

**STOCHASTIC MODEL FOR OPTIMIZING THE PLANNING
OF LEASED BUILDING RENOVATION WORK**

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

**CONSTRUCTION ENGINEERING
AND MANAGEMENT**

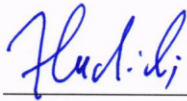
MAY 2023

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

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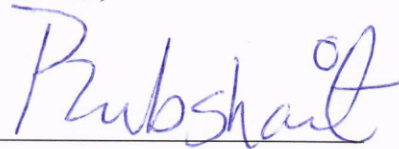
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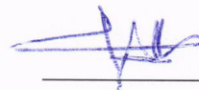


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This research work is sincerely dedicated to all my family members whom have greatly inspired me and helped the personality that I am today. To my wife, who has been the main source of my courage in support throughout this journey, as well as to all of my siblings and friends.

ACKNOWLEDGMENTS

Foremost, I would like to express my sincere appreciation and gratitude to my advisor Dr. Laith A. Al-Hadidi for his continuous assistance of my MS research and study, motivation, immense knowledge. Along with my advisor, I would like to thank the rest of my thesis committee: Prof. Abdullaziz Bubshait, and Dr. Adel Alshibani, for their feedbacks, motivation, and questions. My sincere thanks extends to Dr. Mansour AlOtaibi, who served as my advisor throughout the entire research thesis project. It is a heart to know that he left the university. However, his impact on my academic growth will be left for years to come, and guidance that guided me for the time of this research thesis. Thanks also goes to Dr. Abbas Hassan, for his guidance and knowledge in the python platform. Last but not the least, I would like to appreciate everyone who has assisted me in obtaining the required information.

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ABSTRACT

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Thesis Title : Stochastic Model for Optimizing the Planning Of Leased Building Renovation Work
Major Field : Construction Engineering and Management
Date of Degree : March 2023

This research study presents the development of an innovative stochastic model for optimizing the planning of leased building renovation work to minimize total expected renovation cost while considering uncertainty in crew output. The proposed model utilizes Monte Carlo simulation and Non-dominated Sorting Genetic Algorithm II to (1) consider uncertainties associated with the daily output rates of renovation crews; and (2) identify optimal number of practical decision variables including renovation work sequence, start date, and crew formation of each activity in the leased renovation project that minimize total expected renovation cost including annual lease losses. A real-life case study of a renovation project is analyzed to demonstrate the model practical capabilities and compare its generated results to those provided by two available models. The outcome of this analysis confirms that the proposed stochastic model outperformed available models and prove the contributions of the proposed model to the existing body of knowledge. These novel and practical capabilities of the proposed model are expected to provide decision-makers of leased buildings the needed assistance to minimize the total expected renovation cost while accounting for inherent project risks.

ملخص الرسالة

الاسم الكامل	:	كرامه عبدالله كرامه باخریصة
عنوان الرسالة	:	نموذج مقترح لتحسين التخطيط لأعمال تجديد المباني المستأجرة مع الأخذ في الاعتبار عدم اليقين بشأن معدل إنتاج طاقم العمل
التخصص	:	إدارة المشاريع الإنشائية
تاريخ الدرجة العلمية	:	مارس 2023

تعرض هذه الدراسة البحثية تطوير نموذج مبتكر لتحسين التخطيط لأعمال تجديد المباني المؤجرة لتقليل إجمالي تكلفة التجديد المتوقعة مع الأخذ في الاعتبار عدم اليقين بشأن معدل إنتاج طاقم العمل. يستخدم النموذج المقترح محاكاة (Monte Carlo Simulation) و (Non-dominated Sorting Genetic Algorithm II) من أجل: (1) مراعاة أوجه عدم اليقين المرتبطة بمعدلات الإنتاج اليومية لطاقم التجديد؛ و (2) تحديد العدد الأمثل لمتغيرات القرار العملي بما في ذلك تسلسل أعمال التجديد وتاريخ البدء وتكوين الطاقم لكل نشاط في مشروع التجديد المؤجر لتقليل إجمالي تكلفة التجديد المتوقعة بما في ذلك خسائر الإيجار السنوية. يتم تحليل دراسة حالة واقعية لمشروع التجديد لإثبات القدرات العملية للنموذج ومقارنة النتائج الناتجة عن تلك التي يوفرها نموذجان متاحان. تؤكد نتيجة هذا التحليل أن النموذج المقترح تفوق في الأداء على النماذج المتاحة وإثبات مساهمات النموذج المقترح في الواقع. من المتوقع أن توفر هذه القدرات الجديدة والعملية للنموذج المقترح لصانعي القرار في المباني المستأجرة المساعدة اللازمة لتقليل إجمالي تكلفة التجديد المتوقعة مع مراعاة المخاطر الكامنة في المشروع.

CHAPTER 1 INTRODUCTION

1.1 Overview and Statement Problem

The number of leased units in Saudi Arabia was stated to be around 4 million in 2019 (Housing Statistics Bulletin, 2019). According to Saudi General Authority for Statics (2019), 45% of these existing buildings are aging and in need of renovation, as shown in Figure 1. As a result, the renovation expenditures on leased building projects have been increasing in recent years (Jeddah Chamber, 2016).

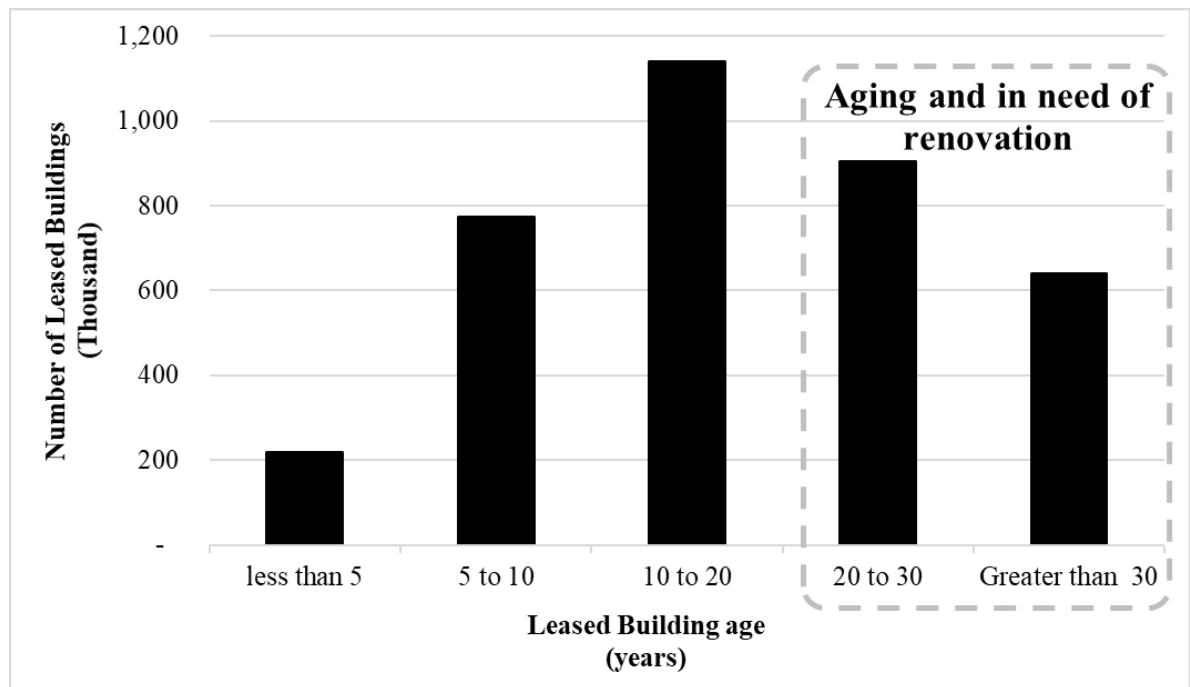


Figure 1: Age Distribution of Leased Units in Saudi Arabia

However, many leased building owners are resisting the idea of renovating their buildings when knowing that these renovations frequently result in a significant drop in the annual lease income since they are required to evacuate during the renewal work (Park, 2017). To address this challenge, a number of available scheduling models are capable of generating renovation plans that quantity and minimize the losses in the lease income of these leased buildings (AlOtaibi et al., 2021; Hassanien & Baum, 2008; Park, 2017). However, renovation projects are often behind the planned schedule since available renovation scheduling models are incapable of considering and simulating the uncertainty

associated with renovation work. Accordingly, a stochastic model capable of assessing and reducing the impact of uncertainty on planning of leased building renovation project is needed.

This recent increase in the leased building renovation work is confronting decision-makers with a two of evolving challenges, including how to: (1) simulate the planning of leased building renovation work under uncertainty; and (2) optimize the leased building renovation planning to minimize total renovation cost including annual lease income losses, as shown in Figure 2:

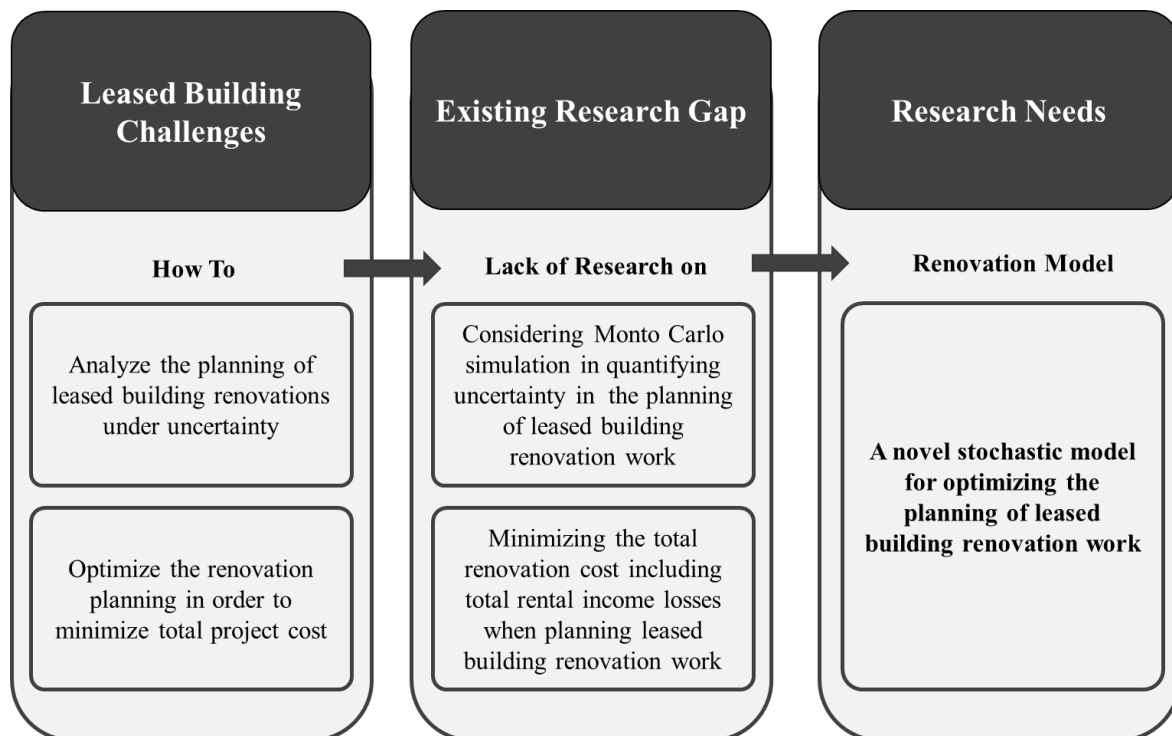


Figure 2: Leased Building Renovation Challenges and Research Needs

Available studies were carried out to: (1) optimize the planning of repetitive construction projects (Altuwaim & El-Rayes, 2018; Ammar, 2012; Ammar & Elbeltagi, 2001; Harris & Ioannou, 1998; Moselhi et al., 2016); (2) analyze the negative effects of renovation activities on building occupants (AlOtaibi et al., 2021A ; AlOtaibi et al., 2021 B; Hassanien & Baum, 2008; Karatas & El-Rayes, 2016; Park, 2017); and (3) Construction project scheduling under the uncertainty (Bakry et al., 2016; A. Hassan et al., 2020; J E Okema, 2000; Kwak & Ingall, 2007; Migilinskas & Ustinovičius, 2008; Öztaş & Ökmen, 2005; Salama & Moselhi, 2019). Despite the importance of the aforementioned

research projects, no study has been published that tackles the aforementioned issues, as shown in Figure 2.

1.2 Objective

The goal of this study is to create a new stochastic model for optimizing the planning of leased building renovation work under uncertainty, in order to overcome the limits of previous research. The study's research aims and related questions are summarized as follow to attain this goal:

First objective: Conducting a literature evaluation of the most recent literature on: (1) optimizing the planning of repetitive construction project, (2) assessing the negative impact of renovation operations on building occupants, and (3) construction project scheduling under uncertainty.

Research Questions: (1) What are the most recent research studies on leased building renovations? (2) What are the most recent research studies on uncertainty in building projects? (3) What are the capabilities and limitations of present leased building renovation techniques? (4) What are the most up-to-date repetitive scheduling strategies for renovation projects? (5) What are the effective optimization approaches for leased building project planning?

Second objective: Develop a stochastic optimization model for the planning of renovation work in leased buildings that will provide the capabilities to: (a) consider the uncertainty in crew daily output rates; and (b) find the optimal start date and crew formation for each renovation activity, as well as the optimal unit renovation order for all leased units, in order to minimize the total expected renovation cost for the project.

Research Questions: (1) What is the suitable available technique to consider and analyze uncertainty in crew daily output rates; (2) What are the possible decision variables that must be addressed and optimized in this problem?; (3) How can an optimization objective function for minimizing overall project cost be developed?; and (4) How can the performance of the created model be evaluated and validated?

1.3 Methodology

A detailed research approach is designed to meet the aforementioned study objectives, as illustrated in Figure 3. The approach planned consists of two tasks that are intended in: (1) conducting a complete literature evaluation on the most recent and related research on planning and risk assessment of leased buildings renovation projects; and (2) developing a stochastic optimization model for plans of renovation work in leased buildings.

Task one: Conduct a detailed review of the literature

The goal of this section is to create strong point of foundation for the proposed study, carry out a detailed review of the literature on the most recent study on planning and risk for leased buildings renovation in order to get a foundational understanding for existing research and methods. The components of this research task are detailed in the subtasks below and illustrated in Figure 3:

- 1.1. Discuss the most recent research studies on leased building renovations.
- 1.2. Discuss available research studies related to the uncertainty in plans of construction buildings.
- 1.3. Identify capabilities and limitations for available leased building renovation models and techniques.
- 1.4. Review the most up-to-date models related to repetitive construction projects.
- 1.5. Investigate effective optimization approaches for leased building project planning.

Task two: Develop a stochastic optimization model for planning of leased buildings renovation work

The goal of this section is to create a stochastic optimization model for plans of renovation work in leased buildings taking into account uncertainty associated with crew production rates and identify optimal start date for each renovation activity as well as optimal unit renovation order for all leased units through minimizing the total renovation cost including direct, indirect, interruption and lease income losses cost. The components of this research task are detailed in the subtasks below and illustrated in Figure 3:

- 2.1. Gather historical data on the uncertainty in crew daily output rates when working in building renovation projects.
- 2.2. Identify the possible decision variables that must be addressed and optimized in this problem.
- 2.3. Discuss the formulation of the optimization objective function to minimize total project cost.
- 2.4. Investigate the most optimization and stochastic techniques that are suitable to develop renovation plans for leased building under uncertainty.
- 2.5. Validate the optimization model's performance.

Task One: Conduct a review of the literature

- 1.1. Discuss the most recent research studies on leased building renovations.
- 1.2. Discuss available research studies related to the uncertainty in plans of construction buildings.
- 1.3. Identify capabilities and limitations for available leased building renovation models and techniques.
- 1.4. Review the most up-to-date models related to repetitive construction projects.
- 1.5. Investigate effective optimization approaches for leased building project planning

Task Two: Develop a novel stochastic optimization model for the planning of renovation work in leased buildings

- 2.1. Gather historical data on the uncertainty in crew daily output rates when working in building renovation projects.
- 2.2. Identify the possible decision variables and constraints that must be addressed and optimized in this problem.
- 2.3. Discuss the formulation of the optimization objective function to minimize total project cost.
- 2.4. Investigate the most optimization and stochastic techniques that are suitable to develop renovation plans for leased building under uncertainty.
- 2.5. Validate the optimization model's performance.

Figure 3: Research Tasks

1.4 Importance of Study

The study proposes a stochastic model which provide the planners of renovation with the following capabilities: (1) considering and analyzing risks and uncertainties faced during the planning of leased building renovation work; (2) selecting optimal crew formation and optimal start date of each renovation activity; (3) identifying optimal work sequence for leased renovation units; (4)

estimating and reducing the lease income losses; and (5) minimizing overall cost for renovation including direct, indirect, interruption and lease income losses cost. Accordingly, these distinct capabilities are likely to offer the renovation planners with desirable assistance in order to consider and analyze uncertainty during the planning of leased building renovation work in terms of getting minimum total project cost.

1.5 Organization of Report

This research study will be organized as following:

Chapter 1: covers the introduction of the thesis topic including: (1) overview and problem statement; (2) research objectives; and (3) research methodology of the topic.

Chapter 2: A detailed review of the literature presented in this chapter. This literature study will provide a foundation about the most recent studies on (1) the planning of building renovation projects; (2) uncertainty associated in leased building renovations; (3) capabilities and limitations of present leased building renovation techniques; (4) repetitive scheduling strategies for renovation projects; and (5) the effective optimization approaches for leased building project planning.

Chapter 3: Development of a proposed model that utilizes Monte Carlo simulation and Non-dominated Sorting Genetic Algorithm II to: (1) consider uncertainties associated with the daily output rates of renovation crews; and (2) identify optimal number of practical decision variables including renovation work sequence, start date, and crew formation of each activity in the leased renovation project that minimize total expected renovation cost including annual lease losses. The results of the proposed model and two available models are then presented and compared to demonstrate the proposed model's contributions and its ability to outperform existing models in: (1) considering the uncertainty of the output rate of crews; and (2) determining the optimal work sequence for all lease renovation units

Chapter 4: Conclusion of the research study and some recommendations for future research areas.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

According to the Saudi General Authority for Statics (Housing Statistics Bulletin, 2019), 45% of Saudi Arabia's existing buildings are aged and are in need of renovation as shown in Figure 1. Leased building renovation has increased steadily over the last five years, in accordance with the construction industry's expansion over the last decade (Jeddah Chamber, 2016). As a result, a number of studies have been done to improve building renovation, with a particular focus on developing risk assessment and uncertainty in construction claims, hotel renovations, and schedule plans. The goal of this chapter is to produce strong point of foundation for the proposed study, carry out a detailed review of the literature on the most recent study on planning and risk for leased buildings renovation in order to get a foundational understanding for existing research and methods of the most recent research studies on leased building renovations, uncertainty in building projects, the capabilities and limitations of present leased building renovation techniques, repetitive scheduling strategies for renovation projects, and effective optimization approaches for leased building project planning. The following sections of this chapter present a comprehensive literature review that is organized as follow: (1) risk assessment and uncertainty in leased building renovation projects; (2) Monte Carlo simulation in construction projects; (3) existing building renovation projects; (4) scheduling techniques for construction projects; and (5) limitations of existing models and research needs.

2.2 Risk Assessment and Uncertainty in Leased Building Renovation Projects

A risk is defined to be "unpredictable occurrence or circumstance which, if happened, has a negative or positive influence on the project objective on at least one" (Lutolf, 1977). Which means that a risk is divided into two quantities: the probability and impact of occurrence. Technical, external, internal, and organizational activities are all types of risk. Risk management requires the modeling and quantification of risk. Maintaining realistic project plan that schedules multiple tasks is required for project management success (Hulett, 2016). Risk detection, evaluation, documentation, and response are all part of the risk management process (Abhi Basu, 1998). A good schedule should estimate the project's completion deadlines. However, a fair project plan is difficult task since the

scheduling criteria are unclear to the planner, especially with unrealistic deadlines and unknown activity durations according to Hulett (2016). Even the most experienced project managers cannot properly forecast when a project will be completed since no two projects are alike. Furthermore, the characteristics of current construction projects are frequently complex. According to Cooper et al. (2021), unforeseen circumstances lead the majority of construction projects to run late or even fail to meet their deadlines. Approximately 80% of projects have a significant level of uncertainty at the start of construction. As a result, an increasing number of project managers are recognizing the consequence of project schedule uncertainty. Subsequently, when faced with unanticipated circumstances, project managers learn to view risk management as a necessary evil as stated by Laufer, A. and Howel (1993).

To imitate the building process in the 1950s, quantitative network modeling approaches were applied. Network diagram approaches may be used to identify activity links and aid in the planning and coordination of building projects. Though, another researcher (Birrell, 1980) pointed out that the critical path method (CPM) uses a single number to estimate each activity, and even the whole construction, ignoring the effects of uncertainty. CPM presupposes that any action has just one potential results and that it will be done successfully. In reality, an excess of potential outcomes for a given behavior, each with its own set of effects. Furthermore, in most situations, the chance of critical path methodology (CPM)-calculated activity durations achieving the goal was less than 25% (Hulett, 2016). Lately, (PERT), the program evaluation and review technique, underestimated schedule risk, ignoring the potential hazard provided by PERT-slack pathways.

PERT was only interested in the longest PERT-critical path. According to Birrell, 1980; Kong et al. (2015). PERT activity durations were practically smaller than the actual statistic mean, with a 30% variation. Furthermore, typical scheduling methods neglect the project's unpredictable and dangerous environment. As a result, network-based planning approaches have been shown to be insufficient for doing realistic risk analysis in scheduling. A more extensive scheduling procedure with explicit awareness and assessment of project uncertainty is necessary to develop an efficient schedule. One of these techniques are called Monte Carlo which consider the uncertainty.

2.3 Monte Carlo simulation in construction projects

Monte Carlo simulation was first developed in the 1940s and is now available due to software, such as Primavera, Crystal Ball, and RISK. Monte Carlo Simulation, is also known as Monte Carlo technique or multiple probability modeling, which also a mathematical approach for estimating the consequences of an uncertain event (Öztaş & Ökmen, 2005). It was created by Stanislaw Ulam and John von Neumann during World War II to help people make better decisions in difficult situations and named after Monaco, a well-known casino town, since the modeling approach relies heavily on chance, comparable to a game of roulette (Eckhardt, n.d.; Metropolis & Ulam, 1949). It was named after a well-known casino town, called Monaco, as the element of chance is key to the modeling technique, comparable to a game called roulette (Metropolis & Ulam, 1949). For many years, Monte Carlo Simulation involved in a variety of social spheres logistical, and industrial. Monte Carlo simulations have lately been used by project managers to anticipate project completion dates and costs (Kwak & Ingall, 2007; Williams, 2003). By computing the CPM schedule several times, it can compute the completion date of the project based on all possible arrangements of unknown activity durations. The project model is iterated several times in Monte Carlo simulation. For each cycle, the input are picked randomly from the probability distributions, for example. activity durations (Vose, 1996).

Monte Carlo simulation has the benefit over other approaches in that it seeks to include uncertainty “the restrictive assumptions making them unusable in any actual scenario” (Williams, 2003) for a chosen random variables. Using probability distributions, these variables can have varying probability of different events occurring. These probability distributions provide a more realistic approach to express uncertainty in risk analysis variables. The following are illustrations probability distributions that are commonly used: (1) normal; (2) uniform; (3) triangular; and (4) lognormal. Figure 4 illustrate these common probability distributions.

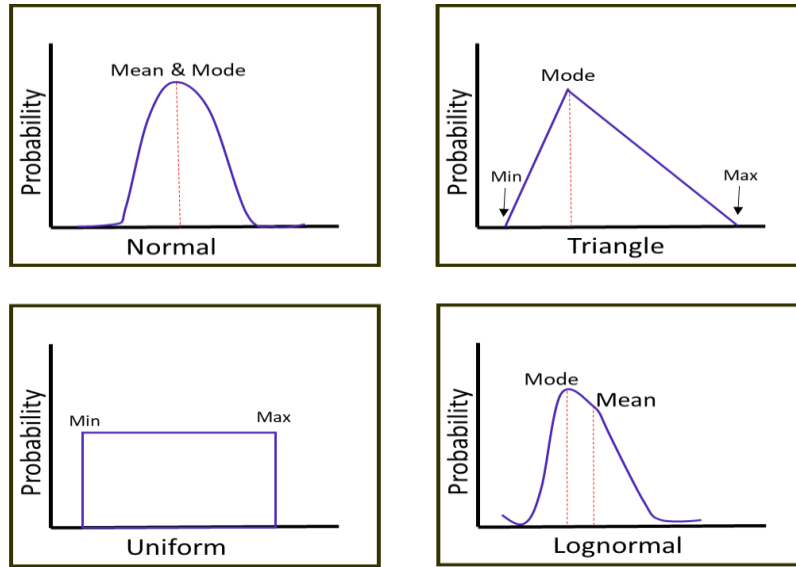


Figure 4: Common Probability Distributions

2.4 Existing Building Renovation Projects

Renovations account for a significant portion of all building activity. Since leased building renovation has increased steadily over the last five years, in accordance with the construction industry's expansion over the last decade as stated by Jeddah Chamber (2016). Renovation projects encounter unique complications not seen in new building, for example: physical restrictions owing to present facilities, such as restricted area or ability limits of present systems, poor accessibility to work zone, and uncertainty regarding the current situation. Building renewal are more difficult to complete since elements of the building must stay functioning while the work is being done according to Krizek et al. (1996). Available studies were carried out to: (1) optimize the planning of repetitive construction projects; (2) analyze the negative effects of renovation activities on building occupants; and (3) Construction project scheduling under the uncertainty.

The first group of these available research papers focused on optimizing the planning of repetitive renovation projects. For example, Altuwaim & El-Rayes (2018) designed a novel model utilizing a two-step process to reduce interruption costs, crew work interruptions, and duration of the renovation project. Ammar (2012) developed a methodology that combines CPM and LOB in order

to schedule building renovation projects with the same repetitive units. This model's computations are carried out in the following steps: (CPM) for scheduling the subnet model which only contains the initial unit in each repeated activity while keeping the least buffer duration; (LOB) for identifying the total duration and number of necessary crews of each activity; defining precedence while keeping the crew consistency in mind for determining the lag time among activities; Computing the network's forward and backward passes, using these activity in all repeating units as a single unit to compute the earliest and latest feasible timings. Ammar & Elbeltagi (2001) designed a scheduling model for multi-unit building projects where activities are repeated from one unit to the subsequent one. This model uses the critical path method network of a single unit and takes into account constraints on both resource continuity and logic. Schedules for these projects require guarantee of the uninterrupted use for resources from the same activity in two consecutive units while sustaining logic restrictions. Moselhi et al. (2016) propose a novel approach for scheduling acceleration of repeated renovation projects by introducing two major improvements—capturing uncertainty related to the acceleration cost and enabling accounting for contractors' own perspective when constructing acceleration plans. Activities are arranged according to the cost slope and contractors' judgment.

The second group of these available research papers focused on analyzing the negative effects of renovation activities on building occupants. For example, AlOtaibi et al. (2021A) developed a model to optimize the plans of hotel renovation projects in order to increase hotel income through minimizing project costs. However, an example of three hotels is analyzed to illustrate the use of the model and demonstrate its capabilities. AlOtaibi et al. (2021 B) developed a planning model for residential buildings renovation projects which detects the optimal plan for renovation that reduces overall cost. Karatas & El-Rayes (2016) proposed an integrated optimization model that used to

optimize housing design and construction decisions in order to produce the best trade-offs between enhancing the environmental performance of housing units and decreasing their initial costs. The model was generated in two primary phases that involved formulating and implementing the model using multi-objective genetic algorithms.

The third group of these available research papers focused on construction project scheduling under the uncertainty. For example, Bakry et al. (2016) presented a fuzzy set theory-based approach for the optimal scheduling of repeated construction projects under uncertainty using several input parameter uncertainties. The optimization component and the buffering component are the two primary parts of this method. While sizing buffers, Agreement Index (AI) is utilized to record the user's desired level of confidence in the generated schedule. Hassan (2019) conducted a study on risk of repetitive projects. This study focused on three developed models: a scheduling model for repeated construction projects that examines and optimizes the consequence of crew deployment dates under uncertainty on the project duration and work consistency of construction crews; a scheduling model for repeated construction projects that examines and optimizes the influence of activity delay on interrupting crew work continuity of its successors; and a novel scheduling model for repeated construction projects that examines and optimizes the impact of activity delay on interrupting crew work continuity of its successors. Moreover, Salama & Moselhi (2019) proposed a multi-objective model for repeated project which takes into account work disruption ,time, and cost considerations when accounting for uncertainty such as availability, quantities, and productivity rates. Monghasemi & Abdallah (2021) created a model for optimizing the plans of repeated projects which identifies the best work sequence, staff deployment timings, and mobility between units to reduce overall project cost.

Juan et al. (2016) developed a data collection decision model on the bases of graph search algorithms and genetic algorithms to assess current hospital conditions and suggest an optimum solution scheme of self-sustaining renovation initiatives, taking into account exchange between maximum quality improvement, minimal renovation cost, and low environmental impact. Their application offers results that show the system is working effectively and that its responses are successful than judgment' actions. Moreover, it has the potential to improve standard hospital building condition assessments while also increasing their efficiency. Fan & Chu (2021) developed an immersive model and figure morphology for data collecting in order to combine domain knowledge of exhibit spatial planning, showing, and machine learning to create a unique suggestion framework. Their application offers results that are good to dissimilar museums by altering the standards that used to establish a new suggestion framework. Pope et al. (2016) developed and tested a renovation vs new building support decision tool for construction stakeholders involved, to use a method to assess educational facility decisions by university authorities with project management expertise. However, the tool's use gives findings that suggest it might be useful in assisting stakeholder groups in determining whether to renovate a current structure or create a new one. Moreover, Le et al. (2021) undertake a literature search on frameworks and buildings sustainable evaluation for sustainable rehabilitation in order to uncover critical lessons from a number of successful restoration projects. Long & Ohsato (2009) created a novel way for planning buildings including time, cost of the project. The work of this method deals with resource work continuity limits as well as priority connections between operations. To create a suitable schedule, it takes into account different characteristics of actions as well as different interactions among durations and costs for that activities.

2.5 Scheduling Techniques for Construction Projects

Construction project planning procedures are characterized by their capacity to evaluate and uncertainty and assess risk into two types: (1) critical path method (CPM); and (2) line of balance (LOB) and/or repetitive scheduling method (RSM) (Ammar, 2012). This section provides a detailed overview of planning models for repeated projects, as well as other correlated modeling approaches for regular projects. Figure 5 illustrates repetitive scheduling representation.

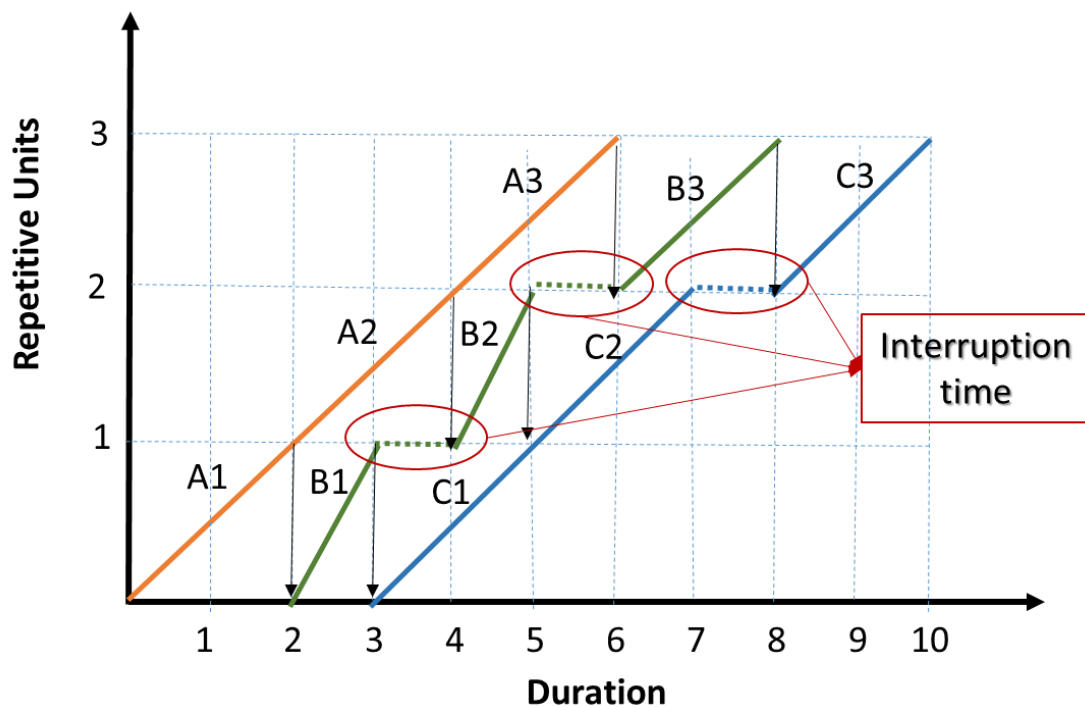


Figure 5: Repetitive Scheduling Representation

2.5.1 Line of Balance

(LOB) was established in the 1940s by the Goodyear Company for organizing and regulating manufacturing production activities (Yang & Chang, 2005). LOB is a graphical approach in which the time is denoted by the (X-Axis) while the units are denoted by the (Y-Axis). Every repetitive activity was denoted by inclined bar, with the width representing the activity's period and the slope

representing the activity's production rate as shown in Figure 6. LOB determines the finished units at a given point in time (Lutz, 1990). Figure 6 illustrates LOB Representation.

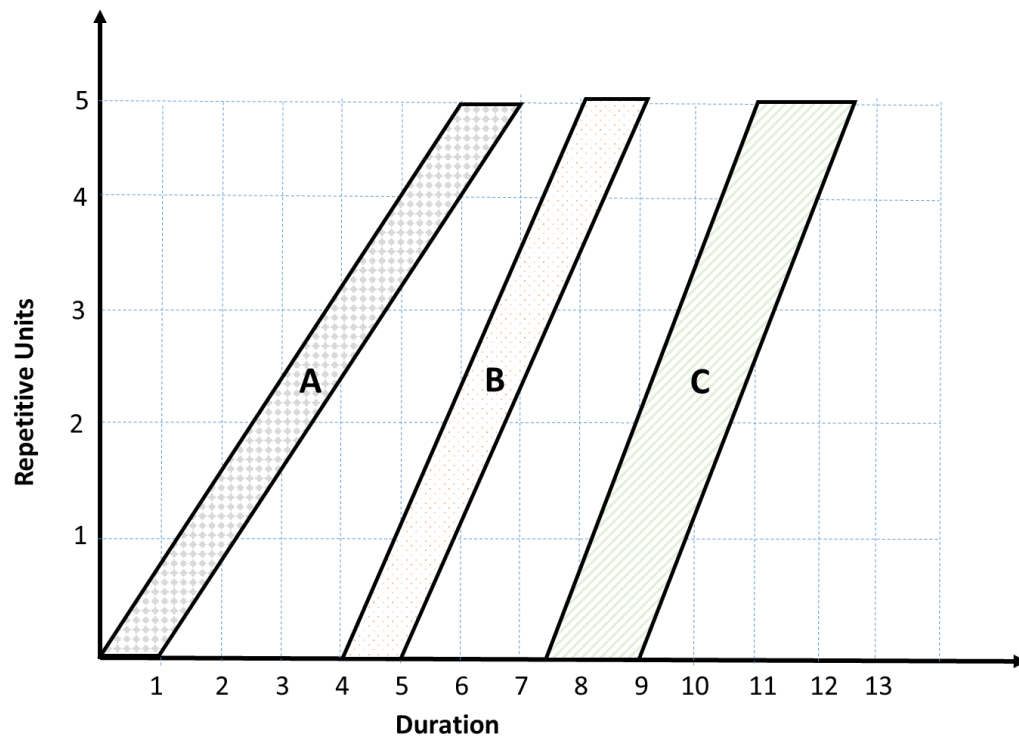


Figure 6: (LOB) Representation

Lutz (1990); Mattila & Abraham (1998) and Srisuwanrat (2009) reached to the conclusion that LOB provide planners with: (1) minimum crew interruptions by regulating the rate of production of each repetitive activity; (2) improvement in the demonstration of the entire project duration; (3) micro-scale scheduling that provide monitoring all repetitive activities; (3) improvement of the process of selecting the best crews to maximize work continuity; and (4) adjustment in resources to meet the required production rate. The challenge of representing two activities with the same output rates was overcome by developing a novel method of presenting the LOB diagram (Hegazy & Kamarah, 2008). It was created with two diagrams, one showing key route activities and the other showing additional activities, to avoid overlapping between concurrent operations. Furthermore, according to Altuwaim & El-Rayes (2018), using different colors and line patterns in the LOB diagram will improve the display of the activities as well as the project schedule.

(Ammar, 2012) developed a methodology that combines CPM and LOB in order to schedule building projects with the same repetitive units. This model's computations are carried out in the following steps: (1) use (CPM) for scheduling the subnet model which only contains the initial unit in each repeated activity while keeping the least buffer duration; (2) use LOB for identifying the total number of necessary crews of each activity; (3) use LOB calculations for calculating the total duration of each repetitive activity; (4) define rationale precedence while keeping the crew task consistency in mind for determining the lag time among activities; (5) Compute the network's forward and backward passes, using these activity in all repeating units as a single unit to compute the earliest and latest feasible timings.

2.5.2 Linear Scheduling Method

(LSM) was created to address the restrictions of (LOB) (Edmund N. Chrzanowski & Johnston, 1986). It is a platform for planning repetitive building projects. LSM methods create a graphical timetable based on the production rate of each repeated activity unit., whereas LOB models focus on balancing production rates among all repetitive activities (Mattila & Park, 2003). Each repeated task is shown as an angled line running along the repeating units (X-axis) and time (Y-axis). LSM can handle repeated activity that are both identical and non-identical. Yamín & Harmelink (2001) compared the (LSM) with the (CPM). They find that LSM outperforms CPM in the following: (1) present clear schedule for complicated plans at the activity level, and (2) update the project plan. Figure 7 illustrates LSM Representation.

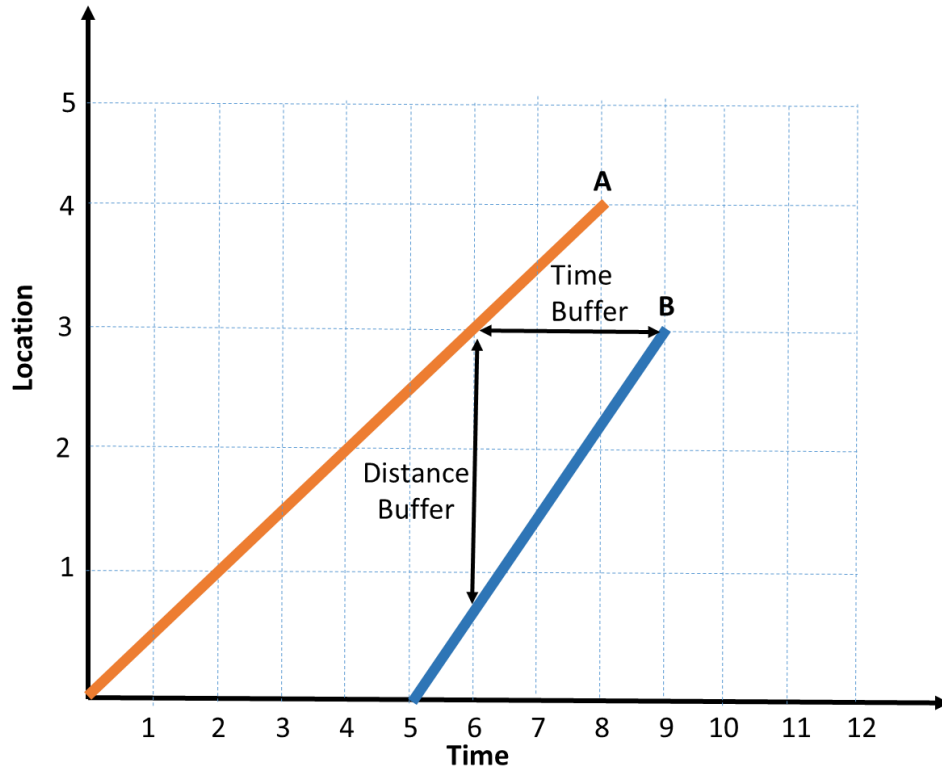


Figure 7: (LSM) Representation

2.5.3 Mathematical Scheduling Models

El-Rayes & Moselhi (2010) developed a model for repeated activities that takes into account the constraint of multiple crews to work on the same task at the same time. This model can handle input factors including accessibility time of crew on site, allowable staff idle time of activity, and right completing order between repeating units. This model is applied in the following: (1) determine an early time for all activity units that satisfy precedence relations and crew accessibility constraints; and (2) sustain the crew work continuousness by removing their idle time that could be produced in the first phase amongst select units. For each unit, it produces the assigned crew, start time, and finish time. This model, on the other hand, ignores non-serial repetitive tasks and is unable to recognize activity which cause project delays that disrupt crew work continuity in its successors. To plan repetitive projects, S.-L. Fan & Tserng (2006) created a methodology based on soft logic approach. Tamimi & Diekmann (1988) developed soft logic to optimize allocation of resources in planning operations. Soft logic relations help to shorten the planning stage of a project (S.-L. Fan & Tserng,

2006; Srisuwanrat, 2009). Input, scheduling, and work-continuity maintenance are the three components that make up this model. To construct a basic project network, the involvement module describes activity factor, including work level, work area, and kind of interaction among these activities and their successors.

2.5.4 Control Path Technique

Ammar & Elbeltagi (2001); Harmelink & Rowings (1998); Harris & Ioannou (1998); and Lucko (2008) reached that the control path is a series of operations that keep the project on track while obeying crew work continuity, availability of construction personnel, and precedence relationship limitations. This approach is used to determine control activity in both forward and backward passes. The forward is to find the earliest start time for each repeating action and the shortest project length while obeying crew job continuity and precedence relationship limitations. The control repeated activity units distributed among control points are identified using a backward pass. These points constitute the important priority connection which controls the earliest periods of repeated operations though maintaining the continuity of crew activity (Harmelink & Rowings, 1998; Harris & Ioannou, 1998; Srisuwanrat & Ioannou, 2007). To recognize crucial and non-crucial tasks, this strategy use the critical path method. According to Yamín & Harmelink (2001), the control path incorporates both crucial and non-crucial tasks because of the continuity restriction of crew work. Figure 8 illustrates controlling-critical activity units.

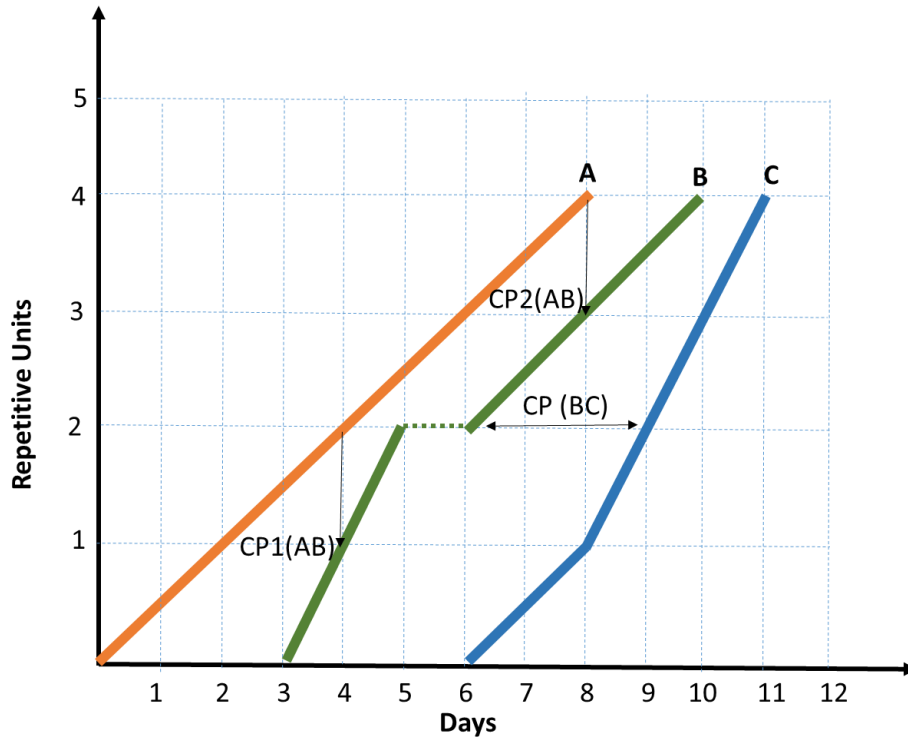


Figure 8: Controlling-Critical Activity Units

2.5.5 Evaluation and Review Technique Models

In the 1957s, United States Navy developed the (PERT) which stands for “projects evaluation and review technique” to plan nuclear-powered submarine developments (Aziz, 2014). It stands for probabilistic estimation of project time. It is a simple statistical mathematical approach for determining probability duration of the project. Which assumes that duration for activities following the Beta (β), also it can be highlighted in the following types of duration: (1) optimistic; (2) pessimistic; and (3) most likely.

(Aziz, 2014) proposed the (RPERT) which stands for “repetitive projects evaluation and review technique” to account for ambiguity in construction project planning. This model takes into account crew production rate and was applied in four steps: (1) use the precedence diagram method (PDM) to show the project network and activities sequence; (2) use the program evaluation and review technique (PERT) to calculate the duration for repeating activity on the bases of optimistic, pessimistic, and most likely duration of its crew production rate; (3) use the line of balance (LOB) to compute the project

plan using the durations from the previous step; and (4) change the results of the LOB schedule to the new values using CPM calculations while considering buffer time.

2.5.6 Simulation Models

Simulation is a common approach for analyzing issues with variables that chooses randomly and/or nonlinear interactions (Senior-Brown, 1993; Srisuwanrat, 2009). A number of simulation models employed in the planning of repetitive building projects to account the uncertainty of different input parameters (Duffy et al., 2010; Francis, 2016; Ioannou & Srisuwanrat, 2006; Lutz, 1990; Yang & Chang, 2005). Simulation of Repeated Network (SIREN) was developed by Kavanagh (1985) to schedule repetitive construction projects using crew queueing approach. Monte Carlo technique is utilized to compute the uncertainty in the time of activity. Each activity is categorized according to its queue: in-progress activities, ready, and unready. The unready queue activities encompass all activities that do not fulfill their priority criteria. After all of its predecessors have completed the requisite work, the activity is transferred to the stage of ready queue. When the construction crew is ready to work, the activity is transferred to the in-progress activities stage. Each activity's work advances in a logical order, starting with the first unit and ending with the last. At various levels of confidence, it can offer the overall project cost and duration.

Duffy et al. (2010) formulated model to determine the variation in each activity's production rate over location and time. It is based on the LSM approach, with certain input and output data. The occupant location and time impact the production rate of each team. Francis (2016) developed a Chronographically Method-based model to imitate project uncertainty. Throughout the project's life cycle, this model takes into account uncertainty. It determines the activity duration's contingency in order to arrive at a safe start and finish time for each activity. But it is difficult to express all project activities in a single graph due to the model's complication.

2.5.7 Fuzzy-Based Scheduling Models

Fuzzy-based is another approach that might be utilized when considering the uncertainty in input parameters (Bakry et al., 2013). Fuzzy-based approach is a valuable tool in cases when there is inadequate data as it can collect specialists' thoughts and take out the essential data. In this theory, production rate and activity duration associated with uncertainty in construction is represented as an

interval duration with value in the interval that have a membership value ranging from zero (low probability) to one (high probability). Figure 9 illustrates fuzzy membership shapes.

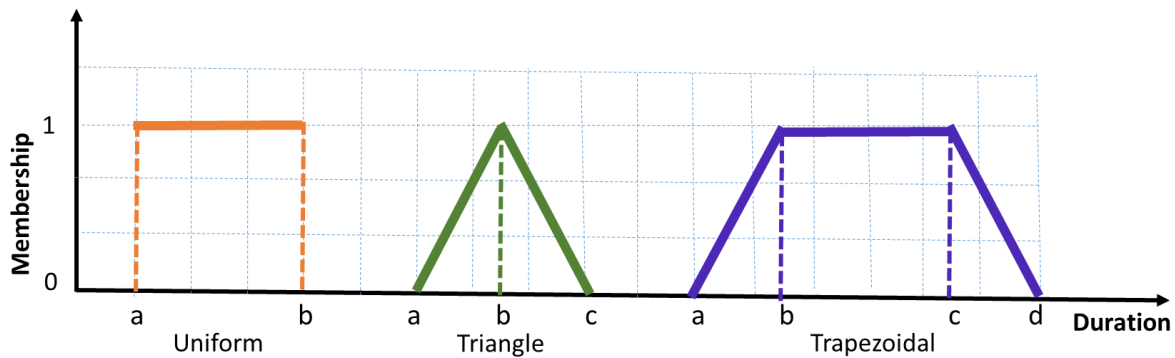


Figure 9: Fuzzy Membership Shapes

A fuzzy dynamic programming scheduling model was created by Bakry et al. (2013). It is implemented using the optimization and planning procedures. The triangle membership was used in the planning stage to allow the uncertainty in various inputs. This stage was created to determine the earliest possible start and finish for all activities while taking into account precedence limits, work continuity, and personnel availability. The optimization process uses a programming technique to discover the ideal crew arrangement for repeating activities while minimizing project duration and cost. There are three processes in this stage; (1) a forward pass to locate the formation of local crew; (2) a backward pass to locate the formation of global crew; and (3) convert the fuzzy schedule into a deterministic equivalent for improved visualization.

2.5.8 Genetic Algorithm

In 1975, John Holland developed an optimization algorithm that used natural systems called Genetic algorithms (GA). Genetic algorithms are designed to emulate the natural evolutionary process. The following are the principles of genetic algorithms: (1) generate a population of individual solutions; (2) compute the objective function(s) for each individual within each individual solutions; (3) assign a fitness value to each individual solution based on the objective function(s); (4) generate new solutions using crossover from the selected individuals; (5) the logarithm is stopped when criteria are met. Genetic algorithms (GA) is the most optimization tool in terms of minimizing total

cost and time of repetitive projects (Altuwaim & El-Rayes, 2018; A. A. A. Hassan, 2019; K. Hyari & El-Rayes, 2006b).

Despite their contributions and importance, the aforementioned research studies have limitations when it comes to risk assessment and crew production rate when simulating and optimizing leased building renovation work under uncertainty. Consequently, to circumvent the limits of present studies and address research gaps, a stochastic model for leased building restorations projects which will reduce overall renovation cost is needed.

2.6 Research Needs

This chapter revealed that there is a need for a stochastic planning model for leased building renovations projects that is able of: (1) considering and analyzing risks and uncertainties experienced during the planning of building renovation work; (2) selecting optimal crew formation and optimal start date of each renovation activity; (3) identifying optimal work sequence for all leased units; (4) calculating and reducing the lease income losses; and (5) minimizing the total expected renovation cost including direct, indirect, and interruption cost. Accordingly, these abilities are intended to provide renovation planners with well assistance to consider and analyze uncertainty during the planning of leased building renovation work in order to minimize total expected renovation project cost.

CHAPTER 3 RESEARCH METHODOLOGY

The goal of this chapter is to highlight the design of stochastic model that optimize the planning of leased building renovation work while considering the uncertainty of the output rate of the crews. The design of this model is divided in two main phases, as illustrate in Figure 10. The first phase, optimization phase, looks for and identifies a near-optimal work sequence for all leased units (w); start date of each renovation activity (s_i); and crew formation (c_i), in order to minimize total expected project cost. The second phase, simulation phase, involves schedule and cost computations for each solution generated in the optimization phase. The following sections of this chapter provide concise details of these development phases.

3.1 Optimization Phase

The main goal of this phase is to formulate the design of a novel stochastic model that optimize the renovation planning of leased buildings under uncertainty, in order to minimize total expected renovation cost. This phase is divided into the following stages: (a) classifying important decision variables; (b) formulating the objective function; (c) identifying the constraints that impact the project; and (d) implementation. Stages of this optimization phase are briefly described in the subsections below.

3.1.1 Decision Variables

The main goal of this stage is to categorize each possible decision variable that influences the total expected cost of leased building renovation projects. Therefore, the significant decision variables utilized in this model are: (1) work sequence for all proposed leased unit (w); (2) start date of each renovation activity (s_i); and (3) crew formation (c_i). These decision variables are explained in further details below.

3.1.1.1 Work Sequence (w)

Work sequence is the first decision variable which indicates the work sequence of leased units ($j = 1 \text{ to } J$), in which renovations are carried out in order to minimize total expected cost, as shown in Eq. (1). For example, a work sequence of [2, 3, 1] implies that there are three

leased units proposed for renovation, where unit [2] will be the first unit to be renovated, followed by unit [3], and finally unit [1]. The entire number of feasible combinations of renovation work sequence (J) is determined by the total number of units (j). For example, if there are 4 leased units being renovated, the number of possible combinations of renovation sequence for these units is equal to $4!$, which is equal to 24 possible combinations.

$$W = [w_1, w_2, \dots, w_J] \quad |w| = J \quad \forall j \in J \quad (1)$$

Where:

J = the entire number of leased units.

3.1.1.2 Start date of each renovation activity (s_i)

Start date (s_i) is the second decision variable in this model which is selected from a set of feasible alternatives in order to identify optimal crew deployment date of each renovation activity (i). Start date (s_i) has a range of a minimum value of leased unit availability date (A_{w_j}) to a maximum value of (T_i) which is the maximum start date for each renovation activity (i) specified by the planner, as shown in Eq. (2).

$$A_{w_j} \leq s_i \leq T_i \quad \forall i \in I \ \& \ j = 1 \quad (2)$$

Where:

s_i = Start date of renovation activity (i);

A_{w_j} = Available date of leased unit (j);

T_i = Maximum start date for each renovation activity (i).

3.1.1.3 Crew formation (c_i)

Crew formation is the last decision variable in this model which indicates the selection of optimal crew formation from a set of alternatives provided by the planner. These options of crew formations have their own daily output rate and idle-time cost rate which affect the cost and duration of the activity (i). This crew formation (c_i) is represented for each activity (i)

using a positive integer variable ranging from one to the maximum number specified by the planner (C_i), as shown in Eq. (3). For example, a value of ($c_1 = 2$) shows that there are two feasible crew formations for the renovation construction of activity ($i = 1$), and a value of ($c_4 = 3$) represents the selection of the third crew formation for activity ($i = 4$) as shown below.

$$1 \leq c_i \leq C_i \quad \forall i \in I \quad (3)$$

Where:

c_i = Selected crew formation for renovation activity (i);

C_i = Number of feasible crew formations to carry out the renovation activity (i).

3.1.2 Objective Function

The main goal of this stage is formulating the objective function that influence the total expected project cost of leased building renovation projects. The objective function, that used in this model, is designed to minimize expected overall renovation cost ($TC(\alpha)$) at a confidence level (α) that specified by the planner. This expected total renovation cost involves the following costs: crew cost (CR), material cost (MA), indirect cost (IND), crew interruption cost (INT), and lease losses (LE), as illustrated in Eq. (4).

$$\text{Minimize } TC(\alpha) = \text{Minimize } (CR + MA + IND + INT + LE) \quad (4)$$

Where:

$TC(\alpha)$ = Expected total renovation cost at a planner-specified confidence level(α);

CR = Crew cost of activities (i) in leased units;

MA = Material cost of activities (i) in leased units;

IND = Indirect cost of all leased units;

INT = Crew interruption cost of renovation activities in leased units;

LE = Lease losses of the rental income during the renovation work.

3.1.3 Constrains Equations

This model is designed to comply with the following constrictions to ensure its practicality: a project allocated budget (BC) and a completion deadline (DL). The project allocated budget (BC) is included in the model to ensure that the overall renovation cost ($TC(\alpha)$) does not exceed the allocated budget amount as stated in Eq. (5). Second, the completion deadline (DL) is incorporated into the model to guarantee that the renovation work is completed before the deadline specified by the planner as stated in Eq. (6).

$$TC(\alpha) \leq BC \quad (5)$$

$$F_{l,w_j}^n \leq DL \quad (6)$$

Where:

s_i = Start date of renovation activity (i);

A_{w_j} = Available date of leased unit (j);

$TC(\alpha)$ = Expected total renovation cost at a planner-specified confidence level(α);

BC = Allocated budget Cost for the project;

F_{l,w_j}^n = Finish date of the last activity in simulation iteration (n);

DL = Completion deadline specified by the planner for the renovation project.

3.1.4 Implementation

The optimization phase of this model is developed to enable decision-makers in identifying the total expected cost of the renovation projects. This phase utilizes Non-dominated Sorting Genetic Algorithm II (Deb et al., 2002) to carry out the implementation stage since Genetic Algorithms are capable of searching and finding near-optimal solutions in large spaces within a reasonable amount of computational time (S. L. Fan et al., 2012; K. Hyari & El-Rayes, 2006; K. H. Hyari et al., 2009). The optimization procedure in this phase is carried out using the Distributed Evolutionary Algorithms structure in Python which involves the following steps:

1. Generating a set of random solutions ($s = 1$ to S) as a first generation ($g = 1$), where each of these solutions represents a random selection of the following: (1) work sequence for all proposed leased units (w), (2) start date of each renovation activity (s_i); and (3) crew formation (c_i) within the specified feasible ranges.
2. Estimating the total expected project cost ($TC(\alpha)$), for each solution ($s = 1$ to S) in this generation ($g = 1$) using the next phase as illustrated in the simulation phase, at a specified confidence level, as shown in Figure 10. Then ranking all these generated solutions (S) with Non-dominated Sorting Genetic Algorithm II.
3. Choosing the best solutions from the parent population for the next generation ($g = g + 1$) with genetic algorithms operators, crossover and mutation, to generate the next child population. Crossover involves swapping the decision variables of two parents at one or more random selection points, while mutation involves changing the value of the decision variables randomly, work sequence for all proposed leased units (w); start date of each renovation activity (s_i); and crew formation (c_i) for all activities (I).
4. Repeating the previous steps 2 and 3 for each generation (g) until the GA stopping criterion is reached, which could be a certain number of generations ($g = G$) or a certain number of consecutive generations without improvements.

3.2 Simulation Phase

Monte Carlo simulation technique (Diaz & Hadipriono, 1993; Öztaş & Ökmen, 2005; Williams, 2003) is used in this phase to simulate uncertainties related to the output rates of the crews. The main goal of simulation phase is to calculate the total expected cost ($TC(\alpha)$) of the project for each generated solution ($s = 1$ to S) at specified confidence level (α). The probability distribution of the crew daily output rates is generated based on a data from similar previous projects to reflect and evaluate uncertainties due to variations in material deliveries, weather, equipment breakdowns, site conditions, and/or labor productivity. Simulation process is carried out for an identified number of iterations (N). Simulation process with 1,000 repetitions is considered sufficient for construction project purposes and is cost-effective (Diaz & Hadipriono, 1993). Though, this simulation phase uses ($N = 1,000$) iterations to achieve very accurate reliable predictions as demonstrated in Figure 10.

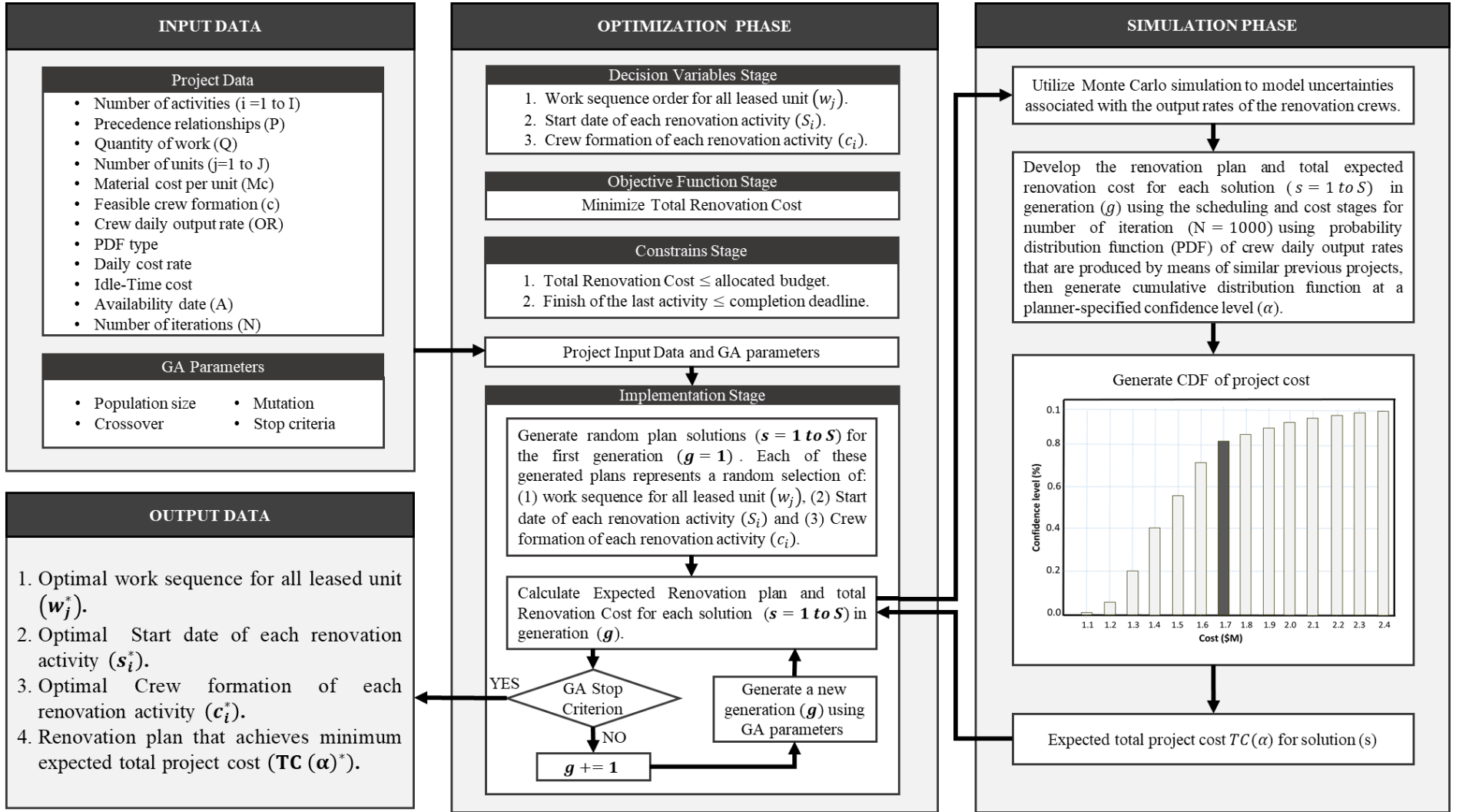


Figure 10: Stochastic Optimization Model for Planning of Leased Building Renovations Projects

3.2.1 Schedule Module

Schedule computations in this section are performed in the following steps for each iteration (n), which are summarized in Figure 11.

1. Calculate the duration (d_{i,w_j}^n) of all activities (i, j) by using the amount of the work needed for each activity, quantity of work (Q_{i,w_j}), and randomly daily output rate ($OR_{c_i}^n$) of the crew formation (c_i) assigned to activity (i) in simulation iteration (n), which is generated from the probability distribution function (PDF_{c_i}), as shown in Eq. (7). Additionally, it allows planners to choose the probability distribution function (PDF_{c_i}) type for each crew formation (c_i) to be a triangle, beta, uniform, or normal distribution.

$$d_{i,w_j}^n = \frac{Q_{i,w_j}}{OR_{c_i}^n} \quad \forall i \in I \ \& \ \forall j \in J \quad (7)$$

Where:

d_{i,w_j}^n = Duration of activity (i, j) in iteration (n);

$OR_{c_i}^n$ = Randomly generated output rate of crew formation (c_i) assigned to activity (i, j) in iteration (n);

Q_{i,w_j} = Quantity of work of activity unit (i, j).

2. Calculate the start date (S_{i,w_j}^n) obtained from simulation iteration (n) of each activity (i, j) using the duration (d_{i,w_j}^n) obtained from previous step while satisfying the precedence relationships between each activity. Start date (S_{i,w_j}^n) of activities with no predecessors ($P_i = \emptyset$) and unit ($j = 1$) is recognized as the selected start date (s_i) of the first activity, as shown in Eq. (8). Start date (S_{i,w_j}^n) of the same activity with no predecessors and unit ($j = 2$ to J) is recognized as the maximum of the leased units' available date (A_{w_j}) and the finish date of the previous unit ($F_{i,w_{j-1}}^n$), as shown in Eq. (9). Start date (S_{i,w_j}^n) of activities and work sequence ($w_{j=1}$) with predecessors (p_i) and unit ($j = 1$) is recognized as the maximum of the start date (s_i) and the finish date of its predecessors (F_{p_i,w_j}^n) plus their specified lag times (Lag_{p_i}), as shown in Eq. (10). Start date (S_{i,w_j}^n) of activities with

predecessors (p_i) and unit ($j = 2 \text{ to } J$) is defined as the maximum of the finish date of its predecessors (F_{p_i, w_j}^n) plus their specified lag times (Lag_{pi}) and the finish date of the previous unit ($F_{i, w_{(j-1)}}^n$), as shown in Eq. (11). Finish date (F_{i, w_j}^n) can be calculated as the summation of the Start date (S_{i, w_j}^n) of the activity (i) and its duration (d_{i, w_j}^n) obtained from the previous steps, as shown in Eq. (12).

$$S_{i, w_j}^n = s_i \quad \forall i \in I \ \& \ j = 1 \ \& \ P_i = \emptyset \quad (8)$$

$$S_{i, w_j}^n = \max(A_{w_j}; F_{i, w_{(j-1)}}^n) \quad \forall i \in I \ \& \ j = 2 \text{ to } J \ \& \ P_i = \emptyset \quad (9)$$

$$S_{i, w_j}^n = \max \left(s_i; F_{p_i, w_j}^n + Lag_{pi} \right) \quad \forall i \in I \ \& \ j = 1 \ \& \ \forall p_i \in P_i \quad (10)$$

$$S_{i, w_j}^n = \max \left(F_{p_i, w_j}^n + Lag_{pi}; F_{i, w_{(j-1)}}^n \right) \quad \begin{array}{l} \forall i \in I \ \& \ \forall p_i \in P_i \\ \& \ \forall j = 2 \text{ to } J \end{array} \quad (11)$$

$$F_{i, w_j}^n = S_{i, w_j}^n + d_{i, w_j}^n \quad \forall i \in I \ \& \ \forall j \in J \quad (12)$$

Where:

S_{i, w_j}^n = Start date of activity (i, j) in iteration (n);

s_i = Selected start date of activity (i);

p_i = Predecessors of activity (i);

Lag_{pi} = Lag duration between activity (i) and its predecessor (p);

F_{i, w_j}^n = Finish date of activity unit (i, j) in iteration (n).

3. Determine the total duration of the project (TD^n) obtained from simulation iteration (n), which is the finish date of the last unit (J) in leased building activities (F_{i, w_J}^n) minus the start date of the first activity (S_{i, w_1}^n), as shown in Eq. (13).

$$TD^n = \max(F_{i, w_J}^n) - \min(S_{i, w_1}^n) \quad \forall i \in I \ \& \ j = 1 \quad (13)$$

Where:

TD^n = Project duration in iteration (n);

F_{i,w_j}^n = Finish date of the last unit (J).

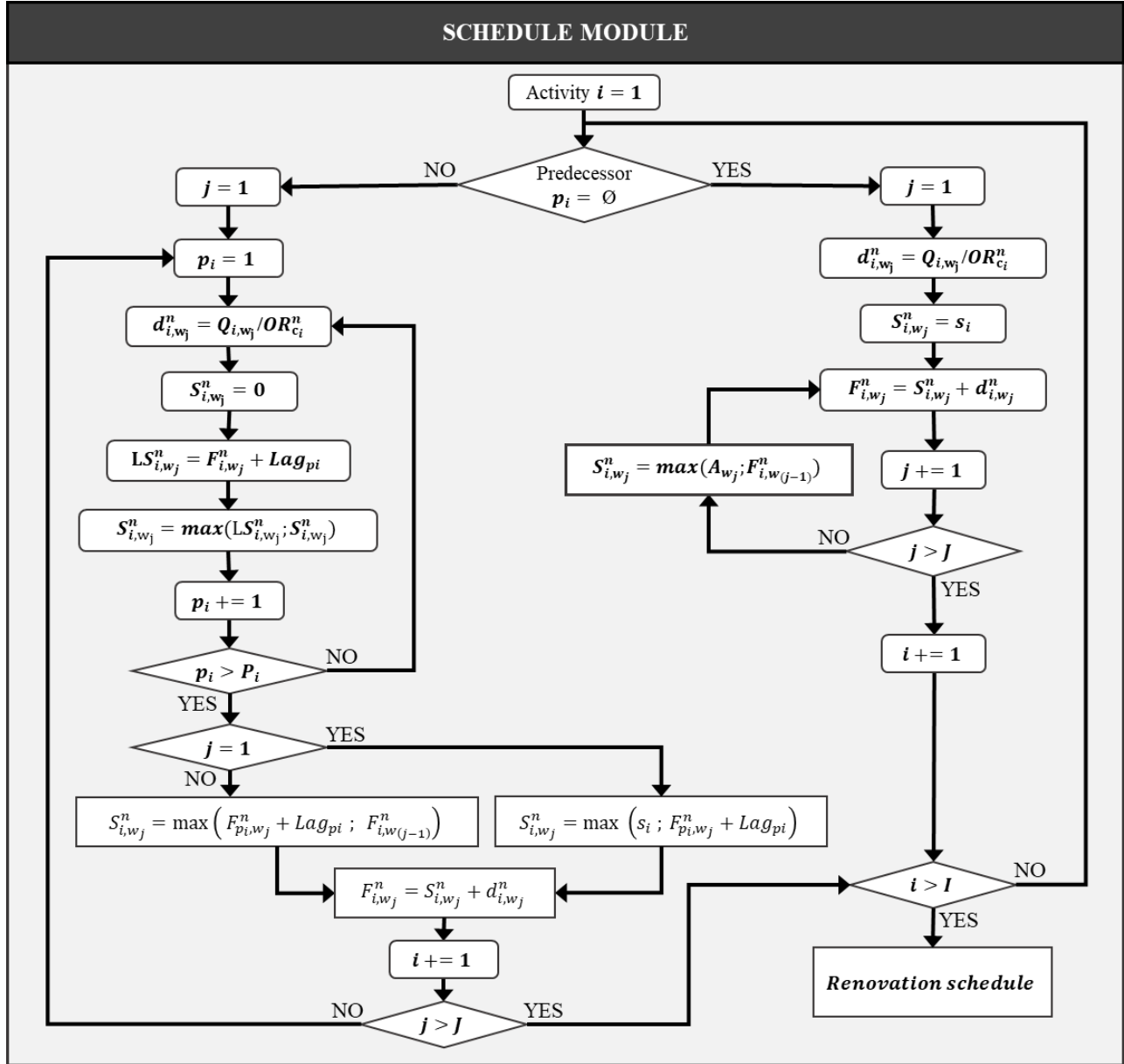


Figure 11: Schedule Module

3.2.2 Cost Calculations

Cost computations in this section are performed in following steps for each iteration (n), which are summarized in Figure 12.

1. Determine the direct cost of the project (DC^n) obtained from simulation iteration (n) which includes material, labor and equipment costs of all activities (i) in all leased units (j), as shown in Eqs. (14) to (16).

$$CR^n = \sum_{i=1}^I \sum_{j=1}^J [(L_{c_i} + E_{c_i}) * d_{i,w_j}^n] \quad (14)$$

$$MA^n = \sum_{i=1}^I \sum_{j=1}^J [Q_{i,w_j} * M_i] \quad (15)$$

$$DC^n = CR^n + MA^n \quad (16)$$

Where:

CR^n = Crew cost of activity unit (i, j);

L_{c_i} = Labor cost rate of crew formation (c_i) for activity (i);

E_{c_i} = Equipment cost rate of crew formation (c_i) for activity (i).

MA^n = Material cost of activity unit (i, j);

M_i = Material cost rate of activity (i);

Q_{i,w_j} = Quantity of work of activity unit (i, j);

DC^n = Direct cost of the project obtained from iteration (n);

2. Determine the interruption cost of the crew (INT^n) of all activities units (i, j) obtained from simulation iteration (n) by considering crew idle-times and interruption costs as shown in Eqs. (17) to (19).

$$int^n = (S_{i,w_j}^n - F_{i,w_{(j-1)}}^n) * Id_{c_i} \quad \forall i \in I \ \& \ j = 2 \text{ to } J \quad (17)$$

$$\text{if } (MT_{c_i} + Tx_{c_i}) \geq (int^n); \quad INT^n = int^n \quad \forall i \in I \ \& \ j = 2 \text{ to } J \quad (18)$$

$$\text{if } (MT_{c_i} + Tx_{c_i}) < (int^n); \quad INT^n = \min(int^n, MC_{c_i}) \quad \forall i \in I \ \& \ j = 2 \text{ to } J \quad (19)$$

Where:

int^n = Interruption cost of the crew on activity (i);

Id_{c_i} = Daily idle-time cost of crew formation (c_i) working on activity (i).

MT_{c_i} = Crew remobilization time of crew formation (c_i) working on activity (i)

Tx_{c_i} = Minimum required work time in the concurrent project of crew formation (c_i).

MC_{c_i} = Crew remobilization cost of crew formation (c_i) working on activity (i)

INT^n = Interruption cost of the crew of all project activities in iteration (n);

3. Determine the indirect cost of the project (IND^n) obtained from simulation iteration (n) by considering the total duration of the project (TD^n) and the indirect cost rate of the contractor (IR), as shown in Eq. (20).

$$IND^n = TD^n * IR \quad (20)$$

Where:

IND^n = Indirect cost of the project in iteration (n);

IR = Indirect cost rate of the contractor.

4. Determine the lease losses of the rental income of units (j) during the renovation work (LE^n) obtained from simulation iteration (n) by considering the duration of the rental income and the rental income rate (RM), as shown in Eq. (21).

$$LE^n = [\max(F_{l,w_j}^n) - A_{w_j}] * RM/30 \quad \forall i \in I \ \& \ \forall j \in J \quad (21)$$

Where:

LE^n = Lease losses of units of the project in iteration (n);

A_{wj} = Availability date of leased unit;

RM = Rental rate of leased unit per month.

5. Determine the total cost of the project (TC^n) obtained from simulation iteration (n) by adding up all the previous calculated costs which include: direct cost (DC^n), interruption cost (INT^n), indirect cost (IND^n), and lease losses (LE^n), as shown in Eq. (22).

$$TC^n = DC^n + IND^n + INT^n + LE^n \quad (22)$$

Where:

TC^n = Total cost of the project

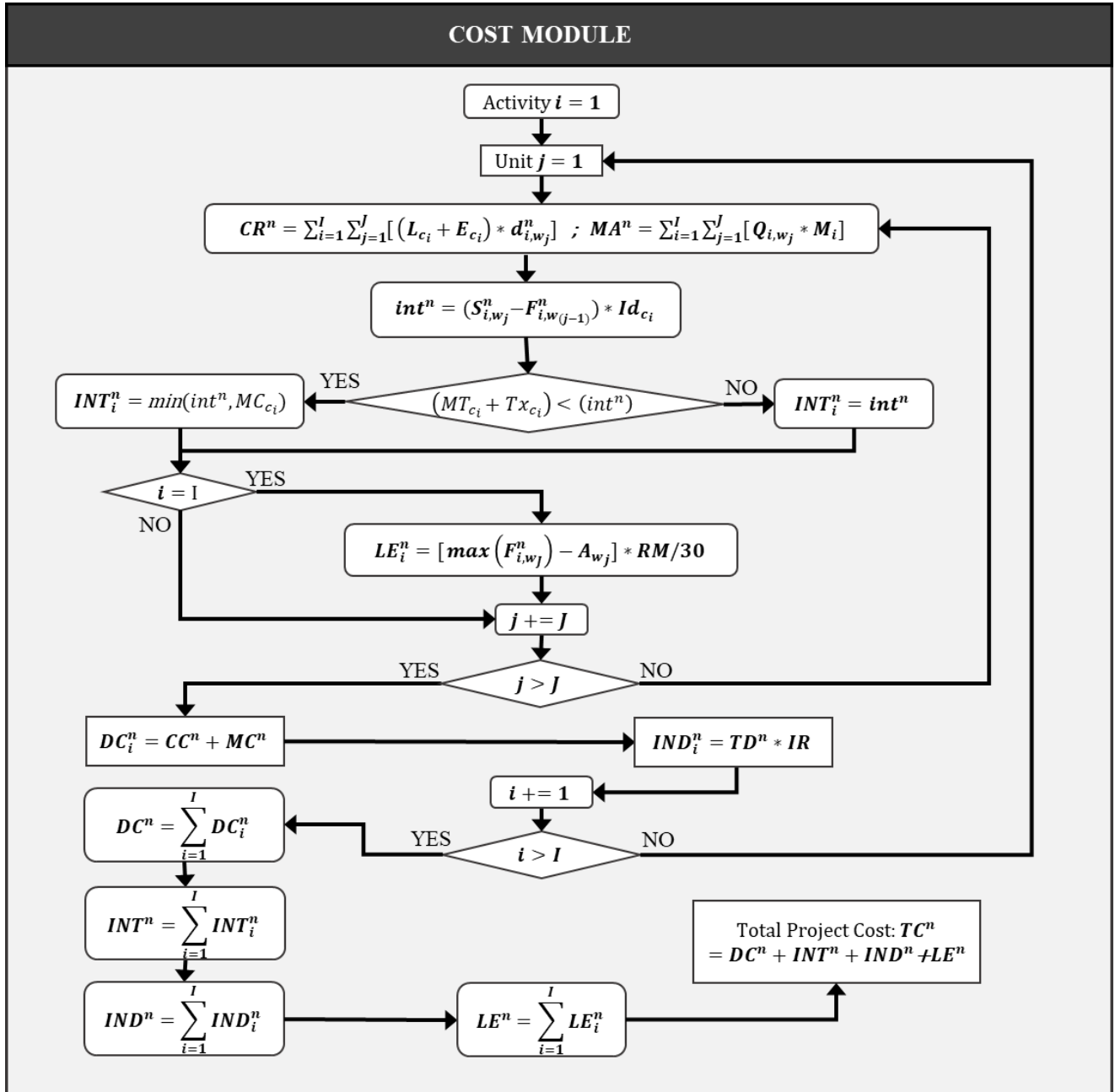


Figure 12: Cost Module

3.3 Model Evaluation

A real-life renovation project of leased houses that was investigated by existing model (AlOtaibi et al., 2021) is adjusted and optimized to demonstrate and validate the practicality and effectiveness of the proposed stochastic model in minimizing the total expected renovation cost. This case study consists of a total of 30 houses ($J = 30$) that are divided into 15 four-bedroom and 15 five-bedroom houses. The renovation activities consist of 22 renovation activities ($I = 22$) that are divided into six groups: (1) demolition and removal; (2) plumbing; (3) electricity and HVAC; (4) carpentry; (5) insulation; and (6) painting and flooring (AlOtaibi et al., 2021). The renovation activities in this example assumed no lag time between activities and the relationship between each activity assumed to be finish-to-start. Table 1 and Table 2 provide a summary of the input data for the investigated project that includes the following: quantities of work in each activity of the project (Q_{i,w_j}), precedence relationships (p_i), and material cost per unit (M_i). The availability dates of the two types of leased units, the 4-bedroom and the 5-bedroom houses are summarized in Table 3. Finally, the construction data of feasible crew formation, days per week, hours per day, crew daily output rate ($OR_{c_i}^n$), PDF type, daily crew cost rate (CR_{c_i}), idle-time cost (Id_{c_i}), and crew remobilization cost (MC_{c_i}), and time (MT_{c_i}) are shown in Table 4, Table 5, and Table 6. The daily indirect cost rate for the leased building renovation project is assumed to be \$1,200/day, and crews can be remobilized to a concurrent project during their work interruptions time if the crew interruption time is longer than the total remobilization time for each crew. The minimum required work time in the concurrent project is estimated to be one day (Tx_{c_i}) for all renovation crews. A similar data such as the quantities of work in each activity, the daily project indirect cost rate and the deterministic daily output rates for all crew formations were used to compare the model practicality with existing available models. However, the rates were converted into stochastic output rates using probability functions such as uniform, triangle, beta and normal distributions to clarify the proposed model's flexibility in assessing a wide range of PDFs and its ability to handle uncertainty, which is the main concern of this research.

Table 1: Construction Data of Leased Renovation Project

Group	Activity (i)	Activity description	Predecessor activities (p_i)	Unit	Quantity (Q_{i,w_j})		Material cost per unit (M_i) (\$)
					Four bedroom house	Five bedroom house	
Demolition and removal	A	Every C28:C49 bathroom has a reinforced, 6" thick concrete slab	-	S.F.	8557	9085	-
	B	Mesh reinforcement, a hydraulic hammer, and six inches of concrete	A	C.Y.	292	292	-
	C	Inside door, 3' 0" x 7' 0", 1-3/4" thick	B	Each	5	5	-
Plumbing	D	PVC pipes come in 4", 3", and 2" sizes	C	L.F.	1535	1608	4.17
	E	PVC pipes come in five various sizes: 1.5", 1", 3/4", and 1/2"	D	L.F.	771	705	2.18
	F	Tub with trim, cast iron, recessed porcelain enamel, 72" x 36"	E	Each	3	5	220
	G	33" x 19" porcelain enamel on cast iron toilets with trim	F	Each	4	6	183
	H	Plastic cleanouts for 2" pipe sizes with a cleanout tee	G	Each	8	10	18
	I	1.6 gpf, bowl-only, wall-hung toilets with a flush valve and a seat	H	Each	4	6	455
	J	Combination of a diverter spout and a bath faucet.	I	Each	12	12	141
	K	Bronze angle valves with 1=2" and 3/4" threads.	J	Each	60	73	15
Electricity & HVAC	L	15-50 A, 2 pole, bolt-on, 240 V, panel board with load center breakers.	C	Each	3	3	733
	M	Circuit breakers and switches are enclosed.	L	Each	131	140	50
	N	Interior lighting fixtures.	M	Each	95	100	114
	O	Tenth, air-cooled packaged refrigerant compressor and condenser systems.	N	Each	2	2	3067
	P	Ceiling diffusers and grilles made of aluminum.	O	Each	42	42	89
Carpentry	Q	Kitchen wall cabinets made of hardwood that are 36 inches wide, 12 inches deep, and have two doors.	C	L.F.	151	151	41
	R	Windows with aluminum sash double-hung.	Q	S.F.	1076	1076	10
	S	A solid wood door that is 1-3/4" thick.	R	Each	36	36	293

Table 2: Construction Data of Leased Renovation Project (cont'd)

Group	Activity (i)	Activity description	Predecessor activities (p_i)	Unit	Quantity (Q_{i,w_j})		Material cost per unit (M_i) (\$)
					Four bedroom house	Five bedroom house	
Insulation	T	Insulation for the roof deck, 1/8" thick fiberglass lining on asphaltic cover board; fastenings not included.	C	S.F.	19612	19612	0.67
Painting & flooring	U	Interior and exterior masonry or concrete block walls should be painted using a roller or brush and latex paint with a smooth finish.	K,P,S ,and T	S.F.	14811	16555	0.59
	V	Porcelain ceramic tiles, 1 color, 2 by 2 inches.	U	S.F.	6932	7276	2

Table 3: Availability Dates of Leased Units

Four bedroom house (rental rate = \$800/ month)		Five bedroom house (rental rate = \$1,000/ month)	
House Unit (j)	Availability date	House Unit (j)	Availability date
1	12-Feb-21	16	14-Sep-21
2	24-Apr-21	17	22-Aug-21
3	17-May-21	18	4-Jul-21
4	10-Oct-21	19	17-Aug-21
5	24-Sep-21	20	30-Jun-21
6	3-Aug-21	21	17-Jul-21
7	9-Aug-21	22	18-Sep-21
8	4-Sep-21	23	9-Jul-21
9	3-Aug-21	24	7-Aug-21
10	19-Sep-21	25	27-Oct-21
11	29-Sep-21	26	7-Sep-21
12	10-Aug-21	27	8-Jul-21
13	9-Sep-21	28	1-Jul-21
14	11-Aug-21	29	11-Oct-21
15	22-Oct-21	30	24-Sep-21

Table 4: Construction Data of Crew Formation

Activity number (i)	Crew Formation (p_i)	Days per week (day/week)	Hours per day (h/day)	Crew Daily Output Rate (OR_{c_i}) (Units/Day)			PDF type	Daily cost rate (CR_{c_i}) (\$/day)	idle-Time cost (Id_{c_i}) (\$/day)	Crew Relocation	
				Min	Mean	Max				Cost (MC_{c_i}) (\$)	Time (Days)
A	1	5	8	2240	3200	3520	Triangle	2855	2141	180	2.0
	2	5	12	3091.2	4416	4857.6	Triangle	5710	2141	180	2.0
B	1	5	8	191.25	255	285.6	Beta	2938	2,204	180	2.0
	2	5	12	264	352	394.24	Beta	5876	2,204	180	2.0
C	1	5	8	14	20	22	Triangle	319	239	180	2.0
	2	5	12	19.6	28	30.8	Triangle	638	239	180	2.0
D	1	5	8	39.75	53	59.36	Beta	895	671	120	1.5
	2	5	12	54.75	73	81.76	Beta	1790	671	120	1.5
	3	6	11	51.75	69	77.28	Beta	1566	671	120	1.5
E	1	5	8	37.6	47	56.4	Uniform	497	373	120	1.5
	2	5	12	52	65	78	Uniform	994	373	120	1.5
F	1	5	8	2.25	3	3.36	Beta	895	671	120	1.5
	2	5	12	3.075	4.1	4.592	Beta	1790	671	120	1.5
	3	6	11	2.925	3.9	4.368	Beta	1566	671	120	1.5
G	1	5	8	4.48	6.4	7.04	Triangle	895	671	120	1.5
	2	5	12	6.3	9	9.9	Triangle	1790	671	120	1.5
	3	6	11	5.81	8.3	9.13	Triangle	1566	671	120	1.5
H	1	5	8	20.25	27	30.24	Beta	895	671	120	1.5
	2	5	12	27.975	37.3	41.776	Beta	1790	671	120	1.5
I	1	5	8	4.35	5.8	6.496	Beta	895	671	120	1.5
	2	5	12	6	8	8.96	Beta	1790	671	120	1.5
	3	6	11	5.625	7.5	8.4	Beta	1566	671	120	1.5

Table 5: Construction Data of Crew Formation (cont'd)

Activity number (i)	Crew Formation (p_i)	Days per week (day/week)	Hours per day (h/day)	Crew Daily Output			PDF type	Daily cost rate (CR_{c_i}) (\$/day)	idle-Time cost (Id_{c_i}) (\$/day)	Crew Relocation	
				Rate (OR_{c_i}) (Units/Day)						Cost (MC_{c_i}) (\$)	Time (Days)
				Min	Mean	Max					
J	1	5	8	7.5	10	11.2	Beta	497	373	120	1.5
	2	5	12	10.5	14	15.68	Beta	994	373	120	1.5
	3	6	11	9.75	13	14.56	Beta	870	373	120	1.5
K	1	5	8	15.4	22	24.2	Triangle	497	373	120	1.5
	2	5	12	21	30	33	Triangle	994	373	120	1.5
	3	6	11	20.3	29	31.9	Triangle	870	373	120	1.5
L	1	5	8	6	8	8.96	Beta	680	510	100	2.0
	2	5	12	8.25	11	12.32	Beta	1360	510	100	2.0
M	1	5	8	2.25	3	3.36	Beta	465	349	100	2.0
	2	5	12	2.925	3.9	4.368	Beta	930	349	100	2.0
N	1	5	8	4.8	6	7.2	Uniform	465	349	100	1.5
	2	5	12	6.4	8	9.6	Uniform	930	349	100	1.5
O	1	5	8	0	0.5	0	Normal	907	680	110	1.5
	2	5	12	0	0.7	0	Normal	1814	680	110	1.5
	3	6	11	0	0.6	0	Normal	1587	680	110	1.5
P	1	5	8	12	15	18	Uniform	450	338	100	1.5
	2	5	12	16.8	21	25.2	Uniform	900	338	100	1.5
	3	6	11	15.2	19	22.8	Uniform	788	338	100	1.5
Q	1	5	8	0	24	0	Normal	816	612	120	1.5
	2	5	12	0	33	0	Normal	1632	612	120	1.5
R	1	5	8	140	200	220	Triangle	874	656	120	1.5
	2	5	12	193.2	276	303.6	Triangle	1748	656	120	1.5

Table 6: Construction Data of Crew Formation (cont'd)

Activity number (i)	Crew Formation (p_i)	Days per week (day/week)	Hours per day (h/day)	Crew Daily Output Rate (OR_{c_i}) (Units/Day)			PDF type	Daily cost rate (CR_{c_i}) (\$/day)	idle-Time cost (Id_{c_i}) (\$/day)	Crew Relocation	
				Min	Mean	Max				Cost (MC_{c_i}) (\$)	Time (Days)
S	1	5	8	10.5	14	15.68	Beta	812	609	120	1.5
	2	5	12	14.25	19	21.28	Beta	1624	609	120	1.5
T	1	5	8	1120	1400	1680	Uniform	350	263	150	1.5
	2	5	12	1545.6	1932	2318.4	Uniform	700	263	150	1.5
	3	6	11	1452	1815	2178	Uniform	613	263	150	1.5
U	1	5	8	862.5	1150	1288	Beta	345	259	150	1.5
	2	5	12	1190.2	1587	1777.4	Beta	690	259	150	1.5
	3	6	11	1118.2	1491	1669.9	Beta	604	259	150	1.5
V	1	5	8	133	190	209	Triangle	672	504	150	1.5
	2	5	12	183.4	262	288.2	Triangle	1344	504	150	1.5

The proposed model used the aforementioned available data for searching and identifying a near-optimal solutions in order to minimize the total expected renovation cost. The proposed model uses a stochastic approach and an optimization algorithm with 1000 iterations, however, the genetic algorithm parameters were set to be a mutation rate of 0.1, a crossover rate of 0.8, and generations of 500 in python (PyCharm Community Edition 2022.3) tool in order to find the best possible solution by reaching the stopping criteria, specified number of generations that have improvement less than the maximum improvement. From the viewpoint of time consumption in finding the results in Python platform, The time consumption for this real-life renovation project was approximately 40 minutes using a personal computer with Intel(R) Core(TM) i7-5500U at a 2.40GHz Processor and 8GM RAM. It should be note that, as the number of leased unit increases as the required computational time increases since they often require a larger genetic algorithms (GAs) computations which were discussed in the implementation stage.

The proposed model is a novel stochastic optimization model that can be used to identify a near-optimal solution for renovation projects that provide a minimum expected project cost. The proposed model implemented using the two aforementioned phases, as shown in Figure 10. First, the optimization phase was designed to identify a number of solutions for the specified decision variables, work sequence (w); start date (s_i); and crew formation (c_i) for each activity ($i = 1 \text{ to } I$). Second, the simulation phase that initially integrates scheduling algorithm with Monte Carlo simulation in the schedule module while considering uncertainty in the output rate of crews, in order to generate a renovation plan for each solution obtained in the optimization phase by calculating the project duration (d_{i,w_j}^n), start date (S_{i,w_j}^n), and finish date (F_{i,w_j}^n) for each activity (i) in each leased unit (j) using Eqs. (14) to (22). Then, cost module calculates the total expected project renovation cost for each solution generated in the optimization phase for the project direct cost (DC^n), interruption cost (INT^n), indirect cost (IND^n), and lease losses (LE^n) using Eqs. (14) to (22). After the completion of cost module, the optimization phase was utilized to identify a near-optimal renovation plan that minimizes the total expected renovation cost once the computations of the simulation phase were finished, as shown in Figure 10.

The optimal renovation plan for this real-life renovation project was obtained by determining an optimal selection of the specified decision variables including: (1) work sequence of all leased

units (w), as illustrated in Table 7; (2) start date (s_i); and (3) crew formation (c_i) for each activities (i), as illustrated in Table 8. Excluding the material costs, this identified near-optimal renovation plan provide a minimum total expected renovation cost of (\$6,769,181) and duration of (1178 days) based on 50% confident level, as illustrated in Table 9. It should be highlighted that the proposed model was also designed and capable of generating optimal solutions to the expected project cost based on different confidence levels (α) that specified by the planner. For instance, Figure 13 shows five alternative optimal solutions to the estimated project cost that were produced for the same real life case study at a confidence levels ($\alpha=50\%$) to ($\alpha=90\%$).

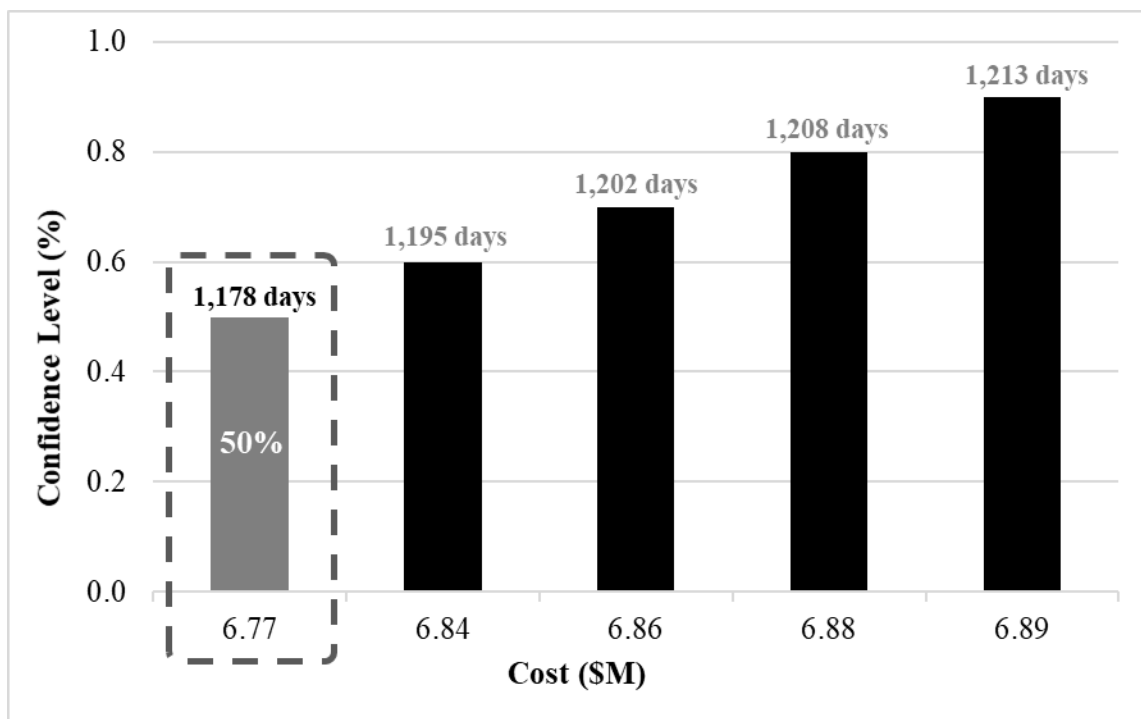


Figure 13: Cumulative Distribution Function of Project Cost

3.4 Discussion

To demonstrate the novel contributions and importance of the proposed model, its generated results were compared with one available deterministic model by AlOtaibi et al. (2021) and another existing stochastic model by Hassan et al. (2020). The following assumptions were made to enable such a comparison: (1) when comparing with the available deterministic model by AlOtaibi et al. (2021), a planner-specified confidence level assigned to be 50% to have a reasonable and fair comparison; and (2) the material cost of all activities was excluded from the computation in this comparison since material cost is identical in all models. It should be noted that AlOtaibi et al. (2021) model is capable of selecting the optimal start date and crew formation for each activity as the proposed model (Table 9); however, it is incapable of considering the uncertainty of the output rate of crews into its calculations that are addressed and optimized by the proposed model. Correspondingly, Hassan et al. (2020) model is capable of considering the uncertainty of the output rate of crews as the proposed model (Table 9); however, it is incapable of considering the work sequence decision variable and leased units availability dates that are considered and optimized by the developed model.

The comparison's results, which are summarized in Table 9, demonstrate the proposed model's novel contributions and its ability to outperform existing models in: (1) considering the uncertainty of the output rate of crews, unlike AlOtaibi et al. (2021) model; and (2) determining the optimal work sequence for all leased renovation units while complying with their availability dates, unlike Hassan et al. (2020) model. The renovation project cost that generated by the proposed model is estimated to be (\$6,769,181) which is (1.03%) higher than the renovation project cost in AlOtaibi et al. (2021) model (\$6,531,147). Correspondingly, the project duration that generated by the proposed model is estimated to be (1178 days) which is (72 days) shorter than the renovation project duration in AlOtaibi et al. (2021) model (1250 days) since the proposed model considers the uncertainty of the output rate of crews, as shown in Table 9. Hassan et al. (2020) model resulted in infeasible schedule since activities were planned prior to the availability date of units, as shown in Table 9.

Table 7: An optimal Selected Work Sequence of all Leased Units by Analyzed Models

Analyzed models	Work sequence of all leased units (w)																													
Proposed model	1	3	2	23	21	7	27	25	22	13	30	6	18	26	14	11	15	12	8	9	16	17	10	29	5	4	24	20	19	28
AlOtaibi et al. (2021)	1	2	3	28	20	21	27	24	19	18	26	23	30	16	29	22	25	17	7	6	8	9	14	10	11	12	5	13	15	4

Table 8: Selected Decision Variables by Analyzed Models

Activity (i)	Proposed model		AlOtaibi et al. (2021)		Hassan et al. (2020)	
	Strat date (s_i)	Crew formation (c_i)	Strat date (s_i)	Crew formation (c_i)	Strat date (s_i)	Crew formation (c_i)
A	24	1	34	1	Infeasible schedule ^a	
B	36	1	37	2		
C	43	1	38	1		
D	49	1	39	1		
E	90	1	68	1		
F	113	1	85	1		
G	114	1	86	1		
H	118	1	87	1		
I	120	1	88	1		
J	137	1	89	3		
K	140	1	90	1		
L	49	1	39	1		
M	55	2	40	2		
N	108	1	74	1		
O	134	1	90	1		
P	140	1	94	1		
Q	48	1	39	1		
R	80	1	46	1		
S	133	1	52	1		
T	64	1	39	1		
U	141	1	97	1		
V	150	2	110	1		

^aAll activities were planned prior to the availability date of units, since Hassan et al. (2020) model is incapable of considering the leased units' availability dates.

Table 9: Project Capability, Cost, and Duration by Analyzed Models

Analyzed models	Project Capability					Project Cost and duration					
	optimal work sequence of all units	Considering uncertainty of output rate of the crews	Considering availability dates of all leased units	Rental losses of leased units per month	Crew remobilization	Total renovation cost (Non-material) (\$)	Cost savings		Duration (days)	Duration savings	
							(\$)	(%)		(days)	(%)
Proposed model	Yes	Yes	Yes	Yes	Yes	6,769,181	---	---	1178	72	1.06
AlOtaibi et al. (2021)	Yes	No	Yes	Yes	Yes	6,531,147	238,034	1.03	1250	---	---
Hassan et al. (2020)	No	Yes	No	No	No	Infeasible schedule ^a					

^aAll activities were planned prior to the availability date of units, since Hassan et al. (2020) model is incapable of considering the leased units' availability dates.

CHAPTER 4 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

A proposed stochastic optimization model was designed to optimize the renovation planning of leased renovation buildings while considering the output rate of crews in order to highlight its capability in minimizing the total expected renovation cost. The model's calculations were carried out in two main phases: (1) optimization phase that identifies a near-optimal renovation plan in order to minimize total expected renovation cost by determining the optimal selection of all specified decision variables: work sequence, start date, and crew formation for each activity; (2) simulation phase that initially determines duration, start date, and finish date for each activity in the schedule module, then determines direct cost, interruption cost, indirect cost, and lease losses in the cost module, in order to calculate the total expected renovation cost for all solutions that were generated in the optimization phase. To highlight the novel capabilities and practicality of the proposed model, a real-life renovation project of leased houses was used to compare the results of the proposed model with two recent existing models, a deterministic model by AlOtaibi et al. (2021) and a stochastic model by Hassan et al. (2020).

The results of this study demonstrate the contributions of the model to the existing body of knowledge, along with its novel methodology in: (1) producing a set of possible renovation plans that fulfill all specified constraints; (2) determining a near-optimal selection of a number of practical decision variables including: work sequence, start date, and crew formation of each activity in the leased renovation project; and (3) calculating the minimum total expected renovation cost of all leased houses. This proposed stochastic model and its unique capabilities are expected to give renovation planners of leased buildings the needed assistance to minimize the total expected renovation cost while considering the uncertainty of the output rate of crews. This can be useful for renovation planners in identifying a near-optimal plan for their projects, providing them with a model to handle the uncertain nature of construction projects, and make better decisions.

4.2 Recommendations

Despite the fact that the proposed study fulfilled all of its research objectives, further research areas have been discovered in order to expand and build on the finished work. Future research areas include the following: (1) developing a novel stochastic optimization model for leased renovation projects that comply with multi-objective functions in order to get a near-optimal trade-off by considering both the total expected cost and duration of the leased renovation project; (2) allowing other precedence relationships across each renovation activity, such as start-to-start, finish-to-finish, and start-to-finish along with the lag time; and (3) extending the model framework in python to incorporate more decision variables and constraints, including material purchase and shipment decisions.

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