start date (t); (2) unit renovation sequence (u); and (3) crew formation (x_i) for each renovation activity (i).

The first decision variable in this model is the project start date (t) which represents the selection of a project start date from a set of feasible alternatives. This decision variable ranges from a minimum value of zero that represents the earliest lease end date among all leased units to a maximum value of T that represents the duration between the latest and earliest lease end dates, as shown in Eq. (3.1) and Eq. (3.2).

$$0 \leq t \leq T \quad (3.1)$$

$$T = LE_J - LE_1 \quad (3.2)$$

Where:

t = Project start date.

T = Duration between the latest and earliest lease end dates in days.

LE_1 = Lease end date of the earliest vacant unit.

LE_J = Lease end date of the latest vacant unit (J).

The second decision variable in this model (u) is a sequence vector of size J that represents the sequence of renovation work in all units $j = 1$ to J , as shown in Eq. (3.3). For example, a sequence vector of [3,2,4,1] indicates that there are four leased units that need to be renovated and their renovation order will start with unit 3, moves to unit 2 then 4, and ends with unit 1. The total number of possible combinations of renovation sequence depends on the total number of units (J) and is equal to $J!$. For example, the total number of possible combinations of renovation sequence for six leased units is equal to $6!$ (i.e. 720 possible combinations).

$$\begin{aligned}
u &= [u_1, u_2, \dots, u_J] & |u| &= J \\
&& u_k &\neq u_j, \forall k \neq j, \quad k, j \in \{1, \dots, J\}
\end{aligned} \tag{3.3}$$

Where:

J = Total number of leased units that are planned for renovation.

The last decision variable in this model is the crew formation (x_i) that represents the selection from a set of feasible alternatives that may include the use of varying crew sizes, overtime hours, and/or multiple shifts for each renovation activity (i). Each of these alternative crew formations has a unique daily output and cost rates that directly affects the activity duration and cost. For each activity (i), this crew formation decision variable (x_i) is modeled using a positive integer variable that ranges from one to the total number of feasible alternative crew formations that is specified by the planner (X_i), as shown in Eq. (3.4). For example, $X_2 = 3$ indicates that there are three feasible crew formations for the construction of the second activity ($i = 2$), and $x_2 = 1$ represents the selection of the first crew formation for the second activity ($i = 2$).

$$1 \leq x_i \leq X_i \quad \forall i \in I \tag{3.4}$$

Where:

X_i = Number of available crew formations to execute renovation activity i .

Phase 2: Objective Function

The objective function of the present model is designed to minimize the total renovation cost that includes direct cost (DC), indirect cost (IDC), total rental income loss during project execution (RL), and total interruption cost (TIC), as shown in Eq. (3.5). These four types of costs are calculated in this model using the schedule and cost modules that are described on the following sections, as shown in Figure 3.2.

$$\text{Minimize } TRC = \text{Minimize } (DC + IDC + TIC + RL) \quad (3.5)$$

Where:

TRC = Total renovation cost.

DC = Total direct cost.

IDC = Total indirect cost.

TIC = Total interruption cost.

RL = Total rental income loss during the renovation period.

Phase 3: Optimization Computations

The model is designed to execute the optimization computations using genetic algorithms (GAs) due to their capabilities of (1) dealing with nonlinear and discontinuous objective functions and constraints; (2) searching for and identifying optimal solutions in a large search set problems with a reasonable computational time (Altuwaim and El-Rayes 2018; Fan et al. 2012; Hyari et al. 2009; Salama and Moselhi 2019). The optimization computations are achieved in six main steps:

1. Read all project information required in the optimization module including (1) project data; (2) crew data; and (3) GA parameters, as shown in Figure 3.1.
2. Generate random schedule solutions $s = 1$ to S for the first generation $g = 1$. Each of these generated schedules represents a random selection of (1) project start date (t), (2) unit renovation sequence vector (u) of size J , and (3) crew formation (x_i) for each activity (i) from their sets of feasible alternatives.
3. Calculate the renovation schedule and total renovation cost for each solution $s = 1$ to S in generation g using the scheduling and cost modules described in the following sections, as shown in Figure 3.2.

4. Evaluate and rank all generated renovation schedule solutions from 1 to S in the generation g and select the fittest renovation schedule. Check if the specified GA stopping criteria was satisfied. If yes, the model ends its optimization computations and generates its output data. Otherwise, the model proceeds to step 5 and 6.
5. Select the best solutions to be the parent population for the new generation $g = g + 1$.
6. Generate a new set of solutions for the new generation $g = g + 1$ utilizing GA operators, crossover, and mutation, as shown in Figure 3.2.

3.3 Scheduling Module

The purpose of this module is to develop a practical schedule for all the renovation activities ($i = 1$ to I) in all leased units ($j = 1$ to J) that is capable of complying with the two aforementioned important constraints of job logic and leased units availability time shown in Figure 1.2. In addition, the module is designed to provide planners with the flexibility to (a) specify the earliest crew deployment date (CD_{x_i}) that may vary from one construction crew (x_i) to another depending on their use in other concurrent projects; (b) input a list of multiple predecessors (P_i) for each renovation activity in the project; and (c) consider varying sequences of renovation work in all leased units $j = 1$ to J using the earlier described sequence vector (u). As shown in Figure 3.1, the computations of this module require the following project and activity input data: total number of leased units (J), total number of activities (I), quantity of work for each activity in each unit ($Q_{i,u[j]}$), list of predecessors for each renovation activity i (P_i), lease end date of each leased unit ($LE_{u[j]}$), daily output rate of each crew formation in each activity (PR_{x_i}), and earliest crew deployment date (CD_{x_i}). The scheduling module utilizes this input data to perform its computations using the following three steps, as shown in Figure 3.2:

1. Identify the predecessors (P_i) of each renovation activity ($i = 1$ to I).
2. For each renovation activity i that has no predecessors ($P_i = 0$), calculate for each leased unit $u[j]$ the following (see Figure 3.2):
 - 2.1. Start date of first unit ($SD_{i,u[1]}$) as the latest of its lease end date ($LE_{u[1]}$) and the selected project start date (t) using Eq. (3.6).
 - 2.2. Start date of subsequent units ($SD_{i,u[j]}$) as the latest of its lease end date ($LE_{u[j]}$) and the finish date of its predecessor unit $u[j - 1]$ the using Eq. (3.7).
 - 2.3. Renovation duration ($D_{i,u[j]}$) based on its quantity of work and the daily output rate of its assigned crew using Eq. (3.8).
 - 2.4. Finish date ($FD_{i,u[j]}$) based on its start date and duration using Eq. (3.9).

$$SD_{i,u[1]} = \max(LE_{u[1]}, t) \quad \text{for unit } j = 1 \quad \forall i \in I \text{ \& } p_i = 0 \quad (3.6)$$

$$SD_{i,u[j]} = \max(LE_{u[j]}, FD_{i,u[j-1]}) \quad \text{for subsequent } j = 2 \text{ to } J \quad \forall i \in I \text{ \& } p_i = 0 \quad (3.7)$$

$$D_{i,u[j]} = \frac{Q_{i,u[j]}}{PR_{x_i}} \quad \forall i \in I \text{ \& } j \in J \quad (3.8)$$

$$FD_{i,u[j]} = SD_{i,u[j]} + D_{i,u[j]} \quad \forall i \in I \text{ \& } j \in J \quad (3.9)$$

Where:

$SD_{i,u[1]}$ = Start date of activity i in leased unit $u[1]$.

$SD_{i,u[j]}$ = Start date of activity i in leased unit $u[j]$.

t = Project start date.

$LE_{u[1]}$ = Lease end date of leased unit $u[1]$.

$LE_{u[j]}$ = Lease end date of leased unit $u[j]$.

$D_{i,u[j]}$ = Duration of activity i in the leased unit $u[j]$.

$Q_{i,u[j]}$ = Quantity of work of activity i in leased unit $u[j]$.

PR_{x_i} = Daily output rate of selected crew formation x_i assigned to activity i .

$FD_{i,u[j]}$ = Finish date of activity i in unit $u[j]$.

$FD_{i,u[j-1]}$ = Finish date of activity i in unit $u[j - 1]$.

3. For each renovation activity i that has one or more predecessors ($P_i > 0$), calculate for each leased unit $u[j]$ the following (see Figure 3.2):

3.1. Job logic start date ($LD_{i,u[j]}$) based on the finish dates of its predecessors using Eq. (3.10).

3.2. Start date of first unit ($SD_{i,u[1]}$) based on its job logic start date and earliest possible deployment date of its crew using Eq. (3.11).

3.3. Start date of subsequent units ($SD_{i,u[j]}$) based on its job logic start date and finish date in predecessor unit $u[j - 1]$ using Eq. (3.12).

3.4. Renovation duration ($D_{i,u[j]}$) based on its quantity of work and the daily output rate of its assigned crew using Eq. (3.8).

3.5. Finish date ($FD_{i,u[j]}$) based on its start date and duration using Eq. (3.9).

$$LD_{i,u[j]} = \max_{p_i=1}^{P_i} (FD_{p_i,u[j]} + lag_{p_i}) \quad \forall i \in I \ \& \ \forall p_i \in P_i \quad (3.10)$$

$$SD_{i,u[1]} = \max(LD_{i,u[1]}, CD_{x_i}) \quad \text{for unit } j = 1 \quad \forall i \in I \ \& \ \forall p_i \in P_i \quad (3.11)$$

$$SD_{i,u[j]} = \max(LD_{i,u[j]}, FD_{i,u[j-1]}) \quad \text{for subsequent } j = 2 \text{ to } J \quad \forall i \in I \ \& \ \forall p_i \in P_i \quad (3.12)$$

Where:

$LD_{i,u[j]}$ = Job logic start date in leased unit $u[j]$.

$LD_{i,u[1]}$ = Job logic start date in leased unit $u[1]$.

$SD_{i,u[1]}$ = Start date of activity i in leased unit $u[1]$.

$SD_{i,u[j]}$ = Start date of activity i in leased unit $u[j]$.

$FD_{p_i,u[1]}$ = Finish date of predecessor activity (p_i) in leased unit $u[j]$.

Lag_{p_i} = Lag duration between activity i and its predecessor p_i .

CD_{x_i} = Earliest possible deployment date of selected crew formation x_i .

$FD_{i,u[j-1]}$ = Finish date of activity i in predecessor unit $u[j - 1]$.

P_i = list of predecessors of activity i .

3.4 Cost Module

The objective of this module is to calculate all the components of the total project renovation cost that account for interruption cost (C1), direct cost (C2), indirect cost (C3), and rental income loss (C4), as shown in Figure 3.2. First, the crew interruption cost in renovation projects is incurred when a construction crew has to wait before it can resume work in its next assigned leased unit. This crew waiting time is often encountered when the next assigned leased unit is unavailable for work due to its lease end data ($LE_{u[j]}$) and/or its ongoing predecessor renovation activities. This module quantifies and minimizes these types of crew interruption costs by enabling planners to relocate interrupted renovation crews to other concurrent projects if (a) the crew relocation time (RT_{x_i}) and its minimum required work time (T_{x_i}) in the other project is less than the crew interruption time in the current project, and (b) the crew relocation cost (RC_{x_i}) is less than the crew interruption cost ($IC_{x_i, u[j]}$) in the current project, as shown in step 1.2 in Figure 3.2.

Second, the direct cost (DC) of renovation projects is calculated in this module to account for all the direct costs of utilized material and crews (labor and equipment) in all activities ($i = 1$ to I) in all leased units. Third, the project indirect cost (IDC) is calculated based on the project duration (PD) and the project daily indirect cost rate (DIR) that accounts for all time-dependent costs such as site supervision, site utilities, and office overhead.

Fourth, the rental income loss (RL) is calculated in this module to account for the rental income loss during the renovation project duration for each leased unit $u[j]$. These rental income losses are encountered whenever occupants are required to leave their leased units during its renovation period. The present model is designed to calculate and consider this important cost component during its optimization of renovation projects. The rental income loss of each leased

unit $u[j]$ is calculated based on (a) the duration of rental income loss that extends from its lease end date ($LE_{u[j]}$) to the finish date of its last renovation activity ($FD_{I,u[j]}$) when it is ready for another lease, and (b) its daily rental income rate, as shown in Eq. (3.16) and step 1.3 in Figure 3.2.

This cost module is designed to calculate the aforementioned four cost components of leased building renovation projects (see Figure 3.2) in three steps as follow:

1. For each renovation activity $i = 1$ to I , apply the following three substeps to calculate for each leased unit $u[j]$:
 - 1.1 Crew renovation cost ($CC_{x_i,u[j]}$) using Eq. (3.13).
 - 1.2 Crew interruption cost ($IC_{x_i,u[j]}$) in each leased unit $u[j]$ except for the last unit that should not cause any crew work interruptions using Eqs. (3.14 to 3.15b).
 - 1.3 Rental income loss for each leased unit $u[j]$ based on the duration of rental income loss and its daily rental income rate using Eq. (3.16).

$$CC_{x_i,u[j]} = C_{x_i} \times D_{i,u[j]} \quad \forall i \in I \ \& \ \forall j \in J \quad (3.13)$$

$$IC_{x_i,u[j]} = (SD_{i,u[j+1]} - FD_{i,u[j]}) \times Idle_C_{x_i,u[j]} \quad \forall i \in I \ \& \ \forall j \in J - 1 \quad (3.14)$$

$$IC_{x_i,u[j]} = \begin{cases} \min(RC_{x_i}, IC_{x_i,u[j]}) & \text{if } (SD_{i,u[j+1]} - FD_{i,u[j]}) > (RT_{x_i} + T_{x_i}) \\ (SD_{i,u[j+1]} - FD_{i,u[j]}) \times Idle_C_{x_i,u[j]} & \text{Otherwise} \end{cases} \quad (3.15a)$$

$$(3.15b)$$

$$RL_{u[j]} = [\max_{i=1}^I (FD_{i,u[j]}) - LE_{u[j]}] \times (MR_{u[j]}/30) \quad \forall i \in I \ \& \ \forall j \in J \quad (3.16)$$

Where:

$IC_{x_i,u[j]}$ = Crew interruption cost of activity i in unit $u[j]$.

$RL_{u[j]}$ = Rental income loss of unit $u[j]$.

$SD_{i,u[j+1]}$ = Start date of activity i in leased unit $u[j + 1]$.

$Idle_C_{x_i,u[j]}$ = Daily interruption cost of selected crew formation x_i .

RC_{x_i} = Relocation cost of selected crew formation x_i .

T_{x_i} = Minimum work duration in another concurrent project for selected crew formation x_i .

RT_{x_i} = Relocation time of selected crew formation x_i .

$CC_{x_i,u[j]}$ = Crew cost of selected crew formation x_i in leased unit $u[j]$.

C_{x_i} = Daily crew cost rate of selected crew formation x_i in leased unit $u[j]$.

$D_{i,u[j]}$ = Duration of activity i in leased unit $u[j]$.

$LE_{u[j]}$ = Lease end date of leased unit $u[j]$.

$MR_{u[j]}$ = Monthly rent rate of leased unit $u[j]$.

2. For each renovation activity ($i = 1$ to I), calculate direct and interruption costs in in all leased units ($j = 1$ to J) using Eqs. (3.17 and 3.18), as shown in Figure 3.2.

$$TIC_i = \sum_{j=1}^J IC_{x_i,u[j]} \quad \forall i \in I \quad (3.17)$$

$$DC_i = \sum_{i=1}^I \sum_{j=1}^J Q_{i,u[j]} * M_i + \sum_{j=1}^J CC_{x_i,u[j]} \quad \forall i \in I \& \forall j \in J \quad (3.18)$$

Where:

TIC_i = Crew interruption cost of activity i in all leased units.

DC_i = Project direct cost of activity i in all leased units.

M_i = Material cost per unit of activity i .

3. Calculate the total renovation project cost that accounts for all the project direct, interruption, indirect, and rental income loss costs using Eqs. (3.19 to 3.23), as shown in Figure 3.2.

$$TIC = \sum_{i=1}^I TIC_i \quad (3.19)$$

$$DC = \sum_{i=1}^I DC_i \quad (3.20)$$

$$IDC = (\max_{i=1}^I (FD_{i,u[j]}) - SD_{1,u[1]}) * DIR \quad (3.21)$$

$$RL = \sum_{j=1}^J RL_{u[j]} \quad (3.22)$$

$$TRC = DC + IDC + TIC + RL \quad (3.23)$$

Where:

TRC = Total project renovation cost.

DC = Project direct cost.

IDC = Project indirect cost.

TIC = Project crew interruption cost.

RL = Project rental income loss.

$SD_{1,u[1]}$ = Start date of first activity ($i = 1$) in first leased unit $u[1]$.

DIR = Daily project indirect cost rate.

$FD_{i,u[j]}$ = Finish date of activity i in leased unit $u[j]$.

3.5 Case Study

A real-life case study of a residential renovation project is analyzed to illustrate the use of the optimization model and demonstrate its capabilities. This residential renovation project data is provided by the Project Management Office at King Fahd University of Petroleum and Minerals. The project focuses on renovating a total of 30 residential houses that consist of two sets of 15 four-bedroom houses and 15 five-bedroom houses. The required renovation activities in this project can be divided into 22 activities that are grouped into eight main categories: (1) demolition; (2) plumbing; (3) electricity; (4) HVAC; (5) carpentry; (6) insulation; (7) painting; and (8) flooring. In this case study, the planner specified that the required demolition work is limited to the removal of interior concrete slabs on grade and doors, and therefore the planned demolition work in each house is not expected to cause significant disturbance to tenants in neighboring houses. In other cases that may require exterior demolition work, construction planners can deploy disturbance mitigating measures such as utilizing equipment that minimize construction noise and vibration.

The precedence relationships among all renovation activities are finish-to-start with no lag time. The input data of the 22 renovation activities in this project including their predecessors (P_i),

quantity of work ($Q_{i,u[j]}$), and material cost per unit of measurement (M_i), are summarized in Table 3.1. For each of these activities, the renovation planner needs to select an optimal crew formation from a set of feasible alternatives. Table 3.2 summarizes the input data of these feasible crew formations including their daily output rates (PR_{x_i}), number of working days per week, number of working hours per day, daily cost rates (C_{x_i}), daily idle-time cost rates ($Idle_C_{x_i}$), and relocation cost (RC_{x_i}) and time (RT_{x_i}) to another concurrent project, if needed. These feasible crew formations (labor and equipment) data were obtained from Building Construction Costs with RSMeans data (2018). The leased residential houses input data including their monthly rental rates ($MR_{u[j]}$), and estimated availability date ($AD_{u[j]}$) are presented in Table 3.3. The daily indirect cost rate for this project was estimated to be \$1200/day, and the renovation crews can be relocated to work in another concurrent project during their work interruptions in this project if the crew relocation time (RT_{x_i}) and its minimum required work time (T_{x_i}) in the other project is less than the crew interruption time in this project. The minimum required work time in the concurrent project is estimated to be one day ($T_{x_i} = 1$) for all renovation crews.

Table 3.1. Renovation activity data

Activity number (i)	Activity description	Predecessor activities (P _i)	Unit	Quantity of work (Q _{i, u[j]})		Material cost per unit (M _i) (\$)
				4 Bedroom house	5 Bedroom house	
Demolition						
1	Concrete slab on grade, 6" thick, reinforced for all bathrooms	-	S.F.	8557	9085	-
2	Concrete, 6" thick, hydraulic hammer, mesh reinforced	1	C.Y.	292	292	-
3	Interior door 1-3/4" thick, 3'-0" x 7'-0"	2	Each	5	5	-
Plumbing						
4	PVC pipes sizes (4", 3", and 2")	3	L.F.	1535	1608	4.17
5	PVC pipes sizes (1.5", 1", 3/4" and 1/2")	4	L.F.	771	705	2.18
6	Bathtub, recessed porcelain enamel on cast iron, with trim 72" x 36"	5	Each	3	5	220
7	Lavatories, with trim, porcelain enamel on cast iron, 33" x 19"	6	Each	4	6	183
8	Cleanouts, Plastic, Cleanout tee, 2" pipe size	7	Each	8	10	18
9	Water closets, bowl only, with flush valve, seat, 1.6 gpf, wall hung	8	Each	4	6	455
10	Bath faucet, diverter spout combination	9	Each	12	12	141
11	Valves, bronze, Angle, threaded 1/2" and 3/4"	10	Each	60	73	15
Electricity						
12	Panelboard and load center circuit breakers, Bolt- on/ 240-volt, 2 pole, 15-50 amp	3	Each	3	3	733
13	Enclosed switch and circuits breakers	12	Each	131	140	50
14	Interior lighting fixtures	13	Each	95	100	114
HVAC						
15	Packaged Air-Cooled refrigerant compressor and condenser units 10 ton	14	Each	2	2	3067
16	Grilles and diffusers, aluminum, ceiling	15	Each	42	42	89
Carpentry						
17	Kitchen wall cabinets, hardwood, 12" deep with two doors, 12' high, 36" wide	3	L.F.	151	151	41
18	Aluminum sash windows, double-hung	17	S.F.	1076	1076	10
19	A solid wood door, 1-3/4" thick	18	Each	36	36	293
Insulation						
20	Roof deck insulation, fastening excluded, Asphaltic cover board, fiberglass lined, 1/8" thick	3	S.F.	19612	19612	0.67
Painting						
21	Painting interior and exterior walls, masonry or concrete block, primer/sealer, latex paint, smooth finish, brushwork/ roller	11, 16, 19, and 20	S.F.	14811	16555	0.59
Flooring						
22	Ceramic tiles, porcelain type, 1 color 2" x 2"	21	S.F.	6932	7276	2

Table 3.2. Feasible crew formation data

Activity (i)	Feasible crew formation (X_i)	Days per week (day/week)	Hours per day (hour/day)	Daily output rate (PR_{x_i}) (unit/day)	Daily cost rate (C_{x_i}) (\$/day)	Idle time cost rate ($Idel_C_{x_i}$) (\$/day)	Crew relocation	
							Cost (RC_{x_i}) (\$)	Time (RT_{x_i}) (day)
1	1	5	8	3200	2,855	2,141	180	1
	2	5	12	4416	5,710	2,141	180	1
2	1	5	8	255	2,938	2,204	180	1
	2	5	12	352	5,876	2,204	180	1
3	1	5	8	20	319	239	180	1
	2	5	12	28	638	239	180	1
4	1	5	8	53	895	671	120	0.5
	2	5	12	73	1,790	671	120	0.5
	3	6	11	69	1,566	671	120	0.5
5	1	5	8	47	497	373	120	0.5
	2	5	12	65	994	373	120	0.5
6	1	5	8	3	895	671	120	0.5
	2	5	12	4.1	1,790	671	120	0.5
	3	6	11	3.9	1,566	671	120	0.5
7	1	5	8	6.4	895	671	120	0.5
	2	5	12	9	1,790	671	120	0.5
	3	6	11	8.3	1,566	671	120	0.5
8	1	5	8	27	895	671	120	0.5
	2	5	12	37.3	1,790	671	120	0.5
9	1	5	8	5.8	895	671	120	0.5
	2	5	12	8	1,790	671	120	0.5
10	3	6	11	7.5	1,566	671	120	0.5
	1	5	8	10	497	373	120	0.5
	2	5	12	14	994	373	120	0.5
11	3	6	11	13	870	373	120	0.5
	1	5	8	22	497	373	120	0.5
	2	5	12	30	994	373	120	0.5
12	3	6	11	29	870	373	120	0.5
	1	5	8	8	680	510	100	1
	2	5	12	11	1,360	510	100	1
13	1	5	8	3	465	349	100	1
	2	5	12	3.9	930	349	100	1
14	1	5	8	6	465	349	100	0.5
	2	5	12	8	930	349	100	0.5
	3	6	11	0.6	1,587	680	110	0.5
15	1	5	8	0.5	907	680	110	0.5
	2	5	12	0.7	1,814	680	110	0.5
	3	6	11	0.6	1,587	680	110	0.5
16	1	5	8	15	450	338	110	0.5
	2	5	12	21	900	338	110	0.5
	3	6	11	19	788	338	110	0.5
17	1	5	8	24	816	612	120	0.5
	2	5	12	33	1,632	612	120	0.5
18	1	5	8	200	874	656	120	0.5
	2	5	12	276	1,748	656	120	0.5
19	1	5	8	14	812	609	120	0.5
	2	5	12	19	1,624	609	120	0.5
20	1	5	8	1400	350	263	150	0.5
	2	5	12	1932	700	263	150	0.5
	3	6	11	1815	613	263	150	0.5
21	1	5	8	1150	345	259	150	0.5
	2	5	12	1587	690	259	150	0.5
	3	6	11	1491	604	259	150	0.5
22	1	5	8	190	672	504	150	0.5
	2	5	12	262	1,344	504	150	0.5

Table 3.3. Monthly rental rates and lease end dates of residential houses

4 Bedroom house (Monthly rental rate = \$800)		5 Bedroom house (Monthly rental rate = \$1000)	
House unit (j)	Lease end date	House unit (j)	Lease end date
1	02/12/2021	16	09/14/2021
2	04/24/2021	17	08/22/2021
3	05/17/2021	18	07/04/2021
4	10/10/2021	19	08/17/2021
5	09/24/2021	20	06/30/2021
6	08/03/2021	21	07/17/2021
7	08/09/2021	22	09/18/2021
8	09/04/2021	23	07/09/2021
9	08/03/2021	24	08/07/2021
10	09/19/2021	25	10/27/2021
11	09/29/2021	26	09/07/2021
12	08/10/2021	27	07/08/2021
13	09/09/2021	28	07/01/2021
14	08/11/2021	29	10/11/2021
15	10/22/2021	30	09/24/2021

The present optimization model utilized the aforementioned input data to search for and identify optimal renovation schedule that minimizes total renovation cost. The GA optimization computations for this case study were performed utilizing Evolver Software genetic algorithm package. In this case study, the GA parameters were specified to be a population size of 200, a crossover rate of 0.8, and a mutation rate of 0.1. The optimization engine was set to terminate the optimization computations when the average relative change in the fitness function value over 25000 trials (generations) is less than 0.005. The computational time for this case study was approximately 50 minutes using a personal computer with AMD FX(tm)-4300 Quad-Core @ 3.80GHz Processor and 16GM RAM.

The optimization computations for this case study were executed using the three aforementioned modules (see Figure 3.2). First, the optimization module was used to generate a set of feasible solutions for the project start date (t), unit renovation sequence (u), and crew formation (x_i) for each renovation activity ($i = 1$ to 22). Second, the scheduling module was

utilized to generate the renovation schedule for each of the obtained feasible solutions that includes the duration ($D_{i,u[j]}$) as well as the start and finish dates ($SD_{i,u[j]}$ and $FD_{i,u[j]}$) of each activity ($i = 1 \text{ to } 22$) in each residential house $u[j]$ using Eqs. (3.6 to 3.12). Third, the cost module was used to estimate the total renovation cost of each generated feasible solution that includes direct cost, rental income loss, interruption cost, and indirect cost, using Eqs. (3.13 to 3.23). Upon the completion of the computations of the cost module, the optimization module was used to search for and identify the optimal renovation schedule that minimizes the total renovation cost, as shown in Figure 3.2. The optimal renovation schedule for this case study was obtained by identifying an optimal selection of (1) project start date (t) of 03/18/2021 as shown in Table 3.4, (2) an optimal unit renovation sequence (u) as shown in Table 3.5, and (3) an optimal crew formation (x_i) for each activity as shown in Table 3.6. This identified optimal renovation schedule provided a minimum total renovation cost of \$6,531,147 excluding material cost as shown in Table 3.4, and an early project finish date of 07/16/2024, as shown in Table 3.5.

3.6 Discussion

To highlight the novel contributions and significance of the developed model, its generated optimization results were compared to those provided by two available related models (Altuwaim and El-Rayes 2018, Long and Ohsato 2009) and three current industry practices that were provided by Project Management Office at King Fahd University of Petroleum and Minerals. To enable such a comparison, the following assumptions were made: (a) project start date in available models and current practices is assumed to be the earliest available unit date (02/12/2021), the latest available unit date (10/27/2021), or a middle date between the earliest and latest available unit dates (06/21/2021) as shown in Table 3.4, because available models/practices are incapable of searching for and identifying an optimal project start date from the feasible range of 257 project

start date alternatives in this case study; and (b) total material cost was excluded from this comparison since it is identical in the generated results by all models/practices, as shown in Table 3.4. It should be noted that Long and Ohsato (2009) is capable of selecting the optimal crew formation for each activity as the developed model (see Table 3.4), however, it is incapable of considering the two important decision variables of project start data and unit renovation sequence that are considered and optimized by the developed model.

The results from the aforementioned comparison that are summarized in Table 3.4. clearly illustrate the novel contributions of the model and its capability to outperform available related models and current practices in (1) identifying the optimal project start date; (2) generating feasible renovation schedules that fully comply with unit availability dates constraint unlike available models, as shown in Figure 3.3 ; (3) identifying the optimal unit renovation sequence for all lease residential units, as shown in Table 3.4; (4) quantifying and minimizing rental income loss; (5) reducing the total renovation cost by \$248,925 (3.8%), \$233,252 (3.6%), and \$257,298 (4%) compared to Altuwaim and El-Rayes (2018), Long and Ohsato (2009) and current practices, respectively; and (6) expediting the project finish date by 452 days (36%), 228 days (18%), and 452 days (36%) compared to Altuwaim and El-Rayes (2018), Long and Ohsato (2009) and current practices, respectively.

Table 3.4. Project cost and finish date performance of present model, available models, and current practices

	Project Schedule				Project cost and finish date performance*								
	Project start date (t)	Project finish date ($FD_{i,u[j]}$)	Optimal unit renovation sequence (u)	Compliance with units availability dates constraint	Crew cost (\$)	Rental income loss (\$)	Interruption cost (\$)	Indirect cost (\$)	Total non-material renovation cost (\$)	Cost savings		Early finish date	
										(\$)	(%)	(days)	(%)
Present model	Optimally identified 03/18/2021	7/16/2024	Yes	Yes	4,546,050	453,453	72,444	1,459,200	6,531,147	-	-	-	-
Altuwaim & El-Rayes (2018)	Earliest available unit 02/12/2021	6/12/2024	No	No	Infeasible schedule**								
	Latest available unit 10/27/2021	3/01/2025	No	Yes	4,588,815	668,127	25,430	1,465,200	6,747,572	216,424	3.3	228	18
Long & Ohsato (2009)	Earliest available unit 02/12/2021	6/12/2024	No	No	Infeasible schedule**								
	Latest available unit 10/27/2021	3/01/2025	No	Yes	4,588,815	668,127	42,258	1,465,200	6,764,400	233,252	3.6	228	18
Current practices	Earliest available unit 02/12/2021	2/01/2025	No	No	Infeasible schedule**								
	Latest available unit 10/27/2021	10/11/2025	No	Yes	4,207,995	774,007	72,444	1,734,000	6,788,446	257,298	3.9	452	36

* Project cost savings and early finish date provided by the present model compared to available models and current practices.

** Activities are scheduled before unit lease end/availability date (see example in Figure 3.3).

Table 3.5. Optimal renovation schedule for sample activities

Unit renovation sequence ($u[j]$)	Activity (i)												
	1			2				21			22		
	Duration (days)	Start Date	Finish Date	Duration (days)	Start Date	Finish Date		Duration (days)	Start Date	Finish Date	Duration (days)	Start Date	Finish Date
1	3	34	37	1	37	38		13	97	110	37	110	147
2	3	71	74	1	74	75		13	134	147	37	147	184
3	3	94	97	1	97	98		13	168	181	37	184	221
28	3	139	142	1	142	143		15	205	220	39	221	260
20	3	142	145	1	145	146		15	241	256	39	260	299
21	3	155	158	1	158	159		15	277	292	39	299	338
27	3	158	161	1	161	162		15	313	328	39	338	377
24	3	176	179	1	179	180		15	349	364	39	377	416
19	3	186	189	1	189	190		15	385	400	39	416	455
18	3	189	192	1	192	193		15	421	436	39	455	494
26	3	207	210	1	210	211		15	457	472	39	494	533
23	3	210	213	1	213	214		15	493	508	39	533	572
30	3	224	227	1	227	228		15	529	544	39	572	611
16	3	227	230	1	230	231		15	565	580	39	611	650
29	3	241	244	1	244	245		15	601	616	39	650	689
22	3	244	247	1	247	248		15	637	652	39	689	728
25	3	257	260	1	260	261		15	673	688	39	728	767
17	3	260	263	1	263	264		15	709	724	39	767	806
7	3	263	266	1	266	267		13	742	755	37	806	843
6	3	266	269	1	269	270		13	776	789	37	843	880
8	3	269	272	1	272	273		13	810	823	37	880	917
9	3	272	275	1	275	276		13	844	857	37	917	954
14	3	275	278	1	278	279		13	878	891	37	954	991
10	3	278	281	1	281	282		13	912	925	37	991	1028
11	3	281	284	1	284	285		13	946	959	37	1028	1065
12	3	284	287	1	287	288		13	980	993	37	1065	1102
5	3	287	290	1	290	291		13	1014	1027	37	1102	1139
13	3	290	293	1	293	294		13	1048	1061	37	1139	1176
15	3	293	296	1	296	297		13	1082	1095	37	1176	1213
4	3	296	299	1	299	300		13	1116	1129	37	1213	1250*

* Early project finish date of 7/16/2024

Table 3.6. Selected crew formations by analyzed models

	Selected crew formation for activity (i)																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Analyzed models																						
Present model	1	2	1	1	1	1	1	1	1	3	1	1	2	1	1	1	1	1	1	1	1	1
Altuwaim & El-Rayes (2018)	1	2	1	1	1	1	1	1	1	3	2	2	2	1	1	1	1	1	1	1	1	1
Long & Ohsato (2009)	1	2	1	1	1	1	1	1	1	3	2	2	2	1	1	1	1	1	1	1	1	1

**Schedule Generated by Available Models When Project is
Planned to Start on Earliest Available Unit Date**

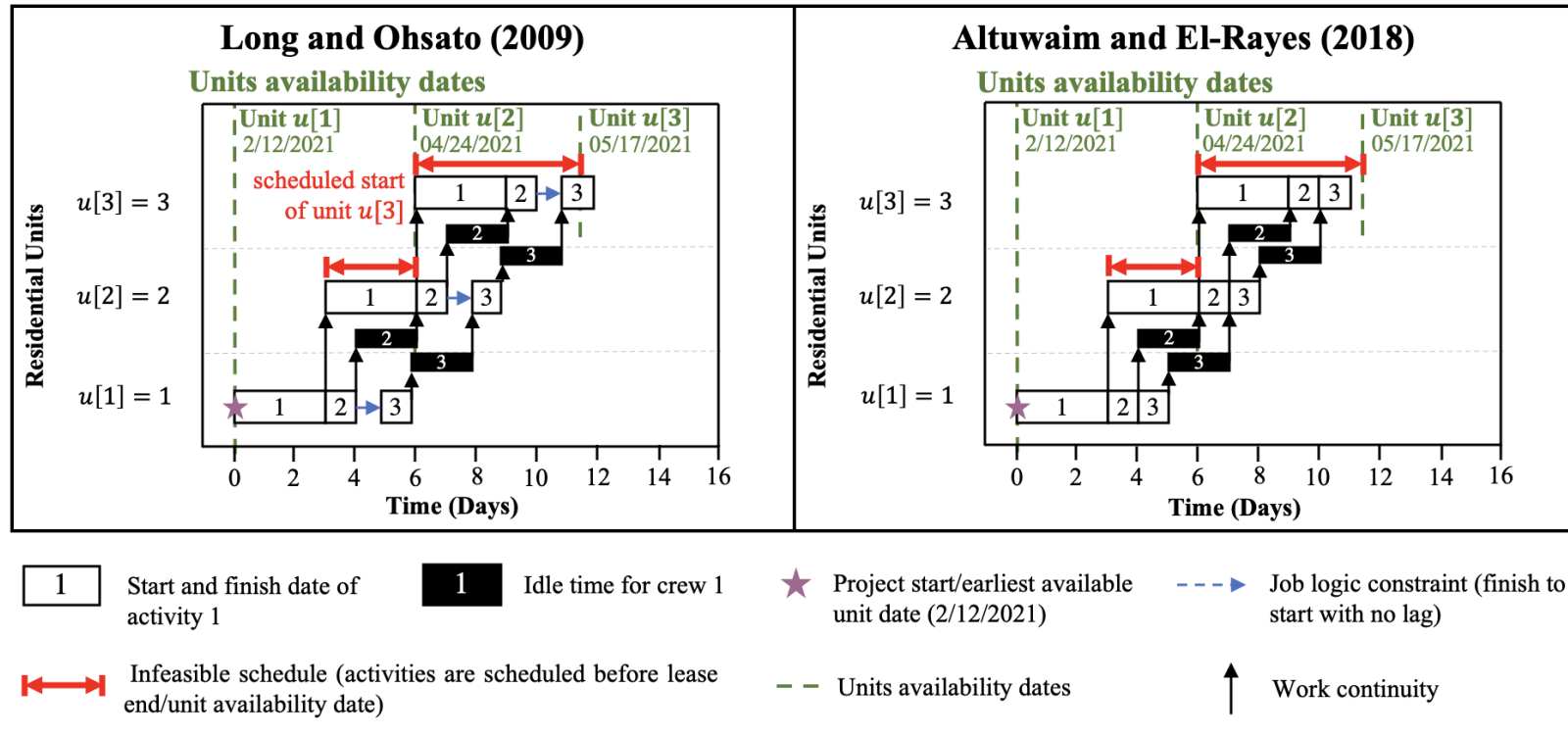


Figure 3.3. Infeasible renovation schedule of available models

3.7 Conclusion

A novel model was developed for optimizing the planning of leased building renovation projects that enables leased building owners to minimize total renovation cost. The computations of the model were performed in three main modules: (a) optimization module that searches for and identifies an optimal renovation schedule that minimizes total renovation cost; (b) scheduling module that calculates the start date, finish date, and total interruption duration for each activity in all leased units; and (c) cost module that computes expected total renovation cost for each generated solution in the optimization module. To highlight the novel contributions of the developed model, a real-life case study of a residential renovation project was analyzed to enable a comparison between its generated results and those provided by two available models and three current industry practices. The outcome of this analysis confirms that the developed model was able to outperform existing models and current practices in minimizing the total renovation cost of leased buildings. The findings of this analysis also highlight the main contributions of the model to the body of knowledge including its novel methodology for (1) generating feasible renovation plans that fully comply with all relevant constraints including the units availability dates constraint, (2) selecting an optimal project start date for the renovation of leased buildings, (3) identifying an optimal unit renovation sequence for all leased units, (4) quantifying and minimizing the rental income loss, and (5) minimizing the total renovation cost of leased buildings. This novel methodology and its original capabilities are expected to provide much-needed support for construction planners who seek to minimize the total renovation cost of leased buildings.

CHAPTER 4: OPTIMAL PLANNING OF RENOVATION WORK IN LEASED BUILDINGS UNDER INTEGRATED PROJECT DELIVERY METHOD

4.1 Introduction

This chapter presents the development of a novel model for optimizing the planning of renovation work in leased buildings that enables contractors working under IPD method to maximize their reward sharing while minimizing total renovation cost. The model is designed to provide renovation contractors with the novel capabilities of (1) minimizing total renovation cost while maximizing IPD reward sharing that can be achieved by the early finish of leased units before their specified target completion dates; (2) identifying optimal scheduling decisions, including crew deployment date (CD_i) for each activity i , renovation order of all leased units (r_j), and number of assigned crews for each activity in all leased units ($C_{i,j}$); and (3) generating a practical plan that complies with the constraints of precedence relationships, availability dates of all renovated units based on their lease end dates, and the availability of renovation crews. The model is developed in three main phases: optimization phase, renovation planning phase, and performance evaluation phase, as shown in Figure 4.1. The following sections of the chapter describe these three development phases of the present model.

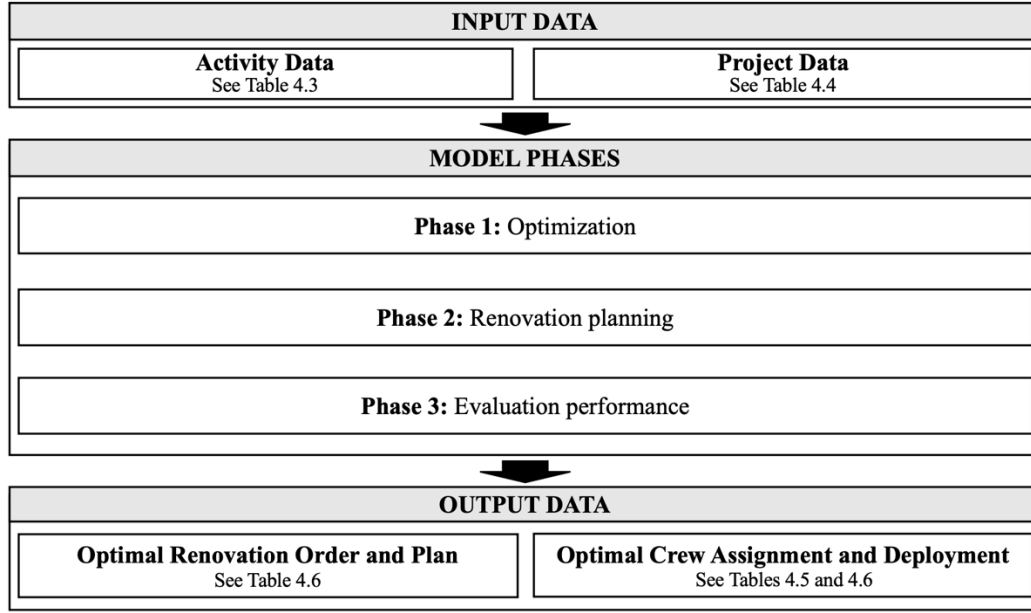


Figure 4.1. Model development phases

4.2 Optimization Phase

The objective of this phase is to formulate and implement a novel model for optimizing the planning of renovation work in leased buildings. The model is designed to minimize total renovation cost while maximizing IPD reward sharing that can be achieved by the early finish of leased units before their specified target completion dates. The model is formulated and implemented in four main stages that are designed to (1) identify all relevant decision variables, (2) define the optimization objective function, (3) model all practical planning constraints, and (4) execute the optimization computations. The following subsections provide a concise description of these four stages.

Stage 1: Decision Variables

The purpose of this stage is to identify all possible decision variables that affect the total cost and IPD reward sharing of renovation work in leased buildings. Accordingly, the identified decision variables in this model are: (1) crew deployment date (CD_i) for each activity i , (2)

renovation order (r_j) of each leased unit j ; and (3) number of assigned crews $(C_{i,j})$ for each renovation activity i in each leased unit j .

1. Crew Deployment Date:

This decision variable represents the selection of a crew deployment date for each renovation activity $(i = 1 \text{ to } I)$ from a set of feasible alternatives that range from an earliest date (CD_i^E) to a latest date (CD_i^L) , as shown in Eq. (4.1). First, the earliest date (CD_i^E) represents the earliest time that each crew can be deployed on site and its identified in this model as (a) the earliest leased end date of all leased units for activities with no predecessors such as activity A in Figure 4., as shown in Eq. (4.2), and (b) the latest finish date of all predecessors in the first leased unit for activities with predecessors such as activity B in Figure 4.2, as shown in Eq. (4.3).

Second, the latest date (CD_i^L) represents the latest time that each crew can be deployed on site. This latest date (CD_i^L) can be utilized when the renovation schedule is planned to eliminate crew idle time and force work continuity in all leased units, as shown in schedule (2) for activities A and B in Figure 4.2. Accordingly, CD_i^L in this model is calculated for activities with no predecessors such as activity A in Figure 4.2 by summing up the earliest date of crew deployment date (CD_i^E) and the total number of idle times in all leased units when the crew is deployed on its earliest date, as shown in Eq. (4.4a). These crew idle times can be encountered when (i) the crew is deployed on its earliest deployment time (CD_i^E) to expedite project completion and maximize IPD reward sharing, and (ii) the availability dates of the next assigned units are later than the finish dates of their predecessor units. For example, renovation crews for activities A and B in Figure 4.2 can experience crew idle time $(Idle_A = 8 \text{ days})$ and $(Idle_B = 11 \text{ days})$ when (i) they are deployed on site on their earliest dates $(CD_A^E = 0)$ and $(CD_B^E = 3)$, and (ii) the lease end dates of their successor units are later than the finish dates of their predecessor units. For activities with

predecessors such as activity B in Figure 4.2, CD_i^L is calculated as the latest of (a) the summation of the earliest date of crew deployment date (CD_i^E) and the total number of idle times in all leased units when the crew is deployed on its earliest date, and (b) the latest finish date of all predecessor activities, as shown in Eq. (4.4b).

$$CD_i^E \leq CD_i \leq CD_i^L \quad \forall i \in I \quad (4.1)$$

$$CD_i^E = LE_1 \quad \forall i \in I \text{ \& } p_i = 0 \quad (4.2)$$

$$CD_i^E = \max_{p_i=1}^{P_i} (F_{p_i,1} + lag_{p_i}) \quad \forall i \in I \text{ \& } \forall p_i \in P_i \quad (4.3)$$

$$CD_i^L = CD_i^E + \sum_{j=1}^J Idle_{i,j} \quad \forall i \in I \text{ \& } p_i = 0 \quad (4.4a)$$

$$CD_i^L = \max [(CD_i^E + \sum_{j=1}^J Idle_{i,j}), (F_{p_i,1}^E + lag_{p_i})] \quad \forall i \in I \text{ \& } \forall p_i \in P_i \quad (4.4b)$$

Where:

CD_i = Crew deployment date for activity i .

CD_i^E = Earliest crew deployment date for activity i

CD_i^L = Latest crew deployment date for activity i .

$Idle_{i,j}$ = Crew idle time for activity i in leased unit j in days.

$F_{p_i,1}^U$ = Latest finish date for activity i in first leased unit ($j = 1$) when selecting latest crew deployment date.

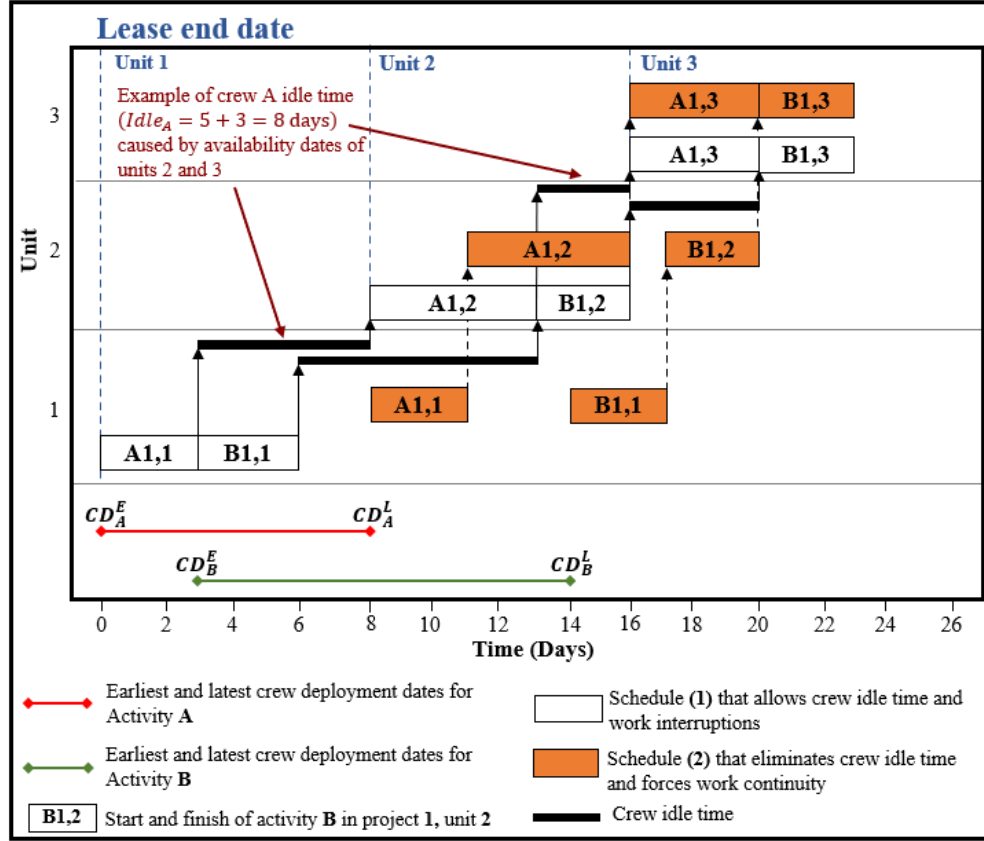


Figure 4.2. Activity crew deployment date limits.

2. Renovation Order:

The renovation order decision variable (r_j) represents the sequence of renovating each leased unit (j) and it is modelled as a unique integer number, as shown in Eq. (4.5). For example, $r_5 = 3$ indicates that the renovation order of the fifth leased unit is planned to be third in the project, as shown in Table 4.1. To enable the optimization of renovation planning in multiple projects, the model is designed to transform the leased unit number in each single project (k, n) to a unique unit number in the entire set of all projects (j). Table 4.2 illustrates the procedure of this transformation using a simple example that consists of three renovation projects ($k = 1, 2, 3$) which require the renovation of two leased units each ($n = 1, 2$). For example, the unit number of the second leased unit in the third project ($k = 3, n = 2$) is transformed by this procedure and represented as the sixth unit in the entire set of multiple projects ($j = 6$), as shown in Table 4.2.

Table 4.1 Renovation order decision variable

Multiple projects unit (j)	1	2	3	4	5	6
Order (r_j)	2	5	1	6	3	4

Table 4.2 Transformation of single to multiple project unit number

Project ($k=1$)		Project ($k=2$)		Project ($k=3$)	
Single project unit (k, n)	Multiple projects unit (j)	Single project unit (k, n)	Multiple projects unit (j)	Single project unit (k, n)	Multiple projects unit (j)
1,1	1	2,1	3	3,1	5
1,2	2	2,2	4	3,2	6

$$1 \leq r_j \leq J \quad \forall j \in J \quad (4.5)$$

Where:

J = Total number of all units in the entire set of multiple renovation projects.

r_j = Renovation order for each unit j in multiple projects.

3. Number of assigned renovation crews:

The third decision variable in this model represents the number of assigned renovation crews ($C_{i,j}$) for each renovation activity (i) in all leased units ($j = 1$ to J). This decision variable ($C_{i,j}$) is modeled using a positive integer variable that ranges from one to the maximum crew availability number that is specified by the planner (CA_i), as shown in Eq. (4.6). For example, $CA_B = 3$ indicates that there is a maximum number of three crews that can be assigned to activity (B), and $C_{B,4} = 2$ represents the assignment of two crews for renovation activity (B) in the fourth leased unit.

$$1 \leq C_{i,j} \leq CA_i \quad \forall i \in I \text{ \& } j \in J \quad (4.6)$$

Where

$C_{i,j}$ = Number of assigned crews to perform renovation activity i in leased unit j .

CA_i = Maximum crew availability for activity i .

Stage 2: Objective Function

The objective function of this model is designed to minimize the net renovation cost (NC) of all projects that is represented by the difference between (1) total renovation cost (RC) that consists of direct renovation cost (DRC), indirect cost (INC), and crew idle cost (IC); and (2) IPD reward sharing (IPD) that represents the difference between shared lease income savings (IS) and late completion penalty (LC), as shown in Eqs. (4.7 to 4.9). These costs are quantified and calculated in the renovation planning phase that is designed to generate practical renovation schedules and estimate their net renovation costs.

$$\text{Minimize } NC = \text{Minimize } (RC - IPD) \quad (4.7)$$

$$RC = DRC + INC + IC \quad (4.8)$$

$$IPD = IS - LC \quad (4.9)$$

Where:

NC = Total net renovation cost of all projects.

IPD = IPD reward sharing of all projects.

RC = Renovation cost of all projects.

DRC = Direct cost of all projects.

INC = Indirect cost of all projects.

IC = Crew Idle cost of all projects.

IS = Lease income savings of all projects.

LC = Late completion penalty of all projects.

Stage 3: Planning Constraints

The purpose of this stage is to identify practical constraints that the model needs to consider and comply with during the planning of renovation work in leased buildings. The identified practical constraints in this model are: (1) availability dates of all renovated units based on their lease end dates (LE_j), (2) maximum number of renovation crews on site (CA_i), and (3) maximum number of renovation crews (A_j) that can work simultaneously in each leased unit.

Units Availability Dates: Each unit in a leased building often has a varying lease end date (LE_j) that should be considered during the planning of its renovation work. Accordingly, this constraint is modeled to ensure that renovation crews are not scheduled to start work prior to that lease end date in each unit, as shown in Eq. (4.10).

$$S_{i,j} \geq LE_j \quad \forall i \in I \ \& \ \forall j \in J \quad (4.10)$$

Where:

$S_{i,j}$ = Start date of activity i in leased unit j .

LE_j = Lease end date of leased unit j .

Maximum Number of Renovation Crews: This constraint ensures that the number of allocated crews for activity (i) in each workday (x) does not exceed the specified maximum number of crews, as shown in Eq. (4.11).

$$\sum_{j=1}^J C_{i,j}^x \leq CA_i \quad \forall i \in I \ \& \ j \in J \quad (4.11)$$

Where:

$C_{i,j}^x$ = Assigned number of crews to perform renovation activity i in leased unit j on day x .

CA_i = Maximum number of crews for activity i .

Maximum Number of Crews in Each Unit: To ensure practicality, the total number of assigned crews for all renovation activities ($i = 1 \text{ to } I$) in each leased unit should not exceed the maximum number of crew (A_j) that can be efficiently utilized in each leased unit (j) on any workday, as shown in Eq. (4.12).

$$\sum_{i=1}^I C_{i,j}^x \leq A_j \quad \forall i \in I \ \& \ j \in J \quad (4.12)$$

Where:

$C_{i,j}^x$ = Assigned number of crews to perform renovation activity i in leased unit j on day x .

A_j = Maximum number of renovation crews that can work simultaneously in leased unit j .

Stage 4: Implementation stage

The model is designed to execute the optimization computations using genetic algorithms (GAs) due to their reported capabilities of (1) dealing with nonlinear and discontinuous objective functions and constraints; and (2) searching for and identifying optimal solutions for a wide range of construction planning problems with a reasonable computational time (Hassan and El-rayes 2019; Hegazy et al. 2007; Salama and Moselhi 2019). The optimization computations are accomplished in seven main steps:

1. Read all project and crew data required by the optimization phase, as shown in Figure 4.1.
2. Specify GA parameters.
3. Generate random schedule solutions $s = 1 \text{ to } S$ for the first generation $g = 1$. Each of these generated renovation schedules represents a random selection of (1) crew deployment date for all renovation activities (CD_i), (2) renovation order (r_j), and (3) number of assigned crew ($C_{i,j}$) for each activity (i) in all leased units ($j = 1 \text{ to } J$).

4. Compute the renovation schedule, total net renovation cost that represents the difference between renovation cost and IPD reward sharing for each solution $s = 1$ to S in generation g using the renovation planning phase described in the following section.
5. Evaluate and rank all generated renovation schedule solutions from 1 to S in generation g and select the fittest renovation schedule. Check if the specified GA stopping criteria was satisfied. If yes, the model ends its optimization computations and generates its output data. Otherwise, the model proceeds to steps 6 and 7.
6. Select the most fit solutions to be the parent population for the next generation $g = g + 1$.
7. Perform GA operations of selection, crossover and mutation to generate a new set of solutions for the next generation $g = g + 1$ and then repeat the evaluation of their fitness in the next iteration starting with step 4.

4.3 Renovation Planning Phase

The purpose of this phase is to develop practical renovation schedule and reliable cost estimate for all the renovation activities ($i = 1$ to I) in each leased units (j) in all projects ($k = 1$ to K). First, the renovation schedule will be designed to comply with all relevant constraints including job logic, availability dates of renovated units, maximum number of available renovation crews on site, and maximum number of renovation crews that can work simultaneously in each leased unit. Second, the cost estimate will quantify and calculate the total net renovation cost (NC) of all projects that is represented by the difference between (i) total renovation cost (RC) that consists of direct cost (DI), indirect cost (IN), and crew idle cost (IC); and (ii) IPD reward sharing (IPD) that represents the difference between shared lease income savings (LS) and late completion penalty (LC). Accordingly, this renovation planning phase is organized in two main stages (scheduling and cost estimating) that are described in the following sections.

A. Scheduling stage

The scheduling computations in this stage are designed to generate a practical renovation schedule that provides planners with the flexibility to (1) utilize single or multiple renovation crews that can be allocated to start working in several leased units simultaneously, (2) schedule multiple concurrent renovation projects with different completion deadlines, (3) consider all types of repetitive renovation activities that may have identical and/or varying durations in different leased units, and (4) consider single and/or multiple predecessors (P_i) for each renovation activity in the project.

The computations of this stage require the following project and activity input data: total number of renovation projects (K), total number of leased units (N_k) in each project k , total number of activities (I_k) in each project k , quantity of work for each renovation activity in each leased unit ($Q_{i,j}$), daily output rate of each renovation crew assigned to each activity (PR_i), maximum number of available crews that can be assigned to activity i in all concurrent projects (CA_i), maximum number of renovation crews that can work simultaneously in each leased unit (A_j), completion deadline for each renovation project (DP_k), and list of predecessors for each renovation activity (P_i). This input data is used to compute: (1) start ($S_{i,j}$) and finish ($F_{i,j}$) dates of each renovation activity ($i = 1$ to I) in all leased units ($j = 1$ to J) in all renovation projects ($k = 1$ to K); and (2) the total duration (D_k) of each renovation project k . The scheduling computations are performed using the following four steps, as shown in Figure 4.3:

1. Identify the predecessors (P_i) of each renovation activity ($i = 1$ to I).
2. For each activity (i) with no predecessors ($P_i = 0$), calculate the duration, start, and finish dates of renovation work in each leased unit. The renovation duration ($D_{i,j}$) of activity i in unit j is calculated based on its quantity of work, number of assigned crews, and the daily output rate

of its crew, as shown in Eq. (4.13). The start date ($S_{i,j}$) of activity i in leased unit j is identified as the latest of the unit lease end date (LE_j) and the selected activity crew deployment date (CD_i), using Eq. (4.14). The finish date ($F_{i,j}$) of activity i in leased unit j is calculated based on the activity start date and duration, as shown in Eq. (4.15).

$$D_{i,j} = \frac{Q_{i,j}}{C_{i,j} * PR_i} \quad \forall i \in I \& j \in J \quad (4.13)$$

$$S_{i,j} = \max (LE_j, CD_i) \quad \forall i \in I \& \forall p_i = 0 \quad (4.14)$$

$$F_{i,j} = S_{i,j} + D_{i,j} \quad \forall i \in I \& j \in J \quad (4.15)$$

Where:

$D_{i,j}$ = Duration of activity i in leased unit j in days.

$Q_{i,j}$ = Quantity of work of activity i in leased unit j .

PR_i = Crew daily output rate of activity i .

$S_{i,j}$ = Start date of activity i in leased unit j .

CD_i = Selected crew deployment date of activity i .

LE_j = Lease end date of unit j .

$F_{i,j}$ = Finish date of activity i in leased unit j .

3. For each activity (i) with at least one predecessor ($P_i \geq 1$), calculate the duration, start, and finish dates of renovation work in each leased unit. The renovation duration ($D_{i,j}$) of activity i in unit j is calculated based on its quantity of work, number of assigned crews, and the daily output rate of its crew, as shown in Eq. (4.13). The start date ($S_{i,j}$) of activity i in unit j is calculated as the latest finish dates of its predecessors and the selected crew deployment date (CD_i) using Eq. (4.16). The finish date ($F_{i,j}$) of activity i in leased unit j is calculated based on the activity start date and duration, as shown in Eq. (4.15).

$$S_{i,j} = \max [\max_{p_i=1}^{P_i} (F_{p_i,j} + lag_{p_i}), CD_i] \quad \forall i \in I \& \forall p_i \in P_i \quad (4.16)$$

Where:

Lag_{pi} = Lag duration between activity i and its predecessor p_i .

4. For each renovation activity (i), verify the compliance of its schedule with the aforementioned constraint of maximum number of available renovation crews. This verification is accomplished by calculating the total number of crews (C_i^x) that are utilized on day x by all concurrent units including unit j in all renovation projects, where day x ranges from the unit start date to its finish date, as shown in Eq. (4.17). If the calculated C_i^x exceeds the maximum number of available renovation crews CA_i , then shift the scheduled start and finish dates of leased unit j by one day at a time using Eqs. (4.18 and 4.19) until compliance with the constraint is achieved.

$$C_i^x = \sum_{j=1}^j C_{i,j}^x \quad \forall i \in I \text{ \& } S_{i,j} \leq x \leq F_{i,j} \quad (4.17)$$

$$S_{i,j} = \begin{cases} S_{i,j} + 1 & \text{if } C_i^x > CA_i \\ S_{i,j} & \text{otherwise} \end{cases} \quad \forall i \in I \text{ \& } \forall j \in J \quad (4.18)$$

$$F_{i,j} = S_{i,j} + D_{i,j} \quad \forall i \in I \text{ \& } \forall j \in J \quad (4.19)$$

Where:

C_i^x = Total number of crews that are utilized on day x by all concurrent units including unit j in all renovation projects.

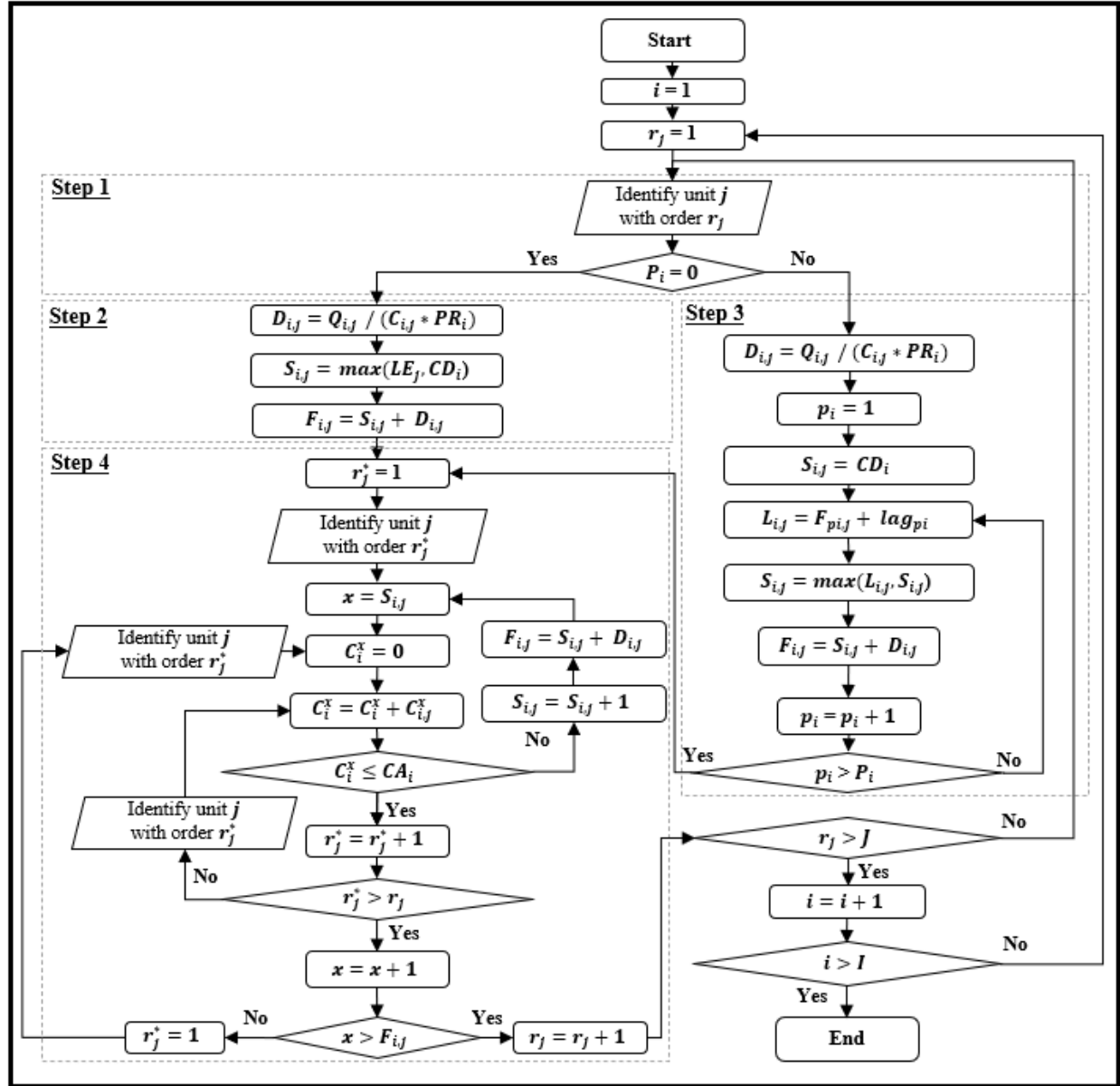


Figure 4.3. Scheduling stage computations

B. Cost estimating stage

The cost estimating computations in this stage are designed to quantify and calculate the total net renovation cost (NC) of all projects that is represented by the difference between total renovation cost (RC) and IPD reward sharing (IPD), as shown in Eq. (4.7). These cost estimating computations are performed using the following five steps:

1. Calculate direct renovation cost (*DRC*) of all projects ($k = 1$ to K) that accounts for all material and crew costs in all activities ($i = 1$ to I) in every leased unit n , as shown in Eq. (4.20).

$$DRC = \sum_{k=1}^K \sum_{n=1}^N \sum_{i=1}^I [M_i * Q_{i,n}^k + D_{i,n}^k * CC_i * C_{i,n}^k] \quad (4.20)$$

Where:

DRC = Direct cost of all projects.

M_i = Material cost per unit of activity i .

$Q_{i,n}^k$ = Quantity of work of activity i in unit n in project k .

$C_{i,n}^k$ = Number of assigned crews to perform activity i in unit n in project k .

CC_i = Daily crew cost rate for activity i .

$D_{i,n}^k$ = Duration of activity i in unit n in project k .

2. Calculate indirect cost (*INC*) for all renovation projects ($k = 1$ to K) based on each renovation project duration (PD_k) and its daily indirect cost rate (INR_k) that accounts for all time-dependent costs such as site supervision, site utilities, and office overhead, as shown in Eq. (4.21).

$$INC = \sum_{k=1}^K [\max_{n=1}^N (F_{I,n}^k) - \min_{n=1}^N (S_{i=1,n}^k)] * INR_k \quad \forall k \in K \quad (4.21)$$

Where:

$F_{I,n}^k$ = Finish date of last renovation activity I in unit n in project k .

$S_{i=1,n}^k$ = Start date of first renovation activity ($i = 1$) in unit n in project k .

INR_k = Daily indirect cost rate for project k .

3. Calculate crew idle cost (*IC*) of all renovation activities ($i = 1$ to I) incurred when a crew has to wait before resuming work in its next assigned leased unit. An idle crew is often encountered when the next assigned leased unit is unavailable for renovation due to its lease end data (LE_j) and/or due to ongoing work of predecessor renovation activities (AlOtaibi et al. 2021). This cost is minimized by enabling construction planners to remobilize idle renovation crews to other concurrent projects if (a) the crew mobilization time (MT_i) and its minimum required work time (T_i) in the other project is less than the crew idle time in the current project, and (b) the crew

mobilization cost (MC_i) is less than the crew idle cost (IC_{r_j}) in the current project, as shown in Eqs. (4.22a to 4.23).

$$IC_{i,r_j} = \begin{cases} (S_{i,r_{j+1}} - F_{i,r_j}) * \min(C_{i,r_j}, C_{i,r_{j-1}}) * Idle_C_i & \text{if } (S_{i,r_{j+1}} - F_{i,r_j}) > 0 \\ Zero & \text{otherwise} \end{cases} \quad \forall r_j \in (r_j = J - 1) \quad (4.22a)$$

$$IC_{i,r_j} = \begin{cases} \min(MC_i, IC_{i,r_j}) & \text{if } (S_{i,r_{j+1}} - F_{i,r_j}) > (MT_i + T_i) \\ (S_{i,r_{j+1}} - F_{i,r_j}) * \min(C_{i,r_j}, C_{i,r_{j-1}}) * Idle_C_i & \text{Otherwise} \end{cases} \quad \forall r_j \in (r_j = J - 1) \quad (4.22b)$$

$$IC = \sum_{i=1}^I \sum_{r_j=1}^J IC_{i,r_j} \quad (4.23)$$

Where:

IC_{i,r_j} = Crew idle cost of activity i in unit r_j .

$S_{i,r_{j+1}}$ = Start date of activity i in successor unit ($r_j + 1$).

F_{i,r_j} = Finish date of activity i in unit r_j .

C_{i,r_j} = Number of assigned crews for activity i in unit r_j .

$C_{i,r_{j-1}}$ = Number of assigned crews for activity i in predecessor unit ($r_j - 1$).

$Idle_C_i$ = Daily crew idle cost of activity i .

MC_i = Mobilization cost of activity i .

T_i = Minimum work duration in another concurrent project for activity i .

MT_i = Mobilization time of activity i .

IC = Crew Idle cost of all renovation activities in all projects.

4. Calculate shared lease income savings (LS) for each leased unit ($j = 1$ to J) that are realized when the actual unit completion date is earlier than its specified targeted completion date (TD_n^k), as shown in Figure 1.3. This saving component is quantified based on the daily lease income rate (DR_n^k) for each leased unit in each renovation project, its actual completion time ($F_{I,n}^k$), its specified targeted completion date (TD_n^k), and specified sharing rate between the project owner and the contractor (SH_{IPD}), as shown in Eqs. (4.24 to 4.26).

$$y_n^k = TD_n^k - \max_{i=1}^I (F_{i,n}^k) \quad \forall n \in N \ \& \ \forall k \in K \quad (4.24)$$

$$LS_n^k = y_n^k * (MR_n^k/30) * SH^k \quad \text{if } \max_{i=1}^I (F_{i,n}^k) < TD_n^k \quad \forall n \in N \ \& \ \forall k \in K \quad (4.25a)$$

$$LS_n^k = \text{zero} \quad \text{if } \max_{i=1}^I (F_{i,n}^k) \geq TD_n^k \quad \forall n \in N \ \& \ \forall k \in K \quad (4.25b)$$

$$LS = \sum_{k=1}^K \sum_{n=1}^N LS_n^k \quad (4.26)$$

Where:

y_n^k = Number of early completion days for unit n in project k .

TD_n^k = Specified target completion date for leased unit n in project k .

LS_n^k = Contractor's share of lease income savings for leased unit n in project k .

MR_n^k = Monthly lease income rate for leased unit n in project k .

SH^k = Agreed upon contractor share of lease income savings for project k .

LS = Total contractor's share of lease income savings for all projects.

5. Calculate late completion penalty (LC) for each project ($k = 1$ to K) that is encountered when the actual project duration exceeds its agreed upon deadline (PD_k), as shown in Figure 1.3. This penalty is calculated based on the specified daily penalty rate (PR_k) for each renovation project (k), its completion time ($F_{l,n}^k$), and deadline (PD_k), as shown in Eqs. (4.27a to 4.28).

$$LC_k = [\max_{n=1}^N (F_{l,n}^k) - PD_k] * PR_k \quad \text{if } \max_{n=1}^N (F_{l,n}^k) - PD_k > 0 \quad \forall k \in K \quad (4.27a)$$

$$LC_k = \text{zero} \quad \text{if } \max_{n=1}^N (F_{l,n}^k) - PD_k \leq 0 \quad \forall k \in K \quad (4.27a)$$

$$LC = \sum_{k=1}^K LC_k \quad (4.28)$$

Where:

PD_k = Deadline for project k .

PR_k = Specified daily penalty rate for project k .

LC_k = Total late completion penalty for project k .

LC = Total late completion penalty for all projects.

4.4 Performance Evaluation

The main purpose of this phase is to illustrate the use of the optimization model and demonstrate its novel capabilities by analyzing a real-life case study. The case study involves renovation work in three residential projects where each project requires the renovation of 6 four-bedroom houses and 9 five-bedroom houses. The renovation activities in these three projects can be divided into 10 activities that are grouped into six main categories: demolition, plumbing, electricity, carpentry, painting, and flooring.

The input data of the 10 renovation activities in the three projects are presented in Table 4.3, including activity predecessors (P_i), quantity of work ($Q_{i,j}$), material cost per unit of measurement (M_i), maximum number of available crews (CA_i), crew daily output rate (PR_i), crew daily cost rates (CC_i), and crew daily idle cost rates ($Idle_C_i$). The precedence relationships in this case study were specified by the planner to be finish-to-start with no lag time for all activities. Table 4.3 summarizes the input data of the three residential projects including house number n in each project k and its corresponding unique number in these three projects j , estimated lease end date for each house (LE_j), house target completion date (TD_j), project deadline (PD_k), project daily penalty rate (PR_k), and agreed upon contractor's share of lease income savings in percentage (SH^k). The monthly lease income of four-bedroom houses was estimated to be \$2000, \$2400, and \$2300 for the three projects ($k = 1, 2, \text{ and } 3$), respectively. Similarly, the monthly lease income of five-bedroom houses was estimated to be \$3200, \$3900, and \$3400 for the three projects ($k = 1, 2, \text{ and } 3$), respectively. The maximum number of crews (A_j) that are allowed to work simultaneously in any house is 2 crews. The daily indirect cost rate for all three projects was estimated to be \$800/day. The crew mobilization time (MT_i) and mobilization cost (MC_i) for all

renovation crews are estimated to be one day and \$300, respectively. The minimum required work time in other concurrent projects is estimated to be two days ($T_i = 2$) for all renovation crews.

Table 4.3 Renovation activity data

Activity number (i)	Activity description	Predecessor activities (P _i)	Unit	Quantity of work (Q _{i,j})		Material cost per unit (M _i)	Renovation crew data			
				4-Bedroom house	5-Bedroom house		Maximum number of available crews (CA _i)	Daily output rate (PR _i) (unit/day)	Daily cost rate (CC _i) (\$/day)	Idle time cost rate (Idle_C _i) (\$/day)
Demolition										
1	Floors, concrete slab on grade, 4” thick, reinforced, wire mesh	-	S.F.	6500	6800	-	8	4000	2,272	1,136
Plumbing										
2	Bathtub, enameled fired steel, 4’-6” long	1	Each	3	5	490	8	5.80	714	357
3	Water closets, bowl only, with flush valve, floor mounted, with floor outlet, 1.28 gpf	2	Each	4	7	550	8	5.8	714	357
4	Bath, press-bal mix valve w/diverter, spout, shower head, arm/flange	3	Each	10	12	175	8	8	397	198
Electricity										
5	Panelboard and load center circuit breakers, Bolt-on/240-volt,3 pole, 15-60 amp	4	Each	2	4	140	5	6.2	372	186
6	Interior lighting fixtures including lamps, mounting, and connections	5	Each	90	112	64	5	8	372	186
Carpentry										
7	Kitchen base cabinets, hardware, 24” deep, 35” high, prefinished	6	L.F.	124	150	200	6	24	624	312
8	Interior, six panel, hollow core, 1-3/8” thick	7	Each	33	38	62	6	17	646	323
Painting										
9	Painting interior and exterior walls and ceilings, latex, primer or sealer coat, smooth finish	8	S.F.	14000	17000	0.06	6	1350	324	162
Flooring										
10	Concrete floor staining, acrylic sealer, one coat	9	S.F.	6600	7500	0.22	8	2600	270	135

Table 4.4 Renovation project data

Project number (k)	Single project unit (k, n)	Multiple projects unit (j)	Lease end date (LE_j)	Target completion date (TD_j)	Single project unit (k, n)	Multiple projects unit (j)	Lease end date (LE_j)	Target completion date (TD_j)	Project deadline (PD_k)	Penalty daily rate (PR_k) (\$/day)	Contractor's share of lease income savings (SH^k) (%)
4-Bedroom house					5-Bedroom house						
1	1,1	1	04/19/2022	07/29/2022	1,7	7	06/19/2022	11/21/2022	12/17/2022	2360	40
	1,2	2	05/18/2022	09/04/2022	1,8	8	07/06/2022	12/17/2022			
	1,3	3	05/28/2022	10/05/2022	1,9	9	05/08/2022	09/16/2022			
	1,4	4	05/24/2022	09/29/2022	1,10	10	06/01/2022	10/25/2022			
	1,5	5	05/19/2022	09/09/2022	1,11	11	06/23/2022	11/24/2022			
	1,6	6	07/01/2022	11/17/2022	1,12	12	05/07/2022	09/15/2022			
	-	-	-	-	1,13	13	06/10/2022	10/29/2022			
	-	-	-	-	1,14	14	07/01/2022	12/06/2022			
	-	-	-	-	1,15	15	04/30/2022	09/06/2022			
	-	-	-	-	-	-	-	-			
2	2,1	16	05/07/2022	08/21/2022	2,7	22	07/25/2022	12/26/2022	12/26/2022	2650	50
	2,2	17	05/04/2022	08/17/2022	2,8	23	07/02/2022	12/09/2022			
	2,3	18	07/02/2022	11/25/2022	2,9	24	05/26/2022	10/13/2022			
	2,4	19	07/22/2022	12/11/2022	2,10	25	04/19/2022	07/29/2022			
	2,5	20	07/17/2022	12/09/2022	2,11	26	04/29/2022	09/04/2022			
	2,6	21	05/07/2022	08/21/2022	2,12	27	06/14/2022	11/03/2022			
	-	-	-	-	2,13	28	06/15/2022	11/07/2022			
	-	-	-	-	2,14	29	04/27/2022	09/02/2022			
	-	-	-	-	2,15	30	05/20/2022	10/02/2022			
	-	-	-	-	-	-	-	-			
3	3,1	31	04/19/2022	07/29/2022	3,7	37	06/14/2022	10/17/2022	01/16/2023	2480	60
	3,2	32	06/15/2022	10/28/2022	3,8	38	05/25/2022	10/13/2022			
	3,3	33	07/12/2022	12/09/2022	3,9	39	05/20/2022	10/02/2022			
	3,4	34	04/25/2022	08/05/2022	3,10	40	08/10/2022	01/16/2023			
	3,5	35	05/11/2022	08/26/2022	3,11	41	07/05/2022	12/11/2022			
	3,6	36	06/20/2022	11/13/2022	3,12	42	06/02/2022	10/28/2022			
	-	-	-	-	3,13	43	05/07/2022	09/15/2022			
	-	-	-	-	3,14	44	05/31/2022	10/18/2022			
	-	-	-	-	3,15	45	06/18/2022	11/08/2022			
	-	-	-	-	-	-	-	-			

The present model utilized the aforementioned input data to search for and identify optimal renovation plan that minimizes the net renovation cost (NC) of all projects. The GA optimization computations for this case study were performed utilizing Evolver Software genetic algorithm package. In this case study, the GA parameters were specified to be a population size of 250, a crossover rate of 0.85, and a mutation rate of 0.2. The optimization engine was set to terminate the optimization computations when the average relative change in the fitness function value over 21000 trials (generations) is less than 0.001.

The optimization computations for this case study were executed using the two aforementioned phases: optimization and renovation planning phases, as shown in Figure 4.. First, the optimization phase was utilized to generate a set of feasible solutions for the crew deployment date for all renovation activities (CD_i), renovation order (r_j), and number of assigned crew ($C_{i,j}$) for each activity (i) in all leased units ($j = 1 \text{ to } J$). Second, the renovation planning phase was used to (1) develop a renovation plan for each of the generated feasible solutions that calculates the work duration ($D_{i,j}$) as well as the start and finish dates ($S_{i,j}$ and $F_{i,j}$) of each activity ($i = 1 \text{ to } 10$) in each residential house j using Eqs. (4.13 to 4.19); and (2) calculate the total net renovation cost of each generated feasible solution that is represented by the difference between total renovation cost (RC) and IPD reward sharing (IPD) using Eqs. (4.20 to 4.28).

Upon the completion of the computations of the renovation planning phase, the optimization phase was used to search for and identify the optimal renovation plan that minimizes the total net renovation cost. The optimal renovation schedule for this case study was obtained by identifying an optimal (1) crew deployment date for each renovation activity as shown in Table 4.5, (2) unit renovation order (r_j) for each leased house, and (3) number of assigned crew ($C_{i,j}$) for each activity (i) in all houses (see. Table 4.6). This identified optimal renovation schedule provided a

minimum total net renovation cost of \$1,357,621 excluding material cost for all three renovation projects, and total work duration for all three projects ($k = 1, 2, \text{ and } 3$) of 151, 126, and 116 days, respectively.

Table 4.5 Optimal crew deployment date

Activity number (i)	Earliest deployment date (CD_i^E)	Latest deployment date (CD_i^L)	Range of feasible days	Optimal deployment date (CD_i^*)
1	04/19/2022	10/11/2022	175	05/09/2022
2	04/22/2022	10/14/2022	175	05/12/2022
3	04/23/2022	10/15/2022	175	05/13/2022
4	04/24/2022	10/16/2022	175	05/14/2022
5	04/26/2022	10/18/2022	175	05/16/2022
6	04/27/2022	10/19/2022	175	05/17/2022
7	05/12/2022	11/02/2022	174	05/29/2022
8	05/18/2022	11/09/2022	175	06/04/2022
9	05/21/2022	11/12/2022	175	06/06/2022
10	06/02/2022	11/24/2022	175	06/17/2022

Table 4.6 Optimal renovation order and number of crews

Multiple projects unit (j)	Renovation order (r_j)	Number of assigned crews ($c_{i,j}$)									
		Activity number (i)									
		1	2	3	4	5	6	7	8	9	10
1	1	2	1	1	1	1	1	1	1	2	1
2	26	1	1	1	1	1	1	1	1	2	1
3	13	1	2	1	1	1	1	1	1	2	1
4	15	1	1	1	1	1	1	1	1	2	1
5	9	1	1	2	1	1	1	1	1	2	1
6	17	1	1	1	1	1	1	1	1	2	1
7	23	1	2	1	1	1	1	1	1	2	1
8	11	1	1	1	2	1	1	1	1	2	1
9	3	1	1	1	1	1	1	1	1	2	1
10	21	1	1	1	1	1	1	1	1	2	1
11	20	1	1	2	1	1	1	1	1	2	1
12	3	1	1	1	1	1	1	1	1	2	1
13	19	1	1	1	1	1	1	1	1	2	1
14	20	1	1	1	1	1	1	1	1	2	1
15	28	1	1	1	1	1	1	1	1	2	1
16	1	1	1	1	1	1	1	1	1	2	1
17	21	1	1	1	1	2	1	1	1	2	1
18	14	1	1	1	1	1	1	1	1	2	1
19	3	2	2	1	1	1	1	1	1	2	1
20	10	1	1	2	1	2	1	1	1	2	1
21	1	1	1	1	1	1	1	1	1	2	1
22	2	1	1	1	1	1	1	1	1	2	1
23	27	1	1	1	1	1	1	1	1	2	1
24	7	1	1	1	1	1	1	1	1	2	1
25	1	2	2	2	2	2	2	2	2	2	2
26	2	1	1	1	1	1	1	1	1	2	1
27	18	1	1	1	1	1	1	1	1	2	1
28	16	1	1	1	1	1	1	1	1	2	1
29	1	1	1	1	1	1	1	1	1	2	1
30	5	1	1	1	1	1	1	1	1	2	1
31	1	2	2	2	2	2	2	2	2	2	2
32	14	1	1	1	1	1	1	1	1	2	1
33	25	1	1	1	1	1	1	1	1	2	1
34	1	1	1	1	1	1	1	1	1	2	1
35	3	1	1	1	2	1	1	1	1	2	1
36	24	2	2	2	2	2	2	2	2	2	2
37	15	1	1	1	1	1	1	1	1	2	1
38	6	1	1	1	2	1	1	1	1	2	1
39	4	1	1	1	1	1	1	1	1	2	1
40	3	1	1	1	1	1	1	1	1	2	1
41	8	1	1	1	1	1	1	1	1	2	1
42	22	1	1	1	1	1	1	1	1	2	1
43	3	1	1	1	1	1	1	1	1	2	1
44	12	1	1	1	1	1	1	1	1	2	1
45	5	1	1	1	1	1	1	1	1	2	1

The novelty of the developed optimization model and its unique capabilities can be highlighted by comparing its results to those provided by Fan et al. (2012). To enable a fair comparison between the two models, the following three main assumptions were made: (1) number of assigned crews ($C_{i,j}$) for each activity (i) in all houses will be limited to one crew per house since Fan et al. (2012) is incapable of assigning multiple crews to individual houses; (2) crew deployment date for the first renovation activity ($CD_{i=1}$) in the Fan et al. (2012) model is assumed to be earliest lease end date, latest lease end date, or three intermediate dates since that model is incapable of considering and complying with the units lease end dates constraint (see Table 4.7); and (3) total material cost was excluded from this comparison since it is identical in both models, as shown in Table 4.7. The results of this comparison analysis confirm the novel contributions of the present model and its capability to outperform available related models in (1) identifying optimal crew deployment date for each activity, optimal renovation order of each leased units, and optimal number of assigned crews for each activity in all leased units; (2) generating feasible renovation schedules that consider and comply with all relevant constraints including the units lease end dates constraint unlike available models; (3) maximizing contractor's share of lease income savings for renovation projects of leased buildings that utilize IPD risk and reward compensation structure; and (4) minimizing the total net renovation cost by 9% (\$132,685) compared to Fan et al. (2012), as shown in Table 4.7.

Table 4.7 Comparing performance of present model and Fan et al. (2012).

	Renovation schedule capabilities						Cost performance					
	First activity crew deployment date ($CD_{l=1}$)	Optimal renovation order (r_j)	Use of multiple renovation crews in leased units ($C_{i,l}$)	Compliance with units lease end dates constraint	Quantifying lease income savings	Duration (days)	Total non-material renovation cost (\$)	IPD reward sharing (IPD)		Total net non-material renovation cost (\$)	Cost savings	
								Contractor's share of lease income savings (\$)	Late completion penalty (\$)		(\$)	(%)
Present model	Optimally identified (05/09/2022)	Yes	Yes	Yes	Yes	Project 1 143 Project 2 156 Project 3 157	1,544,870	141,291	-	1,403,580	-	-
	Earliest lease end date (04/19/2022)	Yes	No	No	No			Infeasible schedule*				
	Intermediate Date (05/19/2022)	Yes	No	No	No			Infeasible schedule*				
	Intermediate Date (06/18/2022)	Yes	No	No	No			Infeasible schedule*				
Fan et al. (2012)	Intermediate Date (07/31/2022)	Yes	No	Yes	No	Project 1 156 Project 2 144 Project 3 142	1,528,612	32,467	40,120	1,536,265	132,685	9
	Latest lease end date (08/10/2022)	Yes	No	Yes	No	Project 1 156 Project 2 144 Project 3 142	1,529,338	24,589	79,620	1,584,369	180,789	13

* Schedule is infeasible because activities are scheduled to start before unit availability date/lease end date.

4.5 Conclusion

A novel model was developed for optimizing the planning of renovation work in leased buildings under Integrated Project Delivery (IPD) risk and reward compensation structure. The model enables renovation contractors working under IPD method to maximize their share of rental income savings while minimizing total renovation cost. The model was developed in three phases: optimization phase, renovation planning phase, and performance evaluation phase. The optimization phase was designed to search for and identify an optimal renovation schedule that minimizes the total net renovation cost. The scope of the renovation planning phase focused on calculating the duration, start date, finish date, and total interruption duration for each activity in all leased units and computing total net renovation cost for each generated solution in the optimization phase.

The performance evaluation phase analyzed a real-life case study of three residential renovation projects to enable a comparison between its generated results and those provided by available models. The results of this phase highlighted the original contributions of the optimization model and its novel capabilities in (1) minimizing total renovation cost while maximizing contractor's share of lease income savings for IPD renovation projects, (2) identifying optimal scheduling decisions including crew deployment date for all activities, renovation order of all leased units, and number of assigned crews for each activity in all units; and (3) developing a practical schedule that complies with the availability dates of all renovated units based on their lease end dates and availability of renovation crews. These novel and unique capabilities are expected to provide much-needed support for construction planners and enable them to generate optimal renovation schedules for IPD projects in order to maximize contractor's share of lease income savings while minimizing project renovation cost.

CHAPTER 5: OPTIMIZE THE PLANNING OF HOTEL RENOVATION PROJECTS

5.1 Introduction

This chapter presents the development of an innovative model for optimizing the planning of hotel renovation projects that enables hotel owners to maximize their revenues during renovation work while minimizing project cost. The model integrates a novel and practical optimization methodology that enables decision-makers to identify (1) which hotels to be renovated during a fiscal year based on allocated renovation budget (R_h); (2) optimal floor renovation start date in each hotel (S_f^h); (3) optimal use of overtime hours (x_i^h) and number of assigned crews (C_i^h) for each renovation activity; and (4) optimal floor renovation order in each hotel (O_f^h) in order to maximize hotels net profit. As shown in Figure 5.1, the present model computations are performed in three main modules: (1) optimization module that searches for and identifies an optimal renovation plan that maximize hotels net profit by maximizing their total revenues while minimizing total renovation cost during planning fiscal years; (2) scheduling module that computes the start and finish dates, and total work disruption for each renovation activity (i) in each floor (f) in all selected hotels ($h = 1$ to H); and (3) hotel profit module that calculates total revenue and renovation cost for each generated renovation plan in the optimization module. The following sections describe the development and computations of these modules.

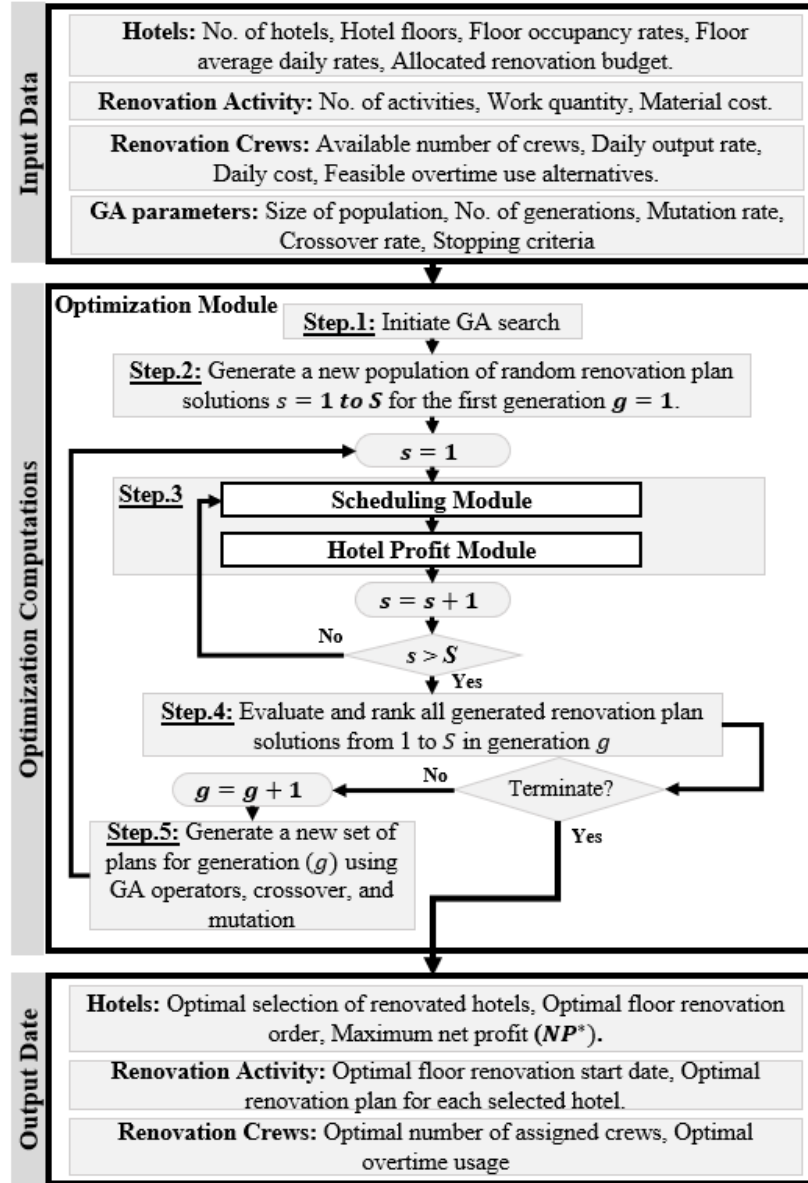


Figure 5.1. Model development modules

5.2 Optimization Module

The objective of this module is to formulate and implement an innovative model for optimizing the planning of hotel renovation projects. The model is designed to maximize hotels net profit by maximizing their total revenues during renovation work while minimizing their renovation during the planning fiscal year. The optimization module is developed in four main phases that are designed to (1) identify all relevant decision variables; (2) formulate the

optimization objective function; (3) define the model constraints, and (4) execute the computations of the optimization model. The following subsections provide a concise description of these development phases of the optimization module.

Phase 1: Decision Variables

The purpose of this phase is to identify all possible decision variables that affect revenues of hotels during renovation work and their renovation cost. Accordingly, the identified decision variables in this model are: (1) hotel renovation selection (R_h); (2) floor renovation start date in each hotel (S_f^h); (3) use of overtime hours for each renovation activity in each hotel (x_i^h); (4) number of assigned crews for each activity in each hotel (C_i^h); and (5) floor renovation order for each hotel (O_f^h). It should be noted that the implementation of the model-generated optimal solutions for these five decision variables require collaboration and agreement between hotel owners and contractors during the renovation planning phase. For example, hotel owners and contractors can utilize the developed model during the planning phase to generate an optimal renovation plan that maximizes total hotel revenues while minimizing total project cost. Successful execution of this optimal renovation plan requires collaboration and agreement between hotel owners and contractors to implement the optimal solutions for the aforementioned five decision variables during renovation work.

1. Hotel Renovation Selection:

This decision variable (R_h) represents the selection of renovated hotels from a set of competing hotels during any fiscal year based on a limited allocated renovation budget that cannot cover the total renovation cost of all competing hotels. R_h is modeled using a binary decision variable that can have a value of either 1 or 0, where a value of 1 represents that hotel h was selected to be renovated and a value of 0 represents that hotel h was not selected for renovation.

2. Floor Renovation Start Date:

The second decision variable (S_f^h) represents the selection of a renovation start date for each floor f in each hotel h . This decision variable (S_f^h) is modeled using a positive integer variable that ranges from a minimum value of zero to a maximum value of (E_f^h) that is specified by the planner for each floor f in each hotel h , as shown in Eq. (5.1).

$$0 \leq S_f^h \leq E_f^h \quad f \in F_h \text{ \& } h \in H \quad (5.1)$$

Where:

S_f^h : Renovation start date of floor f in hotel h .

E_f^h : Planner specified latest renovation start date of floor f in hotel h .

3. Use of overtime hours:

The third decision variable in this model (x_i^h) represents the selection of overtime hours for each renovation activity i in each hotel h . This decision variable (x_i^h) is modeled using a positive integer number that ranges from zero to the specified maximum number of daily overtime hours (X_i), as shown in Eq. (5.2).

$$0 \leq x_i^h \leq X_i \quad \forall i \in I \text{ \& } h \in H \quad (5.2)$$

Where:

x_i^h = Selected daily overtime hours for renovation activity i in hotel h .

X_i = Planner specified maximum number of daily overtime hours for each renovation activity i .

4. Number of Assigned Crews:

The fourth decision variable in this model represents the number of assigned crews (C_i^h) for each renovation activity i in each hotel h . This decision variable (C_i^h) is modeled using a

positive integer number that ranges from one to a planner specified maximum number of available crews (A_i^h) that can be assigned to activity i in each hotel h , as shown in Eq. (5.3). For example, $A_D^3 = 5$ indicates that there is a maximum number of five renovation crews that can be assigned to activity D in the third hotel ($h = 3$), and $C_D^3 = 3$ represents the assignment of three renovation crews for activity D in the third hotel.

$$1 \leq C_i^h \leq A_i^h \quad \forall i \in I \ \& \ h \in H \quad (5.3)$$

Where:

C_i^h : Number of assigned crews to perform renovation activity i in hotel h .

A_i^h : Planner specified maximum number of available crews for activity i in hotel h .

5. Floor Renovation Order:

The last decision variable in this model (O_f^h) represents the renovation order of each floor f in each hotel h and it is modelled as a unique integer number, as shown in Eq. (5.4). For example, $O_4^2 = 3$ indicates that the renovation order of the fourth floor in second hotel is planned to be third in the renovation project.

$$1 \leq O_f^h \leq F_h \quad \forall f \in F_h \ \& \ h \in H \quad (5.4)$$

$$O_k^h \neq O_z^h, \forall k \neq z, \quad k, z \in \{1, \dots, F\}$$

Where:

O_f^h : Renovation order for each floor f in hotel h .

F : Total number of floors in hotel h .

Phase 2: Objective Function

The objective function of this model is designed to maximize hotels net profit (NP) that is represented by the difference between (1) total revenues of all hotels (HR) being consider for renovation during any fiscal year; and (2) total renovation cost (RC) of all hotels selected for

renovation during any fiscal year which consists of material cost (MC), crew cost (CC), work disruption cost (PC), and indirect cost (IC), as shown in Eqs. (5.5 and 5.6). These hotel revenues and renovation costs are quantified in the hotel profit module discussed in the next sections.

$$\text{Maximize } NP = \text{Maximize } (HR - RC) \quad (5.5)$$

$$RC = MC + CC + PC + IC \quad (5.6)$$

Where:

NC = Total net profit of all hotels.

HR = Total hotel revenues during a planning fiscal year.

RC = Total renovation cost of all selected hotels.

MC = Material cost of renovation activities in all selected hotels.

CC = Crew cost of renovation activities in all selected hotels.

PC = Work disruption cost of renovation activities in all selected hotels.

IC = Indirect cost of all selected hotels.

Phase 3: Planning Constraints

In order to ensure the practicality of the developed model, it is designed to comply with two types of constraints: (i) allocated renovation budget constraint, and (ii) hotel completion deadline constraint. First, the renovation budget constraint is integrated in the model to ensure that the total renovation cost of all selected hotels for renovation does not exceed the allocated renovation budget, as shown in Eq. (5.7). Second, the hotel completion deadline constraint is integrated in the model to ensure that the renovation work of all selected hotels is completed before a planner specified completion deadline (DL_h) for each hotel h , as shown in Eq. (5.8).

$$RC \leq \text{allocated renovation budget} \quad (5.7)$$

$$FD_h \leq DL_h \quad (5.8)$$

Where:

FD_h = Finish date of renovation work in hotel h .

DL_h = Planner specified completion deadline for hotel h .

Phase 4: Optimization Computations

The optimization computations are executed using Genetic Algorithms (GAs) due to its capability of (a) dealing with the non-linear objective function and constraints of the model, and (b) identifying near optimal solutions for this class of problems in a reasonable computational time (Abdallah et al. 2015a; Altuwaim and El-Rayes 2018b; Ammar 2019; Salama and Moselhi 2019). The optimization computations are accomplished in five main steps that are designed to: (1) read all required input data provided by the renovation planner including hotel, renovation activity and crew data; (2) generate a new population of random renovation plan solutions $s = 1$ to S for the first generation $g = 1$, where each solution s represents a random selection for each the aforementioned model decision variables; (3) compute the renovation schedule, total net profit for each solution $s = 1$ to S in generation g using the scheduling and hotel profit modules; (4) evaluate and rank all generated renovation plan solutions from 1 to S in generation g ; (5) perform GA operations of selection, crossover and mutation to generate a new set of solutions for the next generation $g = g + 1$ and then repeat the evaluation of their fitness in the next iteration starting with step 3, as shown in Figure 5.1. This iterative process is terminated when the specified GA stopping criteria is satisfied and the model generates its output data.

5.3 Scheduling Module

The goal of this module is to develop a practical schedule for all renovation activities ($i = 1$ to I) in each floor f in each selected hotel h . This developed schedule is designed to comply with all relevant scheduling constraints including job logic, precedence relationship, maximum number of available renovation crews, and specified completion deadline for each hotel h . The scheduling computations in this module are designed to generate a practical renovation schedule that provides

planners with the flexibility to (1) utilize single or multiple renovation crews for each activity in each hotel, (2) schedule multiple concurrent hotel renovation projects with varying completion deadlines, (3) consider all types of repetitive renovation activities that may have identical and/or varying durations in different floors in each hotel, (4) consider single and/or multiple predecessors (P_i) for each renovation activity in the project, and (5) consider varying renovation order for each floor f in each hotel h using the earlier described floor renovation order decision variable.

The computations of this module require the following hotel, renovation activities and crews input data: total number of selected hotels (H), total number of floors in each hotel (F_h), peak (PK_h) and off-peak (OP_h) seasons of each hotel h , completion deadline for each hotel (DL_h), total number of renovation activities I in each hotel h , quantity of work for each activity in each floor in each hotel ($Q_{i,f}^h$), list of predecessors for each renovation activity (P_i), feasible overtime hour use alternatives for each renovation activity (X_i), daily output rate of each feasible overtime alternative for each renovation activity (OR_{x_i}), and earliest crew deployment date for each renovation activity (CD_i), as shown in Figure 5.1. The scheduling module utilizes this input data to perform its computations in four steps:

1. Calculate work duration ($D_{i,f}^h$) of activity i in each floor f in each hotel h based on its quantity of work ($Q_{i,f}^h$), number of assigned crews (C_i^h), and daily output rate of the selected overtime hour use alternative (OR_{x_i}), as shown in Eq. (5.9):

$$D_{i,f}^h = \frac{Q_{i,f}^h}{C_i^h * OR_{x_i}} \quad \forall i \in I \& f \in F \& h \in H \quad (5.9)$$

Where:

$D_{i,f}^h$ = Duration of activity i in floor f in hotel h .

$Q_{i,f}^h$ = Quantity of work of activity i in floor f in hotel h in unit of measurement.

OR_{x_i} = Daily output rate of selected overtime alternative x_i assigned to activity i .

2. Calculate start date ($SD_{i,f}^h$) of each renovation activity i in floor f of hotel h that satisfy job logic and precedence relationship constraints. For activities with no predecessors, $SD_{i,f}^h$ is identified as the latest of the crew deployment date (CD_i) and the floor renovation start date (S_f^h), as shown in Eq. (5.10a). For activities with one or more predecessors, $SD_{i,f}^h$ is identified as the latest of the crew deployment date (CD_i) and the latest activity start date which is dependent on the finish dates of its predecessors and their specified lag times, as shown in Eq. (5.10b).

$$SD_{i,f}^h = \begin{cases} \max(CD_i, S_f^h) & \forall i \in I \text{ \& } p_i = 0 \\ \max(CD_i, \max_{p_i=1}^{P_i} [FD_{p_i,f}^h + lag_{p_i}]) & \forall i \in I \text{ \& } f \in F \text{ \& } p_i \in P_i \end{cases} \quad (5.10a)$$

$$(5.10b)$$

Where:

CD_i = Earliest possible crew deployment date of activity i .

$SD_{i,f}^h$ = Start date of activity i in floor f of hotel h .

$FD_{p_i,f}^h$ = Finish date of predecessor activity p_i in floor f of hotel h .

Lag_{p_i} = Specified lag time between finish date of predecessor p_i and start date of activity i .

3. Calculate finish date ($FD_{i,f}^h$) of each renovation activity i in each floor f of hotel h based on the activity start date and duration, as shown in Eq. (5.11):

$$FD_{i,f}^h = SD_{i,f}^h + D_{i,f}^h \quad \forall i \in I \text{ \& } f \in F \text{ \& } h \in H \quad (5.11)$$

Where:

$FD_{i,f}^h$ = Finish date of activity i in floor f of hotel h .

4. Compute crew work disruption time (W_i^h) of each renovation activity i in hotel h based on its start date in successor floor with renovation order of (O_{f+1}^h) and its finish date in floor (O_f^h), using in Eq. (5.12):

$$W_i^h = SD_{i,O_{f+1}^h} - FD_{i,O_f^h} \quad \forall i \in I \ \& \ \forall O_f \in F - 1 \quad (5.12)$$

Where:

W_i^h = Crew work disruption time of activity i in hotel h .

SD_{i,O_{f+1}^h} = Start date of activity i in successor floor with renovation order $O_f^h + 1$ in hotel h .

FD_{i,O_f^h} = Finish date of activity i in floor with renovation order O_f^h in hotel h .

5.4 Hotel Profit Module

The objective of this module is to quantify and calculate the net profit (NP) of each generated renovation plan solution. This net profit (NP) is calculated as the difference between (1) total revenues of all hotels (HR) being consider for renovation during any fiscal year; and (2) total renovation cost (RC) of all hotels selected for renovation during any fiscal year which consists of material cost (MC), crew cost (CC), work disruption cost (PC), and indirect cost (IC), as shown in Eq. (5.5). The hotel net profit (NP) is calculated in this module using the following five steps:

1. Calculate total hotel revenues (HR) based on (i) daily occupancy rates of each floor f in each hotel h before renovation ($BO_{f,n}^h$) and after renovation ($AO_{f,n}^h$), and (ii) average daily rates of each floor f in each hotel h before renovation ($BDR_{f,n}^h$) and after renovation ($ADR_{f,n}^h$), as shown in Eqs. (5.13 to 5.18). It should be noted that the model provides planners with the flexibility to specify the need to vacate the upper and/or lower floors of each floor being renovated to mitigate renovation work noise and its negative impact on hotel residence. In these cases, the model is designed to calculate the associated noise

mitigation cost due to the additional floor closures and consider its impact on total hotel revenues, as shown in Eqs. (5.15 to 5.17).

$$BR = \begin{cases} \sum_{h=1}^H \sum_{f=1}^F \sum_{n=1}^{N=365} BO_{f,n}^h * BDR_{f,n}^h & \text{if } n < S_f^h \\ \text{zero} & \text{otherwise} \end{cases} \quad (5.13)$$

$$AR = \begin{cases} \sum_{h=1}^H \sum_{f=1}^F \sum_{n=1}^{N=365} AO_{f,n}^h * ADR_{f,n}^h & \text{if } n > FD_f^h \\ \text{zero} & \text{otherwise} \end{cases} \quad (5.14)$$

$$NC_L = \begin{cases} \sum_{h=1}^H \sum_{f=2}^F \sum_{n=1}^{N=365} BO_{f,n}^h * BDR_{f,n}^h & \text{if } S_{f-1}^h \leq n \leq FD_{f-1}^h \text{ and } NM_L^h = 1 \\ \text{Zero} & \text{otherwise} \end{cases} \quad (5.15)$$

$$NC_U = \begin{cases} \sum_{h=1}^H \sum_{f=1}^{F-1} \sum_{n=1}^{N=365} BO_{f,n}^h * BDR_{f,n}^h & \text{if } S_{f+1}^h \leq n \leq FD_{f+1}^h \text{ and } NM_U^h = 1 \\ \text{Zero} & \text{otherwise} \end{cases} \quad (5.16)$$

$$NC = NC_L + NC_U \quad (5.17)$$

$$HR = BR + AR - NC \quad (5.18)$$

Where:

$BO_{f,n}^h$ = Daily occupancy rate of floor f in hotel h on calendar day n before renovation in %.

$BDR_{f,n}^h$ = Average daily rate of floor f in hotel h on calendar day n before renovation in \$/day.

$AO_{f,n}^h$ = Daily occupancy rate of floor f in hotel h on calendar day n after renovation in %.

$ADR_{f,n}^h$ = Average daily rate of floor f in hotel h on calendar day n after renovation in \$/day.

FD_f^h = Finish date of renovation work in floor f in hotel h .

BR = Total revenue gains of all hotels before renovation in \$.

AR = Total revenue gains of all hotels after renovation in \$.

NC_L = Total noise mitigation cost of all hotels resulting from closures of lower floors in \$.

NC_U = Total noise mitigation cost of all hotels resulting from closures of upper floors in \$.

NC = Total noise mitigation cost of all hotels resulting from closures of upper and/or lower floors in \$.

2. Calculate total material cost (MC) of all activities ($i = 1$ to I) in each floor f of hotel h based on material cost rate of each renovation activity, and its quantity of work in floor f of hotel h , as shown in Eq. (5.19):

$$MC = \sum_{h=1}^H \sum_{f=1}^F \sum_{i=1}^I M_i * Q_{i,f}^h \quad (5.19)$$

Where:

M_i : Material cost rate of activity i .

$Q_{i,f}^h$: Quantity of work of activity i in floor f of hotel h .

3. Calculate total crew cost (CC) that account for labor and equipment costs of all activities ($i = 1$ to I) in each floor f of hotel h based on the number of assigned crews to perform activity i , their daily crew cost rates, and duration of activity i in floor f of hotel h , using Eq. (5.20):

$$CC = \sum_{h=1}^H \sum_{f=1}^F \sum_{i=1}^I C_i^h * DC_{x_i}^h * D_{i,f}^h \quad (5.20)$$

Where:

$DC_{x_i}^h$: Daily crew cost rate of selected overtime alternative x_i for renovating activity i in hotel h .

4. Calculate total work disruption cost (PC) of all renovation activities ($i = 1$ to I) incurred when a crew has to wait before resuming work in its next assigned floor. A work disruption is often encountered when the next assigned floor is unavailable for renovation due to (1) planner-specified delay in the renovation start date of selected floors to minimize their closures and hotel revenue losses during high peak seasons, as shown in Figure 1.4 (B); and/or (2) ongoing work of predecessor renovation activities. This cost is calculated based

on number of work disruption period (W_i^h) for each activity i and its associated daily work disruption cost (DPC_i) specified by the planner, using Eq. (5.21):

$$PC = \sum_{i=1}^I \sum_{h=1}^H W_i^h * DPC_i \quad (5.21)$$

Where:

W_i^h = Work disruption of activity i in hotel h .

DPC_i = Daily work disruption cost of activity i .

5. Calculate total indirect cost (IC) for each selected hotel (h) based on project duration (PD_h) and daily indirect cost rate (INR_h) that accounts for all time-dependent costs such as site supervision, site utilities, and office overhead, as shown in Eq. (5.22).

$$IC = \sum_{h=1}^H PD_h * INR_h \quad \forall h \in H \quad (5.22)$$

Where:

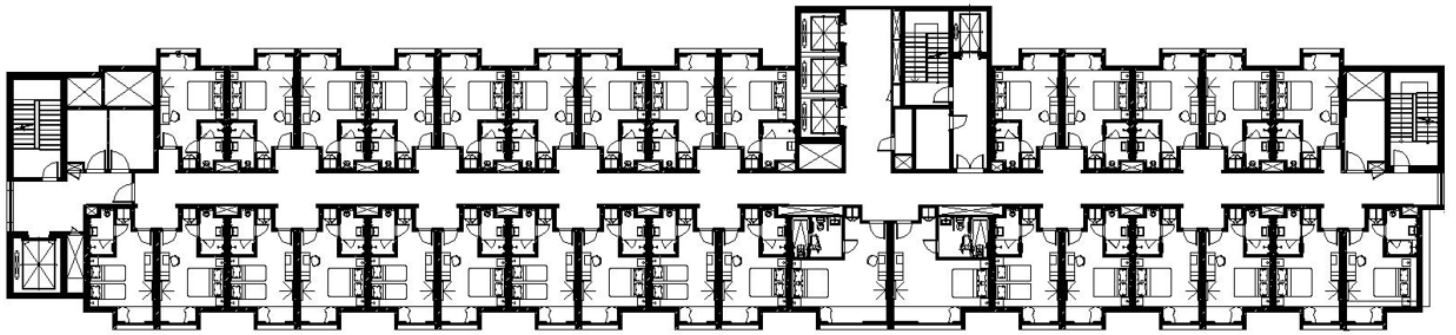
PD_h : Duration of renovation work in hotel h .

INR_h : Daily indirect cost rate for hotel h .

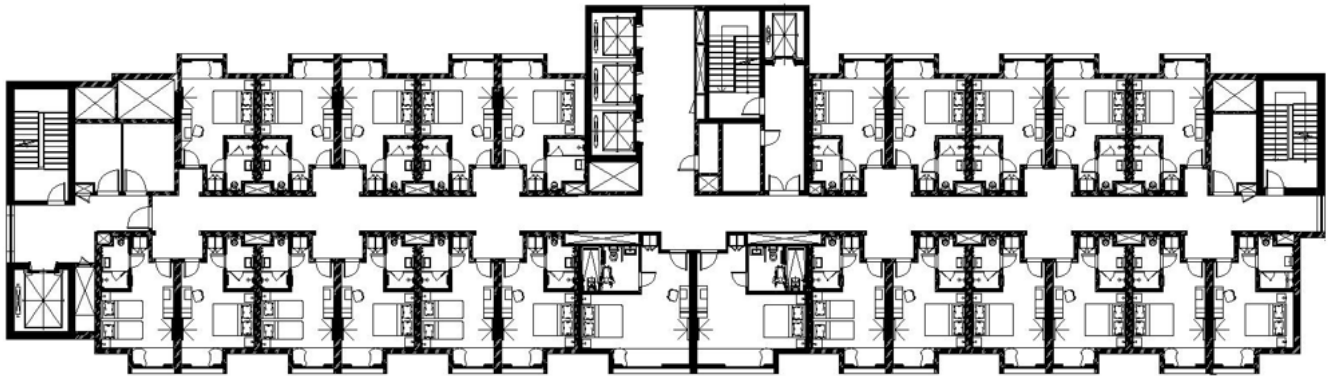
5.5 Application Example

An application example is analyzed to illustrate the use of the developed model and demonstrate its capabilities in optimizing the planning of renovation work in three hotels. The scope of work in this example focuses on the renovation of 10 floors with 32 rooms per floor in the first hotel ($h = 1$), 15 floors with 24 rooms per floor in the second hotel ($h = 2$), and 12 floors with 28 rooms per floor in the third hotel ($h = 3$), as shown in Figure 5.2. In this example, a renovation planner needs to make decisions on (1) which hotels to select for renovation for the upcoming fiscal year from the three competing alternatives based on an allocated renovation

budget of \$12.5M; (2) floor renovation start date in each hotel; (3) use of overtime hours and number of assigned crews for each renovation activity; and (4) floor renovation order in each hotel. The planned renovation work in the three hotels can be represented by 16 activities that are grouped into six main categories: demolition and removal, plumbing, electricity, painting, flooring, and furniture, as shown in Table 5.1. The precedence relationships among all activities are specified to be finish-to-start with no lag time. Table 5.1 summarizes the required scope of work for each of the 16 activities in this example including its predecessors (P_i), unit of measurement, quantity of work per floor in each hotel ($Q_{i,f}^h$), material cost per unit of measurement (M_i) and maximum number of available crews for each hotel (A_i^h). Table 5.2 summarizes all feasible overtime alternatives for each of the 16 activities including number of overtime hours per workday, crews daily output rates (OR_{x_i}), their daily cost rates (C_{x_i}). Table 5.3 summarizes daily work disruption cost (DPC_i^h) for each renovation activity i . The expected revenue data of the three hotels are summarized in Tables 5.4 to 5.7 that specify daily occupancy rates of each floor f in each hotel h before renovation ($BO_{f,n}^h$) and after renovation ($AO_{f,n}^h$), average daily rates of each floor f in each hotel h before renovation ($BDR_{f,n}^h$) and after renovation ($ADR_{f,n}^h$). The daily indirect cost rate and the completion deadline (DL_h) for all the three hotels were specified to be \$830/day and 12/20/2023, respectively. In this application example, the three hotels do not require noise mitigation measures that specify closures of upper and/or lower floors during renovation work (NM_L^h and $NM_U^h = 0$).



Hotel One



Hotel Two



Hotel Three

Figure 5.2. Hotels floor layouts

Table 5.1 Renovation activity data

Activity number (i)	Activity description	Predecessor activities (P _i)	Unit of Measurement	Quantity of work per floor (Q _{if} ^h)			Material cost (M _i) (\$)	Maximum available crews for each hotel (A _i ^h)
				Hotel 1	Hotel 2	Hotel 3		
Demolition and Removal								
1	Carpet, bonded, including surface scraping	-	S.F.	2080	1560	1820	0	9
2	Bathtub and showerhead	1	Each	32	24	28	0	10
3	Sink, single compartment, and faucets	2	Each	32	24	28	0	9
4	Water closets (Toilet)	3	Each	32	24	28	0	9
5	Tile, ceramic, thin set	4	S.F.	4782	3672	4206	0	6
Plumbing								
6	Bathtub, soaking, acrylic, w/pop-up drain 66"x36"x20" deep	5	Each	32	24	28	1675	10
7	Sink, with trim, porcelain enamel on cast iron, 22" x 19", single bowl	6	Each	32	24	28	690	8
8	Bath faucet, diverter spout combination	7	Each	32	24	28	86	10
9	Water closets, bowl only, with flush valve, seat, 1.6 gpf, wall hung	8	Each	32	24	28	970	9
Electricity								
10	Switch plates, 1 gang, 2 switch, plastic	9	Each	90	112	102	5	9
11	Receptacle, duplex, 120volt, grounded, 15 amp	10	Each	96	72	84	1.3	9
12	Interior lighting fixtures	11	Each	192	144	168	75	10
Painting								
13	Paint interior, and exterior walls, complete, including surface prep, primer & 2 coats finish for all rooms	12	S.F.	2534	1932	2226	0.21	6
Flooring								
14	Ceramic tiles, recycled glass, standard colors, 2"x2"	13	S.F.	2080	1560	1820	22	7
15	Sheet carpet, Nylon, level loop, 28 oz., light to medium traffic	14	S.F.	4782	3672	4206	39.5	10
Furniture								
16	Hotel Furniture, Standard quality set, minimum	15	Each	32	24	28	2550	8

Table 5.2 Feasible alternatives for overtime use

Activity (i)	Feasible alternative (x_i)	Daily		
		Overtime hours (hour/day)	Output rate (OR_{x_i}) (unit/day)	Cost rate (C_{x_i}) (\$/day)
1	1	0	675	667
	2	2	803	1,001
	3	4	932	1,334
2	1	0	4	521
	2	2	5	781
	3	3	5	911
3	1	0	8	521
	2	3	10	911
4	1	0	8	521
	2	4	11	1,042
5	1	0	5000	683
	2	2	5950	1025
	3	3	6975	1366
6	1	0	5.5	942
	2	3	7	1,648
7	1	0	8	941
	2	3	10	1,646
	3	4	11	1,882
8	1	0	8	521
	2	4	11	1,042
9	1	0	5.8	938
	2	3	7	1,641
10	1	0	80	487
	2	2	95	731
	3	4	110	974
11	1	0	40	489
	2	3	51	856
12	1	0	6	756
	2	4	8	1,512
13	1	0	325	358
	2	3	418	627
14	1	0	190	706
	2	2	226	1,058
	3	3	244	1,235
15	1	0	75	394
	2	2	89	591
	3	4	104	788
16	1	0	10	158
	2	3	13	276

Table 5.3 Renovation work disruption cost

Activity number (<i>i</i>)	Daily renovation work disruption cost (DPC_i) (\$/day)				
	One week or less	Two weeks	Three weeks	Four weeks	Five weeks or more
1	500	334	233	133	0
2	391	260	182	104	0
3	391	260	182	104	0
4	391	260	182	104	0
5	512	342	239	137	0
6	706	471	330	188	0
7	706	470	329	188	0
8	391	260	182	104	0
9	703	469	328	188	0
10	365	244	171	97	0
11	367	245	171	98	0
12	567	378	265	151	0
13	269	179	125	72	0
14	529	353	247	141	0
15	295	197	138	79	0
16	118	79	55	32	0

Table 5.4 Daily occupancy rates before renovation for sample days.

Hotel No.	Floor No.	Daily Occupancy Rate Before Renovation ($BO_{f,n}^h$)							
		(%)							
		Monday 1/16/2023	Tuesday 1/17/2023	...	Saturday 7/29/2023	Sunday 7/30/2023	...	Thursday 12/21/2023	Friday 12/22/2023
1	1	87	91		58	58		91	74
	2	89	93		61	61		93	76
	3	90	95		63	63		95	79
	4	92	97		67	67		97	80
	5	93	98		71	71		98	80
	6	97	100		71	71		100	81
	7	100	100		72	72		100	82
	8	100	100		74	74		100	84
	9	100	100		76	76		100	86
	10	100	100		81	81		100	88
2	1	76	76		58	81		73	59
	2	73	75		58	80		77	61
	3	78	77		56	77		80	59
	4	81	73		56	75		82	56
	5	82	81		64	77		73	69
	6	98	93		69	88		89	65
	7	92	93		63	99		83	69
	8	91	83		64	84		89	67
	9	87	94		72	90		89	68
	10	92	94		72	95		93	66
	11	96	91		84	96		89	77
	12	89	97		76	93		83	80
	13	96	100		73	96		95	74
	14	94	85		77	83		93	77
	15	87	99		76	93		94	83
3	1	63	68		93	69		71	91
	2	61	67		96	67		64	79
	3	64	71		80	63		66	90
	4	63	67		85	64		64	78
	5	65	63		92	64		71	99
	6	68	68		87	71		64	85
	7	66	74		82	69		62	81
	8	67	69		84	61		67	78
	9	66	63		86	60		64	88
	10	62	65		83	61		73	85
	11	69	75		81	64		63	89
	12	70	62		90	68		65	85

Table 5.5 Daily occupancy rates after renovation for sample days

Hotel No.	Floor No.	Daily Occupancy Rate After Renovation ($AO_{f,n}^h$)							
		(%)							
		Monday 1/16/2023	Tuesday 1/17/2023	...	Saturday 7/29/2023	Sunday 7/30/2023	...	Thursday 12/21/2023	Friday 12/22/2023
1	1	90	94		60	60		94	76
	2	92	96		63	63		96	78
	3	93	98		65	65		98	81
	4	95	100		69	69		100	82
	5	96	100		73	73		100	82
	6	100	100		73	73		100	83
	7	100	100		74	74		100	84
	8	100	100		76	76		100	87
	9	100	100		78	78		100	89
	10	100	100		83	83		100	91
2	1	80	80		61	85		77	62
	2	77	79		61	84		81	64
	3	82	81		59	81		84	62
	4	85	77		59	79		86	59
	5	86	85		67	81		77	72
	6	100	98		72	92		93	68
	7	97	98		66	100		87	72
	8	96	87		67	88		93	70
	9	91	99		76	95		93	71
	10	97	99		76	100		98	69
	11	100	96		88	100		93	81
	12	93	100		80	98		87	84
	13	100	100		77	100		100	78
	14	99	89		81	87		98	81
	15	91	100		80	98		99	87
3	1	67	73		100	74		76	97
	2	65	72		100	72		68	85
	3	68	76		86	67		71	96
	4	67	72		91	68		68	83
	5	70	67		98	68		76	100
	6	73	73		93	76		68	91
	7	71	79		88	74		66	87
	8	72	74		90	65		72	83
	9	71	67		92	64		68	94
	10	66	70		89	65		78	91
	11	74	80		87	68		67	95
	12	75	66		96	73		70	91

Table 5.6 Avg. daily rate before renovation for sample days

Hotel No.	Floor No.	Avg. Daily Rate Before Renovation ($BDR_{f,n}^h$)							
		(\$/day)							
		Monday 1/16/2023	Tuesday 1/17/2023	...	Saturday 7/29/2023	Sunday 7/30/2023	...	Thursday 12/21/2023	Friday 12/22/2023
1	1	3040	3040		2584	2584		3040	2584
	2	3040	3040		2584	2584		3040	2584
	3	3040	3040		2584	2584		3040	2584
	4	3040	3040		2584	2584		3040	2584
	5	3040	3040		2584	2584		3040	2584
	6	3040	3040		2584	2584		3040	2584
	7	3040	3040		2584	2584		3040	2584
	8	3040	3040		2584	2584		3040	2584
	9	3040	3040		2584	2584		3040	2584
	10	3040	3040		2584	2584		3040	2584
2	1	3408	3408		2880	3408		3408	2880
	2	3408	3408		2880	3408		3408	2880
	3	3408	3408		2880	3408		3408	2880
	4	3408	3408		2880	3408		3408	2880
	5	3408	3408		2880	3408		3408	2880
	6	3408	3408		2880	3408		3408	2880
	7	3408	3408		2880	3408		3408	2880
	8	3408	3408		2880	3408		3408	2880
	9	3408	3408		2880	3408		3408	2880
	10	3408	3408		2880	3408		3408	2880
	11	3408	3408		2880	3408		3408	2880
	12	3408	3408		2880	3408		3408	2880
	13	3408	3408		2880	3408		3408	2880
	14	3408	3408		2880	3408		3408	2880
	15	3408	3408		2880	3408		3408	2880
3	1	3332	3332		4172	3332		3332	4172
	2	3332	3332		4172	3332		3332	4172
	3	3332	3332		4172	3332		3332	4172
	4	3332	3332		4172	3332		3332	4172
	5	3332	3332		4172	3332		3332	4172
	6	3332	3332		4172	3332		3332	4172
	7	3332	3332		4172	3332		3332	4172
	8	3332	3332		4172	3332		3332	4172
	9	3332	3332		4172	3332		3332	4172
	10	3332	3332		4172	3332		3332	4172
	11	3332	3332		4172	3332		3332	4172
	12	3332	3332		4172	3332		3332	4172

Table 5.7 Avg. daily rate after renovation for sample days

Hotel No.	Floor No.	Avg. Daily Rate After Renovation ($ADR_{f,n}^h$)							
		(\$/day)							
		Monday 1/16/2023	Tuesday 1/17/2023	...	Saturday 7/29/2023	Sunday 7/30/2023	...	Thursday 12/21/2023	Friday 12/22/2023
1	1	3557	3557		3023	3023		3557	3023
	2	3557	3557		3023	3023		3557	3023
	3	3557	3557		3023	3023		3557	3023
	4	3557	3557		3023	3023		3557	3023
	5	3557	3557		3023	3023		3557	3023
	6	3557	3557		3023	3023		3557	3023
	7	3557	3557		3023	3023		3557	3023
	8	3557	3557		3023	3023		3557	3023
	9	3557	3557		3023	3023		3557	3023
	10	3557	3557		3023	3023		3557	3023
2	1	3919	3919		3312	3919		3919	3312
	2	3919	3919		3312	3919		3919	3312
	3	3919	3919		3312	3919		3919	3312
	4	3919	3919		3312	3919		3919	3312
	5	3919	3919		3312	3919		3919	3312
	6	3919	3919		3312	3919		3919	3312
	7	3919	3919		3312	3919		3919	3312
	8	3919	3919		3312	3919		3919	3312
	9	3919	3919		3312	3919		3919	3312
	10	3919	3919		3312	3919		3919	3312
	11	3919	3919		3312	3919		3919	3312
	12	3919	3919		3312	3919		3919	3312
	13	3919	3919		3312	3919		3919	3312
	14	3919	3919		3312	3919		3919	3312
	15	3919	3919		3312	3919		3919	3312
3	1	3998	3998		5006	3998		3998	5006
	2	3998	3998		5006	3998		3998	5006
	3	3998	3998		5006	3998		3998	5006
	4	3998	3998		5006	3998		3998	5006
	5	3998	3998		5006	3998		3998	5006
	6	3998	3998		5006	3998		3998	5006
	7	3998	3998		5006	3998		3998	5006
	8	3998	3998		5006	3998		3998	5006
	9	3998	3998		5006	3998		3998	5006
	10	3998	3998		5006	3998		3998	5006
	11	3998	3998		5006	3998		3998	5006
	12	3998	3998		5006	3998		3998	5006
	13	3998	3998		5006	3998		3998	5006
	14	3998	3998		5006	3998		3998	5006
	15	3998	3998		5006	3998		3998	5006

In this application example, the developed model was used to search for and identify an optimal renovation plan for all hotels that maximize their net profits (NP) in the upcoming fiscal year. The optimization computations were executed using five main steps (see Figure 5.1) that were designed to (1) read all required input data provided by the renovation planner including hotel, renovation activity and crew data, as shown in Figure 5.1 and Tables 5.1 to 5.7; (2) generate a new population consists of 250 random renovation plan solutions for the first generation $g = 1$, where each solution s represents a random selection for each the aforementioned model decision variables; (3) compute the renovation schedule, total net profit for each solution $s = 1$ to 250 in generation g using the scheduling and hotel profit modules; (4) evaluate and rank all generated renovation plan solutions from 1 to 250 in generation g ; (5) perform GA operations of selection, crossover and mutation to generate a new set of solutions for the next generation $g = g + 1$ and then repeat the evaluation of their fitness in the next iteration starting with step 3, as shown in Figure 5.1. This iterative process was set to terminate when the average relative change in the fitness function value over 32000 trials (generations) is less than 0.001. The computational time for this application example was approximately 40 minutes using a personal computer with 11th Gen Intel Core i7 Processor and 12GM RAM.

The generated optimal renovation plan by the developed model for this application example recommends (1) optimal selection of first hotel ($R_1 = 1$) and third hotel ($R_3 = 1$) for renovation during the upcoming fiscal year, as shown in Table 5.8, (2) optimal renovation start date for each floor in the selected hotels (S_f^h), as shown in Table 5.8, (3) optimal use of overtime hours (x_i^h) and number of assigned crews for each activity in the selected hotels (C_i^h), as shown in Table 5.9, and (4) optimal renovation order for each floor in the selected hotels (O_f^h), as shown in Table 5.8. This identified optimal renovation plan provided a maximum total net profit of

\$28,975,181 for the upcoming fiscal year that represents the difference between maximum total revenue of \$40,645,527 for all three hotels ($h = 1, 2, \&3$) and a minimum total renovation cost of \$11,670,347 to renovate the first and third hotels ($h = 1 \& 3$).

Table 5.8 Optimal hotel selection, floor start date, and floor renovation order

Optimal hotel selection (R_h)	Floor No.	Optimal floor start date (S_f^h)	Optimal floor order (O_f^h)
1	1	109.9	10
	2	109.6	9
	3	109.3	8
	4	42.6	6
	5	109.0	7
	6	42.3	5
	7	0.0	1
	8	0.6	3
	9	0.3	2
	10	42.0	4
3	1	1.5	5
	2	2.1	7
	3	1.3	4
	4	32.5	10
	5	1.8	6
	6	33.1	12
	7	0.0	1
	8	1.0	3
	9	32.8	11
	10	0.3	2
	11	32.3	9
	12	32.0	8

Table 5.9 Optimal overtime use and number of crews

Activity number (i)	Optimal overtime use alternative (x_i^h)		Optimal number of crews (C_i^h)	
	Hotel 1	Hotel 3	Hotel 1	Hotel 3
1	1	1	9	5
2	2	2	10	10
3	1	1	10	10
4	1	1	10	10
5	1	1	4	5
6	1	1	10	10
7	1	1	8	8
8	1	1	8	9
9	1	1	10	9
10	1	1	5	6
11	1	1	9	6
12	1	1	10	10
13	1	1	6	6
14	1	1	6	5
15	2	2	10	10
16	2	2	6	5

To highlight the novelty of the developed optimization model, the same application example was analyzed using 10 different scenarios where each one represents a possible set of selections for each of the four planning decisions: hotel renovation selection, floor renovation order, use of overtime hours, and number of assigned crews. First, all hotel selection combinations were analyzed in these 10 different scenarios by either selecting all hotels, first and second hotels, first and third hotels, or second and third hotels to be renovated during the upcoming fiscal year. Second, ascending and descending floor renovation orders were analyzed in these scenarios where renovation crews can start working either from the first to the top floor, or from the top to the first floor. Third, two overtime use alternatives were considered in these scenarios which are either having maximum overtime use, or no overtime use for all renovation activities. Fourth, the number of assigned crews were randomly selected from either maximum, half, or minimum number of available crews. This sample of 10 possible renovation plans were analyzed and compared to the optimal renovation plan, as shown in Table 10. The results of this comparison illustrate that (1) two of the considered renovation plans were infeasible because their total renovation cost exceeded

the allocated renovation budget of \$12.5M; and (2) all 10 possible renovation plans underperformed the generated optimal solution as they all provided lower net profits compared to the optimal plan that ranged from \$1,277,967 (4%) to \$9,677,435 (33%), as shown in Table 10. This illustrates the novel contributions of the present model and its unique capabilities of identifying optimal renovation planning decisions for hotel selections, floor renovation start dates, use of overtime hours and number of assigned crews, and floor renovation order. These optimal renovation decisions enable owners to maximize hotel revenues during renovation work while minimizing project cost.

Table 5.10 Sample set of possible renovation plans

Renovation Plan Plan (p)	Set of possible renovation planning decisions				Net profit performance				
	Hotel renovation selection (R_h)	Floor renovation order (O_f^h)	Overtime hours alternative (x_i^h)	Number of crews for each activity (C_i^h)	Hotel revenues (\$)	Renovation cost (\$)	Net profit (\$)	Loss in net profit compared to optimal renovation plan ^a	
								(\$)	(%)
1	1 2 3	Ascending	No overtime	Max	Infeasible solution*				
2	1 2	Ascending	No overtime	Max	38,882,673	12,042,991	26,839,682	2,135,499	7
3	1 3	Ascending	Max overtime	Max	39,262,750	11,565,566	27,697,214	1,277,967	4
4	1 2	Descending	Max overtime	Max	Infeasible solution**				
5	2 3	Ascending	No overtime	Max	38,413,047	12,342,433	26,070,614	2,904,567	10
6	1 3	Descending	Max overtime	Half	37,497,125	12,207,775	25,289,350	3,685,832	13
7	1 3	Descending	No overtime	Half	35,452,997	11,593,667	23,859,331	5,115,850	18
8	1 2	Ascending	No overtime	Half	35,166,837	12,069,883	23,096,954	5,878,227	25
9	2 3	Ascending	No overtime	Half	33,589,751	12,367,586	21,222,165	7,753,016	27
10	1 3	Ascending	No overtime	Min	31,276,431	11,978,686	19,297,746	9,677,435	33
11 ^a	1 and 3	Optimal	Optimal	Optimal	40,645,527	11,670,347	28,975,181	0	0

* Infeasible plan because renovation cost exceeds allocated budget of \$12.5M when selecting all three hotels for renovation.

** Infeasible plan because renovation cost exceeds allocated budget of \$12.5M due to additional cost of overtime premiums.

^a Optimal renovation plan generated by developed model.

5.6 Conclusion

A novel model was developed for optimizing the planning of hotel renovation projects that enables hotel owners to maximize hotel revenues during renovation work while minimizing project cost. The present model computations are performed in three main modules: optimization module that searches for and identifies an optimal renovation plan to maximize hotels net profit during any fiscal year; scheduling module that computes the start and finish dates as well as total work disruption time for each renovation activity in all hotels; and hotel profit module that calculates total hotel revenues and total renovation cost for each generated renovation plan in the optimization module. To highlight the novel contributions of the developed model, an application example of three hotels was analyzed. The outcome of this analysis confirms that the developed model was capable of identifying optimal selection of hotels to be renovated during a fiscal year based on allocated renovation budget, optimal floor renovation start date in each hotel, optimal use of overtime hours and number of assigned crews for each renovation activity, and optimal floor renovation order in each hotel. This novel methodology and its original capabilities are expected to provide much-needed support for renovation planners who seek to maximize hotel revenues while minimizing their renovation cost.

CONCLUSION

6.1 Summary

This research study focused on optimizing the planning of building renovation projects. The new research developments of this study include: (1) a novel model for optimizing the planning of leased building renovation projects that enables owners of leased buildings to minimize total renovation cost including rental income losses; (2) an innovative model for optimizing the planning of renovation work in leased buildings that enables contractors working under IPD method to maximize their reward sharing while minimizing total renovation cost; and (3) a novel model for optimizing the planning of hotel renovation projects that enables hotel owners to maximize revenues during renovation work while minimizing project cost.

First, a novel model was developed for optimizing the planning of leased building renovation projects that enables building owners to minimize total renovation cost including rental income losses. To highlight the novel contributions of the developed model, a real-life case study of a residential renovation project was analyzed to enable a comparison between its generated results and those provided by two available models and three current industry practices. The findings of this analysis highlight the main contributions of the model to the body of knowledge including its novel methodology for (1) generating feasible renovation schedules that fully comply with all relevant constraints including units availability dates constraint, (2) selecting an optimal project start date for the renovation of leased buildings, (3) identifying an optimal unit renovation sequence for all leased units, (4) quantifying and minimizing the rental income loss, and (5) minimizing the total renovation cost of leased buildings.

Second, an innovative model was developed for optimizing the planning of renovation work in leased buildings under IPD method. The model enables renovation contractors working

under IPD method to maximize their reward sharing while minimizing total renovation cost. The performance evaluation phase analyzed a real-life case study of three residential renovation projects to enable a comparison between its generated results and those provided by available models. The results of this phase highlighted the original contributions of the optimization model and its novel capabilities in (1) minimizing total renovation cost while maximizing contractor's share of lease income savings for IPD renovation projects, (2) identifying optimal scheduling decisions including crew deployment date for all activities, renovation order of all leased units, and number of assigned crews for each activity in all units; and (3) developing a practical schedule that complies with the availability dates of all renovated units based on their lease end dates and availability of renovation crews.

Third, a novel model was developed for optimizing the planning of hotel renovation projects that enables hotel owners to maximize their revenues during renovation work while minimizing project cost. To highlight the novel contributions of the developed model, an application example of three hotels was analyzed. The outcome of this analysis confirms that the developed model was capable of identifying optimal selection of hotels to be renovated during a fiscal year based on allocated renovation budget, optimal floor renovation start date in each hotel, optimal use of overtime hours and number of assigned crews for each renovation activity, and optimal floor renovation order in each hotel.

6.2 Research Contributions

The main research contributions of this study include:

1. Developing a novel model for optimizing the planning of leased building renovation projects that enables building owners to minimize total renovation cost including rental income losses.

2. Generating feasible renovation schedules that fully comply with all practical constraints including the availability dates of leased units and hotel floors.
3. Quantifying and minimizing rental income losses during the renovation of leased buildings.
4. Developing an innovative model for optimizing the planning of renovation work in leased buildings that enables contractors working under IPD method to maximize their reward sharing while minimizing total renovation cost.
5. Developing an innovative model for optimizing the planning of hotel renovation projects that enables hotel owners to maximize revenues during renovation work while minimizing project cost.

6.3 Future Research Work

Although the present study was able to fully achieve its research objectives, a number of additional research thrusts have been identified during the course of this study, including: (a) developing a model for optimizing the planning of building renovation projects under uncertainty to support owners and contractors in minimizing total project cost; and (b) developing a machine learning methodology to estimate the impact of unforeseen conditions on renovation project cost and duration during the design stage.

6.3.1 Optimizing the planning of building renovation projects under uncertainty

The developed models in Chapters 3, 4 and 5 provide the capability of analyzing and minimizing the disruptive impact of renovation activities on the revenues of leased buildings and hotels through the consideration of a number of practical planning decisions. These developed models can be expanded to consider the impact of uncertainty in labor productivity, weather, site conditions, material deliveries, and equipment availability that are often encountered in renovation projects. To account for that, the formulation of the developed models can be expanded to (1)

model uncertainties associated with the production rates of renovation crews and their deployment dates through the use of Monte-Carlo simulation and/or fuzzy set theory; (2) include additional decision variables such as material procurement and delivery decisions; and (3) utilize historical weather data to account for and model the impact of weather on the planning of renovation work. These expansions are expected to provide much-needed support for renovation planners and enable them to consider the impact of uncertainty during the planning of renovation work in leased buildings and hotels.

6.3.2 Developing a machine learning model for estimating the impact of unforeseen conditions

This proposed future research focuses on developing a machine learning methodology that is capable of estimating the impact of unforeseen conditions on renovation project cost and duration during the early design phase. Many studies have reported that change orders related to unforeseen conditions in renovation projects have significant effect on project cost overruns due to the lack of detailed project design information during the early design phase (Shrestha et al. 2018; Jackson 2004). Accordingly, there is a pressing need to develop a machine learning model that is capable of predicting the impact of unforeseen conditions on renovation project cost and duration during the early design phase. The development of this model requires a number of steps including: (1) gathering historical data on unforeseen project conditions and their impact on final project cost and duration; (2) preparing and organizing the collected data to correct errors, remove duplicates, and address missing values; (3) dividing the collected data into training and testing data sets; (4) training the model using machine learning techniques to enable accurate estimating of the impact of unforeseen project conditions on duration and cost; and (5) evaluating the prediction accuracy of the developed model using the testing data set. This is expected to provide much-

needed support for renovation planners and enable them to estimate the impact of unforeseen conditions that are often encountered in renovation projects on cost and duration during the design stage.

REFERENCES

- Abdallah, M., & El-Rayes, K. (2015). Optimizing the selection of building upgrade measures to minimize the operational negative environmental impacts of existing buildings. *Building and Environment*, 84, 32–43. <https://doi.org/10.1016/j.buildenv.2014.10.010>
- Abdallah, M., Khaled El-Rayes & Liu, L. (2015a). Minimizing Upgrade Cost to Achieve LEED Certification for Existing Buildings. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001053](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001053)
- Abdellatif, M. A., and A. A. E. Othman (2006). "Improving the Sustainability of Low-Income Housing Projects: The Case of Residential Buildings in Musaffah Commercial City in Abu Dhabi." *Emirates Journal for Engineering Research*, vol. 11, no.2, pp. 47-58. Available at <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.492.3472&rep=rep1&type=pdf>
- Abdul Hamid, A., Farsäter, K., Wahlström, Å., & Wallentén, P. (2018). Literature review on renovation of multifamily buildings in temperate climate conditions. *Energy and Buildings*, 172, 414–431. <https://doi.org/10.1016/j.enbuild.2018.04.032>
- Al Sarrig, Z. M. (1990). "Formal Development of Line-of-Balance Technique." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 116(4), 689–704.
- Alanne, Kari (2004). "Selection of Renovation Actions Using Multi-Criteria "Knapsack" Model." *Automation in Construction*, vol. 13, no.3, pp. 377-391. Available at <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.211.4121&rep=rep1&type=pdf>
- AlOtaibi, M., El-Rayes, K., and Altuwaim, A. (2021). "Optimizing the Renovation Scheduling of Leased Residential Buildings to Minimize Total Project Cost." *Journal of Construction Engineering and Management*, 147(7), 1–13.
- Altuwaim, A. A. (2018). "Optimal Scheduling and Resource Utilization for Repetitive." <http://hdl.handle.net/2142/101757>
- Altuwaim, A., & El-Rayes, K. (2018). Automation in Construction Minimizing duration and crew work interruptions of repetitive construction projects. *Automation in Construction*, 88(November 2017), 59–72. <https://doi.org/10.1016/j.autcon.2017.12.024>
- Altuwaim, A., and K. El-Rayes. (2018). "Optimizing the scheduling of repetitive construction to minimize interruption cost." *Constr. Eng.Manage.* 144 (7): 1–12. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001510](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001510).
- American Hotel & Lodging Association. (2021). AHLA's State of the Hotel Industry 2021.
- Ammar, M. A. (2019). "Optimization of line of balance scheduling considering work interruption." *International Journal of Construction Management*, Taylor & Francis, 0(0), 1–12.

- Bakry, I., O. Moselhi, and T. Zayed. (2014). "Optimized acceleration of repetitive construction projects." *Autom. Constr.* 39 (Jan): 145–151. <https://doi.org/10.1016/j.autcon.2013.07.003>.
- Bloom, B. A. N. (2012). "The relationship among guestroom renovation, customer satisfaction, and profitability." *Journal of Hospitality Financial Management*, 20(1), 97–97.
- Bucoń, R., & Sobotka, A. (2015). Decision-Making Model for Choosing Residential Building Repair Variants. *Journal of Civil Engineering and Management*, 21(7), 893–901. <https://doi.org/10.3846/13923730.2014.895411>
- Chantrelle, F. P., Lahmidi, H., Keilholz, W., Mankibi, M. El, & Michel, P. (2011). Development of a multicriteria tool for optimizing the renovation of buildings. *Applied Energy*, 88(4), 1386–1394. <https://doi.org/10.1016/j.apenergy.2010.10.002>
- Cooper, L., and Cooper, M. W. (1981). *Introduction to Dynamic Programming*, Pergamon Press, New York.
- De Luca, P., I. Carbone, and J. B. Nagy (2017). "Green Building Materials: A Review of State-of-the-Art Studies of Innovative Materials." *Journal of Green Building*, vol. 12, no.4, pp. 141–161.
- Dean, Brian, et al. (2016.) "Towards Zero-emission Efficient and Resilient Buildings Global Status Report." *Orbit*. pp. 1–12. Available at https://orbit.dtu.dk/files/127217327/GABC_Global_Status_Report.pdf
- Dwaikat, Luay N. (2017) "Green Buildings Actual Life Cycle Cost Control: A Framework for Investigation." *Journal of Quantity Surveying and Construction Business*, vol. 8, no.1, pp. 1–21. Available at <http://jqscb-my.com/ojs/index.php/jqscb/article/download/24/2>
- Echarri, V., Aldea, F. J., Gómez, J. G., and Romero Del Hombrebueno, J. (2017). "The integrated renovation of high-rise hotels on the Spanish Mediterranean coast." *International Journal of Sustainable Development and Planning*, 12(2), 205–216.
- El Asmar, M., Hanna, A. S., and Loh, W.-Y. (2013). "Quantifying Performance for the Integrated Project Delivery System as Compared to Established Delivery Systems." *Journal of Construction Engineering and Management*, 139(11), 04013012.
- Elghaish, F., Abrishami, S., and Hosseini, M. R. (2020). "Integrated project delivery with blockchain: An automated financial system." *Automation in Construction*, Elsevier, 114(March), 103182.
- El-Rayes, B. K. (2001). "Optimum Planning of Highway Construction A/B Bidding Method." *Construction Engineering and Management*, 127(August), 261–269.
- El-Rayes, K., and O. Moselhi. (2001). "Optimizing Resource Utilization for Repetitive Engineering." *J. Constr. Eng. Manage.* 127 (1): 18–27. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2001\)127:1\(18\)](https://doi.org/10.1061/(ASCE)0733-9364(2001)127:1(18)).

- Engebo, A., Klakegg, O. J., Lohne, J., and Lædre, O. (2020). "A collaborative project delivery method for design of a high-performance building." *International Journal of Managing Projects in Business*, 13(6), 1141–1165.
- Evangelista, Patricia PA, et al. (2018). "Environmental Performance Analysis of Residential Buildings in Brazil Using Life Cycle Assessment (LCA)." *Construction and Building Materials*, vol. 169, no. 1, pp. 748-761.
- Fan, S. L., K. S. Sun, and Y. R. Wang. (2012). "GA optimization model for repetitive projects with soft logic." *Autom. Constr.* 21 (1): 253–261. <https://doi.org/10.1016/j.autcon.2011.06.009>.
- Fan, S.-L., and Lin, Y.-C. (2007). "Time-Cost Trade-Off In Repetitive Projects With Soft Logic." *Computing in Civil Engineering*.
- Farahani, A., Wallbaum, H., & Dalenbäck, J.-O. (2018). Construction Management and Economics Optimized maintenance and renovation scheduling in multifamily buildings-a systematic approach based on condition state and life cycle cost of building components. <https://doi.org/10.1080/01446193.2018.1512750>
- Fiedler, K. (1987). "Special conditions for time scheduling of building modernization process." *International Journal of Project Management*, 5(1), 35–38.
- Galiotto, N., Heiselberg, P., and Knudstrup, M. A. (2015). "The integrated renovation process: Application to family homes." *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 168(6), 245–257.
- Ghassemi, R., and Becerik-Gerber, B. (2011). "Transitioning to integrated project delivery: Potential barriers and lessons learned." *Lean Construction Journal*, 2011, 32–52.
- Gómez-Soberón, José Manuel, et al. (2018). "Fresh-state Properties of Mortars With Recycled Glass Aggregates: Global Unification of Behavior." *Advances in Materials Science and Engineering*, pp. 10-32. Available at <https://www.hindawi.com/journals/amse/2018/1386946/>
- Grussing, M. N., Asce, M., and Liu, L. Y. (2014). "Knowledge-Based Optimization of Building Maintenance, Repair, and Renovation Activities to Improve Facility Life Cycle Investments."
- Hassan, A., & El-Rayes, K. (2019). Quantifying the interruption impact of activity delays in non-serial repetitive construction projects. *Construction Management and Economics*, 0(0), 1–19. <https://doi.org/10.1080/01446193.2019.1657922>
- Hassanien, A. (2006). "Exploring hotel renovation in large hotels: A multiple case study." *Structural Survey*, 24(1), 41–64.
- Hassanien, A. (2007). "Exploring the relationship between hotel renovation and hotel inspection." *International Journal of Hospitality and Tourism Administration*, 8(4), 1–21.

- Hassanien, A., and Baum, T. (2002). "Hotel Innovation Through Property Renovation." *International Journal of Hospitality & Tourism Administration*, 3:4(2008), 5–24.
- Hassanien, A., and Losekoot, E. (2002). "The application of facilities management expertise to the hotel renovation process." *Facilities*, 20(7), 230–238.
- Hegazy, T., and N. Wassef. (2001). "Cost optimization in projects with repetitive nonserial activities." *J. Constr. Eng. Manage.* 127 (3): 183–191. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2001\)127:3\(183\)](https://doi.org/10.1061/(ASCE)0733-9364(2001)127:3(183)).
- Hegazy, T., and Kamarah, E. (2007). "Efficient Repetitive Scheduling for High-Rise Construction." *Construction Engineering and Management*.
- Hegazy, T., Moselhi, O., and Fazio, P. (1993). "BAL: An algorithm for scheduling and control of linear projects." *Proc., Transactions of the 1993 Association for the Advancement of Cost Engineering 37th Annual Meeting, Association for the Advancement of Cost Engineering Int., Morgantown, W.V., C.8.1–C.8.14*.
- Huang, Beijia, et al. (2019). "Embodied GHG Emissions of Building Materials in Shanghai." *Journal of Cleaner Production*, vol. 210, no. 1, pp. 777-785. Available at <https://www.sciencedirect.com/science/article/pii/S0959652618334309>
- Huang, Haihong, et al. (2011) "Multi-Criteria Decision Making and Uncertainty Analysis for Materials Selection in Environmentally Conscious Design." *The International Journal of Advanced Manufacturing Technology*, vol. 52, no.5-8, pp. 421-432.
- Hyari, K. H., K. El-Rayes, and M. El-Mashaleh. (2009). "Automated Trade-Off Between Time and Cost in Planning Repetitive Construction Projects." *Constr. Manage. Econ.* 27 (8): 749–761. <https://doi.org/10.1080/01446190903117793>.
- Hyari, K., and El-Rayes, K. (2005). "Optimal Planning and Scheduling for Repetitive Construction Projects." *Management in Engineering*, 22(1), 11–19.
- Hyari, K., and K. El-Rayes. (2006). "Optimal Planning and Scheduling For Repetitive Construction Projects." *J. Manage. Eng.* 22 (1): 11–19. [https://doi.org/10.1061/\(ASCE\)0742-597X\(2006\)22:1\(11\)](https://doi.org/10.1061/(ASCE)0742-597X(2006)22:1(11)).
- Ihsan, B., and Alshibani, A. (2018). "Factors affecting operation and maintenance cost of hotels." *Property Management*, 36(3), 296–313.
- Ipsilandis, P. G. (2007). "Multiobjective Linear Programming Model for Scheduling Linear Repetitive Projects." *J. Constr. Eng. Manage.* 133 (6): 417–424. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2007\)133:6\(417\)](https://doi.org/10.1061/(ASCE)0733-9364(2007)133:6(417)).
- Janjua, Shahana Y., Prabir K. Sarker, and Wahidul K. Biswas (2019). "A Review of Residential Buildings' Sustainability Performance Using a Life Cycle Assessment Approach." *Journal of Sustainability Research*, vol. 1, no. 1, pp. 1-8. Available at https://www.hapres.com/htmls/JSR_1038_Detail.html

- Jackson, B. J. 2004. Construction management jumpstart. 2nd ed. San Francisco, CA: Sybex.
- Jaskowski, P., and Biruk, S. (2020). "Scheduling of Repetitive Construction Processes With Concurrent Work of Similarly Specialized Crews." *Journal of Civil Engineering and Management*, 26(6), 579–589.
- Jensen, P. A., and Maslesa, E. (2015). "Value based building renovation – A tool for decision-making and evaluation." *Building and Environment*, 92, 1–9.
- Jeunesse, E. (2019). Healthy home remodeling: Consumer trends and contractor preparedness. Cambridge, MA: Joint Center for Housing Studies of Harvard Univ.
- Karatas, A., & El-Rayes, K. (2016). "Optimal Trade-Offs Between Housing Cost and Environmental Performance". *Journal of Architectural Engineering*, 22(2), 1–9. [https://doi.org/10.1061/\(ASCE\)AE.1943-5568.0000199](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000199)
- Kent, D. C., and Becerik-Gerber, B. (2010). "Understanding Construction Industry Experience and Attitudes toward Integrated Project Delivery." *Journal of Construction Engineering and Management*, 136(8), 815–825.
- Khalafallah, A., Asce, M., and Shalaby, Y. (2019). "Change Orders: Automating Comparative Data Analysis and Controlling Impacts in Public Projects."
- Lahdenperä, P. (2012). "Making sense of the multi-party contractual arrangements of project partnering, project alliancing and integrated project delivery." *Construction Management and Economics*, 30(1), 57–79.
- Lawania, Krishna, and Prabir Sarker (2015). "Global Warming Implications of The Use Of By-Products And Recycled Materials in Western Australia's Housing Sector." *Materials*, vol. 8, no. 10, pp. 6909-6925. Available at <https://www.mdpi.com/1996-1944/8/10/5347/pdf>
- Lee, H.-Y. (2011). "Renovation scheduling to minimize user impact of a building that remains in operation." *Autom. Constr.* 22 (Mar): 398–405. <https://doi.org/10.1016/j.autcon.2011.09.018>.
- Li, Guo-Dong, Daisuke Yamaguchi, and Masatake Nagai (2007). "A grey-based Decision-Making Approach to the Supplier Selection Problem." *Mathematical and Computer Modelling*, vol. 46, no.3-4, pp. 573-581. Available at <https://www.sciencedirect.com/science/article/pii/S0895717706004298>
- Liu, L. (2017). "A systematic approach for major renovation of residential buildings"
- Liu, S. S., and C. J. Wang. (2007). "Optimization model for resource assignment problems of linear construction projects." *Autom. Constr.* 16 (4): 460–473. <https://doi.org/10.1016/j.autcon.2006.08.004>.
- Lombard, Richard (2017). "It's not Easy Being Green: Difficulties in Sourcing Sustainable Building Materials." *QScience Connect*, vol. 2017, no. 2, pp. 10. Available at <https://www.qscience.com/content/journals/10.5339/connect.2017.qgbc.10?crawler=true>

- Long, L. D., and A. Ohsato. (2009). "A Genetic Algorithm-Based Method for Scheduling Repetitive Construction Projects." *Autom. Constr.* 18 (4): 499–511. <https://doi.org/10.1016/j.autcon.2008.11.005>.
- Lumsden, P. (1968). *The Line-of-balance method*, London: Pergamon Press Ltd.
- Lutz, J., and Halpin, D. (1992). "Analyzing linear construction operations using simulation and line of balance." *Transportation Research Record*, (1351), 48–56.
- Mahdi, I. M., and Alreshaid, K. (2005). "Decision support system for selecting the proper project delivery method using analytical hierarchy process (AHP)." *International Journal of Project Management*, 23(7), 564–572.
- Mattila, K. G., & Abraham, D. M. (1998). Linear scheduling: past research efforts and future directions. *Engineering, Construction and Architectural Management*, 5(3), 294–303. <https://doi.org/10.1108/eb021083>
- Meerendonk, P. van. (2014). "Maximizing Hotel Profits Even While Renovating." *Hospitality Net Organization*, 1–6.
- Mihindu, Sas, and Yusuf Arayici (2008). "Digital Construction Through BIM Systems Will Drive the Re-engineering of Construction Business Practices." 2008 International Conference Visualisation. IEEE.
- Monghasemi, S., and Abdallah, M. (2021). "Linear Optimization Model to Minimize Total Cost of Repetitive Construction Projects and Identify Order of Units." *Journal of Management in Engineering*, 37(4), 1–15.
- Muryadi, A. D., and Christensen, Clayton M., Bower, J. L. (1994). "Choosing Appropriate Construction Contracting Method." *Journal of Construction Engineering*, 843(4), 963–964.
- Nanu, L., Ali, F., Berezina, K., and Cobanoglu, C. (2020). "The effect of hotel lobby design on booking intentions: An intergenerational examination." *International Journal of Hospitality Management*, 89(April).
- Nielsen, A. N., Jensen, R. L., Larsen, T. S., & Nissen, S. B. (2016). Early stage decision support for sustainable building renovation – A review. *Building and Environment*, 103, 165–181. <https://doi.org/10.1016/j.buildenv.2016.04.009>
- Park, C. Y. (2017). "Managing tenant movement scenarios based on tenant satisfaction during occupied renovation activities." Master's thesis, Dept. of Architecture and Architectural Engineering, College of Engineering/Engineering Practice School.
- Penner, R. H. (1996). "Hotel Renovation Planning & Design." *Cornell Hotel and Restaurant Administration Quarterly*, 37(4), 9–9.

- Pillai, Radhakrishna G., et al. (2019). "Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3)." *Cement and Concrete Research*, vol. 118, no. 1, pp. 111-119.
- Pishdad-Bozorgi, P., and Srivastava, D. (2018). "Assessment of integrated project delivery (IPD) risk and reward sharing strategies from the standpoint of collaboration: A game theory approach." *Construction Research Congress 2018: Construction Project Management - Selected Papers from the Construction Research Congress 2018*, 2018-April, 196–206.
- Potter, B. (2020). *Every building in America - an analysis of the US Building Stock*. Brian Potter. Retrieved October 20, 2021, from <https://constructionphysics.substack.com/p/every-building-in-america-an-analysis>.
- Rosenfeld, Y., & Shohet, I. M. (1999). Decision support model for semi-automated selection of renovation alternatives. *Automation in Construction*, 8(4), 503–510. [https://doi.org/10.1016/S0926-5805\(98\)00097-1](https://doi.org/10.1016/S0926-5805(98)00097-1)
- Russell, A. D., and W. F. Caselton. (1988). "Extensions to linear scheduling optimization." *J. Constr. Eng. Manage.* 114 (1): 36–52. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1988\)114:1\(36\)](https://doi.org/10.1061/(ASCE)0733-9364(1988)114:1(36)).
- Salama, T., and O. Moselhi. (2019). "Multi-objective optimization for repetitive scheduling under uncertainty." *Eng. Constr. Archit. Manage.* 26 (7): 1294–1320. <https://doi.org/10.1108/ECAM-05-2018-0217>.
- Selinger, S. (1980). "CONSTRUCTION PLANNING FOR LINEAR PROJECTS." *Journal of the Construction Division, ASCE*, 106(2), 195–205.
- Shiue, F. J., Zheng, M. C., Lee, H. Y., Khitam, A. F. K., and Li, P. Y. (2019). "Renovation construction process scheduling for long-term performance of buildings: An application case of university campus." *Sustainability (Switzerland)*, 11(19).
- Shrestha, P. P., Asce, M., and Zeleke, H. (2018). "Effect of Change Orders on Cost and Schedule Overruns of School Building Renovation Projects."
- Shrestha, P. P., Asce, M., Kabindra, Shrestha, K., Asce, S. M., and Kandie, T. K. (2017). "Effects of Change Orders on the Cost and Schedule of Rural Road Maintenance Projects."
- Srisuwanrat, C. (2009). *The Sequence Step Algorithm a Simulation-Based Scheduling Algorithm For Repetitive Projects With Probabilistic Activity Durations*. The University of Michigan.
- Su, G., Hastak, M., Deng, X., and Khallaf, R. (2021). "Risk Sharing Strategies for IPD Projects: Interactional Analysis of Participants' Decision-Making." *Journal of Management in Engineering*, 37(1), 04020101.
- Thabet, W. Y., and Beliveau, Y. J. (1994). "Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings." *Journal of Construction Engineering and Management, American Society of Civil Engineers*, 120(1), 96–116.

- Turner, M. J., and Hesford, J. W. (2019). "The Impact of Renovation Capital Expenditure on Hotel Property Performance." *Cornell Hospitality Quarterly*, 60(1), 25–39.
- U.S. Energy Information Administration - EIA - Independent Statistics and Analysis- "How much energy is consumed in U.S. residential and commercial buildings?" <https://www.eia.gov/tools/faqs/faq.php?id=86&t=1>, 2018.
- US Census Bureau. (2019). "2015-2019 American community survey 5-year estimates." Accessed March 16, 2021. <https://www.census.gov/search-results.html?searchType=web&cssp=SERP&q=residential%20units>.
- Whiteman, W. E., and H. G. Irwig. (1988). "Disturbance scheduling technique for managing renovation work." *J. Constr. Eng. Manage.* 114 (2): 191–213. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1988\)114:2\(191\)](https://doi.org/10.1061/(ASCE)0733-9364(1988)114:2(191)).
- Wu, Shaomin, et al. (2006). "Reliability in the Whole Life Cycle of Building Systems." *Engineering, Construction and Architectural Management*, vol. 13, no. 2, pp. 136-153. Available at <https://kar.kent.ac.uk/31023/1/JournalPaperV13.pdf>
- Yang, I., & Ioannou, P. G. (2004). "Scheduling system with focus on practical concerns in repetitive projects." *Construction Management and Economics*, 22(6), 619–630. <https://doi.org/10.1080/01446190310001649065>
- Yee, P., Fischer, M., Haymaker ; Yee, J., Fischer, P., and Haymaker, M. (2013). "Automated identification of occupant interactions in renovations of occupied buildings." *Journal of Information Technology in Construction (ITcon)*.
- Zuo, Jian, and Zhen-Yu Zhao. (2014). "Green Building Research—Current Status and Future Agenda: A Review". *Renewable and Sustainable Energy Reviews*, vol. 30, no. 1, 2014, pp. 271-281.