Agile-Based Optimized Planning and Scheduling Methodology for Multiple Scattered Projects

by

Ali Bayesteh

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Construction Engineering and Management

Department of Civil and Environmental Engineering

University of Alberta

ABSTRACT

Effective project planning involves complex procedures crucial to project management's success. Resource allocation and project scheduling are at the core of these planning processes, which require careful attention to project and resource constraints. Allocating resources can be daunting, especially when resources are limited and must be shared among multiple projects. The scheduling of projects can compound this challenge, especially when projects have strict deadlines, are geographically dispersed, and require extensive preparation. Urban infrastructure construction and public/private utility companies face this challenge as they are responsible for the timely completion of many geographically dispersed construction projects with limited resources available. Implementing effective planning methods in such a dynamic resource constrained multi-project setting is paramount to avoid potential roadblocks from derailing the projects. Nonetheless, there is currently a lack of established methodologies that can effectively tackle the challenges inherent in this problem. The current project management techniques and scheduling methods fall short in their ability to explicitly state, model, analyze, and optimize the problem of resource allocation and scheduling multiple concurrent projects. Therefore, this dissertation explores the problem and offers an academic and practical methodology to tackle this significant industry challenge through collaboration with Epcor Drainage Construction Services.

This research makes academic contributions by clearly and effectively defining a short-term planning problem in a multi-project management domain with dynamic constraints on project information, resource availability, and contractual obligations (penalty/cancel charges), merges agile project management and optimization as a novel solution to the problem, proposes an innovative agile-based framework tailored to the context of the problem to govern the planning

process at the level of the projects, and develops advanced simplified mixed integer linear (MIP) and binary (0-1) models to enhance the optimization process without compromising the complexity of the problem. The developed models contribute to the body of knowledge by transforming many "If-Then" conditions conceived from the problem's combinatorial nature and incorporating commonly applicable project terms and contract conditions in the real world. This feature makes optimization more efficient and expeditious, catalyzing agile project management. Performance metrics are devised to evaluate the goodness of the resultant plans, and a heuristic algorithm, based on a generalized representation of the current industry practice, is developed for validating the model outcomes. Additionally, the uncertainties inherent in the multi-project environment of the problem are thoroughly explored, and a creative management approach to address uncertainties is proposed as a valuable addition to the holistic approach undertaken by the research. Finally, a novel analytical method is proposed to address underlying issues with the subjectivity of expert opinions and quantify the results in a Multi-Criteria Decision Making (MCDM) application, which is applied to model the crew productivity in this research. This method is an additional contribution and adds value to the research, especially when dealing with the lack of adequate data to account for crew productivity variation.

The practical research outcomes yield direct cost savings in the industry by planning for more projects, maximizing resource utilization and work continuity, preventing or minimizing delay penalties, and eliminating cancellation charges. Furthermore, it reduces the application cost of optimization by using cost-effective optimization engines to find solutions in line with the agile project management framework. The cutting-edge methods established in this research can be adapted to facilitate the time-sensitive dispatching of finite crew resources to multiple projects across various sectors. The insights and innovative solutions presented in this dissertation have the potential to yield significant benefits for both academic and industry communities. Ultimately, this work contributes to a deeper understanding of complex project management challenges and enables organizations to develop more effective project management strategies and methods.

ACKNOWLEDGEMENTS

Writing a thesis, particularly a Ph.D. thesis, is a journey, and while at times it is one that you must take your own, there are times when I have not walked this path without the support and guidance of many people whom I want to thank.

Firstly, this research would not have been possible without my supervisor, Prof Ming Lu. I am very grateful for his unwavering support, invaluable guidance, and contributions to this research. Secondly, I extend my heartfelt appreciation and gratitude to the research committee, Prof Yasser Mohamed and Prof Hooman Askari Nasab, and distinguished examiners, Prof Robert Driver, Prof Eric Jing Du, Prof Zhigang (Will) Tian, for their insightful feedback and invaluable time and support throughout this research.

Furthermore, I acknowledge and thank the Senior Manager, Jason Neufeld, Senior Construction Manager, Frank Policicchio, Construction Manager, Prasanna Lakshminarasimhan, Planning team Paige Watt and Pamela Sacknea, and all other participants at Epcor Drainage Construction Services for their generous knowledge and data sharing, as well as their valuable support and time.

I would also like to thank Ms. Maria Al-Hussein, who provided invaluable support as the university project manager with the industry partner company.

Lastly, I take this opportunity to honor my late father, who passed away two years ago due to Covid. He was a constant source of inspiration with his faithful love. Although he will not be present physically at my graduation, his spirit will always hold a special place in my heart.

It has been a long and, at times, challenging journey, yet I have truly enjoyed this journey and this research. May we all continue to be blessed in our future endeavors.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction and Problem Statement

1.1 Introduction

Project planning consists of dynamic processes and systematic procedures for activity sequencing and resource allocation broadly accepted as the foundation of project management by prominent project management associations such as the Project Management Institute (PMI), Association for Project Management (APM), International Project Management Association (IPMA), and British Standards Institution (BSI), among others (Lester 2006). In this research, the core planning processes involve allocating resources and scheduling multiple projects while adhering to project and resource constraints. Resource allocation can be daunting, especially when a limited number of resources, such as skilled workers and equipment, are shared among several projects. The scheduling of projects compounds this challenge, especially when projects have strict deadlines, are spread out over a wide geographic area and require preconstruction activities to prepare them for construction. In its simplest case, like fitting all the falling blocks together in a limited space in the game of Tetris, a multi-project manager must strategically allocate and schedule resources to ensure all projects are completed on time and within budget. It is about finding the right fit.

Urban infrastructure construction and public/private utility companies face this challenge as they are responsible for the timely completion of many geographically dispersed construction projects with limited resources available. Implementing effective planning methods in such a dynamic multi-project setting is paramount to avoid potential roadblocks from derailing the projects. Nonetheless, there is currently a lack of established methodologies that can effectively tackle the challenges inherent in this problem. The primary reasons can be attributed to the imposed constraints, the complex multi-concurrent project environment, and the nature of this type of project itself. For instance, projects are of a particular kind, and their scheduling deviates from existing construction scheduling due to their relatively short duration, typically lasting only a few days to weeks. It is essential to note that distinctive project characteristics carry significant implications for the scheduling and management of these projects, requiring a distinct approach from their longer-term counterparts. The current project management techniques and scheduling methods focus on projects with longer timeframes. They fall short in their ability to explicitly state, model, analyze, and optimize resource allocation and schedule multiple concurrent projects. These limitations challenge businesses and academics who seek to manage complex projects effectively. It is crucial to develop more practical approaches that address these issues and allow for the successful completion of such projects.

Therefore, to bridge this gap in research, this dissertation explores the problem and offers an academic and practical methodology to tackle this significant industry challenge through collaboration with Epcor Drainage Construction Services (the industry partner). The main processes and steps of conducting this research are outlined as follows.

1. A detailed, comprehensive research methodology is devised and followed throughout the research. It incorporates iterative investigations of a real-world problem through on-site observations, participating in preconstruction, construction planning, and construction work to identify, document, and characterize the problem as best as possible.
2. A short-term, multiple-project management problem with dynamic constraints on project information, resource availability, and contractual obligations (penalty/cancel charges) is

thoroughly and effectively defined.

3. An extensive multidisciplinary literature review is conducted, exploring opportunities to assist in tackling the problem.
4. Based on the problem specifications, comprehensive literature review, and close collaboration with the industry partner, it is determined to merge agile project management and optimization as the solution to the planning and scheduling processes, mainly due to constant changes in the planning scope and associated uncertainties.
5. Innovative simplified mixed integer linear (MIP) and binary (0-1) models that incorporate the constraints imposed on the problem are formulated.
6. Performance metrics are devised to evaluate the goodness of the resultant plans, and a heuristic algorithm, a generalized representation of the current industry practice, is developed for validating the model products. The outcomes achieved using the developed Excel-based program are compared with those obtained through the heuristic algorithm.
7. A customized framework utilizing Agile methodology is presented through a step-by-step flowchart and forms tailored to the problem's context. The Agile-based framework is complemented by an Excel-based program implemented in VBA to provide pragmatic solutions.
8. The uncertainties inherent in the multi-project environment of the problem are thoroughly explored and categorized. Common approaches for addressing uncertainties are reviewed. An innovative management approach to address uncertainties is proposed as a valuable addition to the holistic approach undertaken by the research.
9. Finally, an analytical method is proposed to address underlying issues with the subjectivity of expert opinions and quantify the results in a Multi-Criteria Decision Making (MCDM)

application, which is applied to model the crew productivity in this research.

It is noteworthy that project scheduling determines the start and end dates of project activities, while resource allocation ensures that limited resources are provided in a timely and adequate manner for project execution (Schultmann and Sunke 1999). Through effective project planning, organizations can optimize their resource utilization and ensure the timely completion of multiple projects.

1.2 Problem Statement

Project resources are limited in amount and capacity, particularly when multiple activities or projects share the same resources (Lu and Li 2003). For instance, construction, consulting, and maintenance organizations usually employ a limited number of skilled workers and equipment shared between multiple projects. Allocating limited shared resources to a set of projects that do not exceed resource availability boundaries, especially when the projects are tied to restricted deadlines and scattered over a wide geographical area, is a daunting task. Project managers in public organizations that manage annual construction programs that comprise many new or rehabilitation projects, such as bridges and highway administration, school boards, municipalities' construction works, and utility provider companies, are challenged with this distressing task (Draude et al. 2022, Sarker, et al. 2012).

The diagram depicted in Figure 1.1 provides an overview of the problem, pulling from the investigation findings of the industry partner (i.e., the drainage construction department as a part of Epcor Utilities Inc., herein called the department) and the standard procedures employed by infrastructure maintenance organizations.

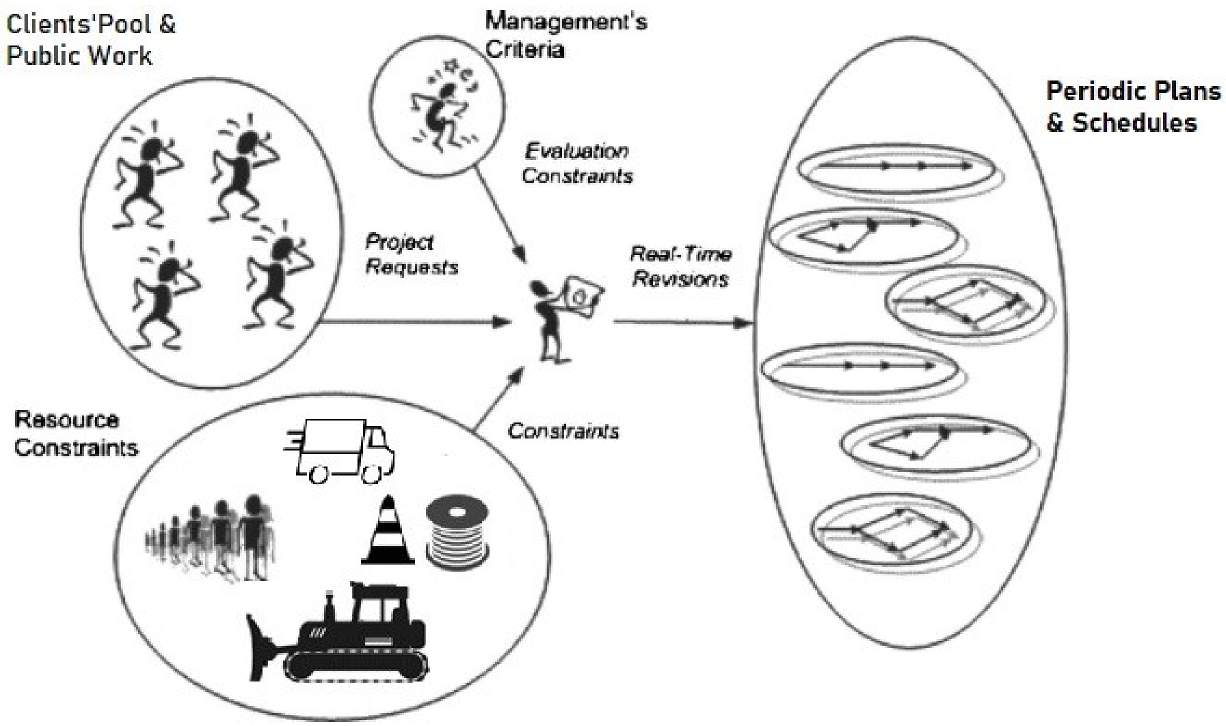


Figure 1.1: Resource Constrained Multi-Project Planning Domain

The process commences with the submission of work orders from clients located in various areas throughout the city. The maintenance department may also create work orders based on periodic preventative inspections, adding to the project pool.

Projects are required to be completed by the limited full-time crews hired by the department within the deadlines. The department's planner is responsible for allocating crews to the projects. It is up to the planner, shown in the middle of the diagram, to plan a dynamic set of many construction projects and utilize crews considering their availability within management constraints to complete the client-requested and public projects while not exhausting crews. At the same time, during a workday, the planner may need to revise the plan based on new incoming projects or updates from the field, as depicted on the right side of Figure 1.1.

Notably, the current practice has no standard procedure or does not utilize quantitative methods for project scheduling and crew assignment and rarely allows for considering better alternatives. With many projects (ongoing, planned, and newly added) and tight constraints on the availability of crews (weekends off, leaves, or holidays) and project deadlines, the current planning and scheduling practice requires tedious trial and error to arrive at a practically feasible solution.

Existing resource allocation methods provide valuable results on single projects; however, these methods become less effective as the number of concurrent projects grows and changes over time (Dasović et al. 2020; Kastor and Sirakoulis 2009; Pellerin and Perrier 2018). Additionally, in relation to the present problem, it is worth noting that projects function independently of one another, and as such, there is no logical relationship to form an activity-on-node (AoN) network. Moreover, as can be noticed in Figure 1.1, once projects are planned, each node represents a project within a larger multi-project plan that is susceptible to change and, therefore, cannot serve as a base for existing project management tools such as Oracle Primavera P6 or Microsoft Project (MSP). Even if a basis could have been formed, these commonly used project planning software are not a viable solution for this particular problem. And this is because the resource allocation in these programs is conducted manually, with a few visualization reports, such as resource allocation layouts and resource usage profiles, which can be generated only to navigate and observe over or under-allocations. The solution can become quickly irrelevant and outdated as the situation in the system evolves over time. Therefore, typical software applications do not provide a reliable means for optimizing resource allocation. Furthermore, the current project planning programs are not equipped to handle other constraints inherent to the problem effectively, such as project deadlines and priorities.

Another fundamental feature distinguishing these types of construction projects from others is their shorter timeframe for completion. It is essential to recognize that this difference has considerable ramifications for the planning and supervision of these projects, necessitating a unique approach compared to those with longer timelines.

Consequently, conventional project planning techniques and tools fall short in addressing this multi-concurrent project problem, especially since project and resource constraints are involved. In addition, established practices lack the practical means and methods to explicitly articulate, model, analyze, optimize resource allocation, and schedule many concurrent projects in this situation. The second chapter of this study will further elaborate on the incompatibility of existing methods in dealing with this specific class of problem.

In light of this, the research aims to develop models and techniques tailored for planning such construction projects with the constraints mentioned earlier. The following section expounds on the problem specifications.

1.3 Problem Specifications

This section outlines the general specifications of the problem. The specifications have been recognized through a prudent iterative problem investigation in collaboration with the industry partner company, coupled with an extensive review of pertinent literature. The intention is to provide a more detailed practical perspective to cater the mathematical modeling of the problem. To illustrate the general problem, it is helpful to briefly examine the different types of projects that the industry partner company typically undertakes. I refer the reader to Kung et al. (2008) for a more in-depth interpretation of the operational process. The operation comprises a high volume of projects classified in the following categories, each with its respective specifications listed in the subsequent subsection. The term "job" can be used interchangeably in reference to this type of project in industry due to their relatively short time frames.

The department operates an extensive network of water and sewer lines comprised of three categories of projects as follows.

1. *Standard Projects (Service connections)*: this category comprises new water and sewer line installations or repairs demanded by clients.
2. *Prioritized Projects*: in addition to clients-demanded projects, the maintenance department inspects and monitors the network to identify any issue that demands the construction department's attention, resulting in the triage of projects with various priorities. The prioritized projects that do not pose a significant risk to the public are fixed later within regulatory deadlines dictated by the risk involved.
3. *Emergency Projects*: inspections may raise the affirmation of emergencies (such as collapsed or broken pipes, sewer backups, lost services, and unexpected floods), or they may come through the department's hotline. The department's policy is to respond to an emergency report within 72 hours of receiving it.

1.3.1. Projects Specifications

The multi-concurrent projects share unique features, which are recapped as follows.

- Each project has a unique location (i.e., a specific site or a client premise), specific site conditions, unique scope, and may have separate contract/agreement, unique priority ranking, and its unique contract terms and conditions, and unique client.

- Projects are distinct from activity, each comprising several activities (e.g., excavation/ trenching, laying the bedding, sloping, piping, and backfilling).
- Projects are independent of one another with no dependency or logical relationship.

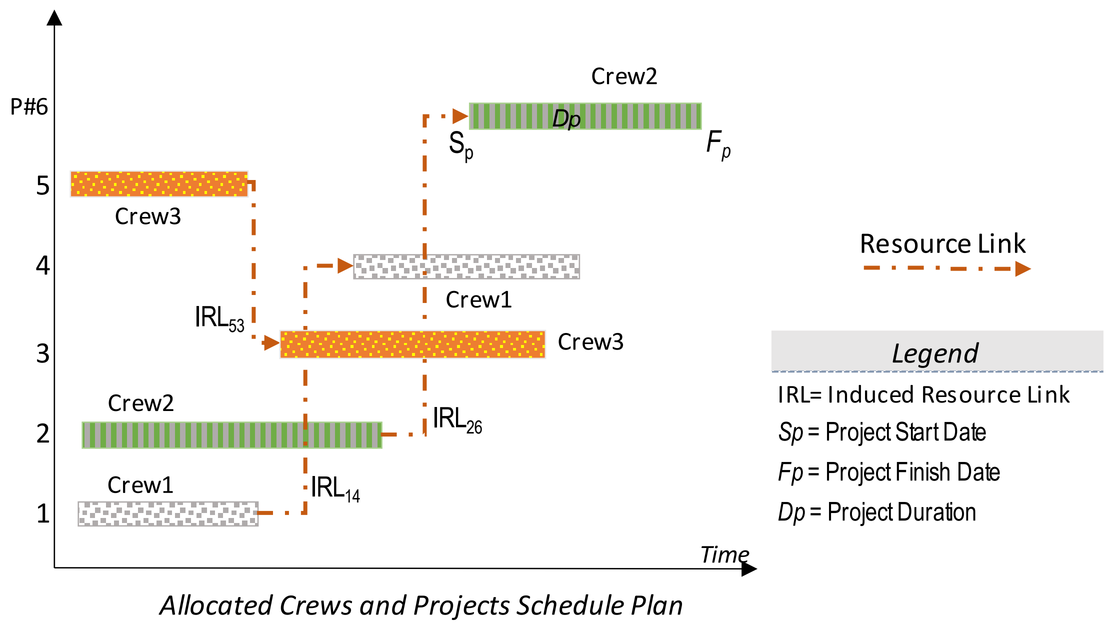


Figure 1.2: Projects dependency induced by crews constraints

- Nevertheless, it is essential to note that crew constraints are the only factor that induces dependency among projects following the allocation of crews, as exemplified in Figure 1.2.
- Unlike other construction undertakings that can last months or years, this particular category of construction projects typically does not require an extended timeline. Project time duration falls within a relatively narrow range depending on the type of project.
- Each has a specific received date and is registered with a unique work order or project ID.
- The target duration for the projects is associated with deterministic values. However, they do not necessarily have identical durations, as seen in Figure 1.2.

- Projects are executed by the available professional construction crews who must visit each site to render the construction service within the project duration.
- Each prioritized project is assigned with a priority index; some projects that demand immediate attention are prioritized, resulting in the triage of projects by various priorities.
- Each may have a due date, and deadline by when they must be finished. These dates are known several weeks to a few months in advance, and they are often mandated by regulatory authorities or required by clients through a binding contract.
- Notably, the project deadline is generally dictated by the allotted time for work permits or temporary road closure orders, as well as a buffer to account for uncertainties and the limited associated risks with these types of projects.
- Delays from due dates and deadlines may result in penalties similar to liquidated damages. Liquidated damage refers to an amount of money agreed upon in advance and paid to the party that did not break the contract if a breach of contract occurs. It is predetermined compensation for the damage caused. In addition, delays may lead to social costs and reputation damage. Although the penalty may not be real dollars, it could reflect the importance of project cancellation or losing the client. That makes it differ from liquidated damages in the conventional contract.
- The number of emergency projects in a typical week is random, reflecting the actual situation.
- The overall scope of portfolio management is dynamic due to new projects' arrivals, client cancellations, changes to the project deadlines, and emergent projects.

1.3.2. Crews' Characteristics

A finite professional crew executes these projects within limited working days at specific site locations. Before elaborating on the main crew characteristics, the term "crew" in the undertaken problem is defined as follows.

Crew definition: in a construction project, a crew typically refers to a group of skilled laborers, tradespeople (e.g., carpenters, plumbers, masons, landscapers, welders), and technicians (e.g., electricians, HVAC technicians) with the necessary expertise and qualifications. The crew members work in coordination with each other under the supervision of a foreman. The typical crew definition in construction projects also applies to the context of this problem.

- Although crew composition may change over time based on company-wide work projections and strategic planning, the composition is fixed for short-term planning due to tactical staffing decisions.
- Each crew can perform at most one project at a time, as seen in Figure 1.2. Therefore, each client is served by exactly one crew, and various crew visits are not planned to accommodate better communication with the clients.
- Each crew carries the required tools and materials to the site. It is to be noted that this research assumes a central inventory depot that allows crews to restock material and prepare onboard equipment to accomplish the planned work for the projects.

1.4 Scope and Assumptions

Without compromising the generality of the problem, the research makes certain assumptions about the projects, the level of planning detail required, and the planning scope. These assumptions are summarized in the following subsections.

1.4.1. Project Assumptions

The following attributes and assumptions are made based on the nature of the projects.

- The required duration for each project is generally fixed as the most likely value by experienced practitioners based on checking similar projects completed recently in the neighboring area.
- The required duration for each project is generally fixed as the most likely value by experienced practitioners based on checking similar projects completed recently in the neighboring area.

1.4.2. Crew Resources Assumptions

- The nature of the projects necessitates the formation of crews with identical compositions consisting of four or five skilled workers, a foreman, and a vehicle.
- The vehicle assigned to each crew is equipped with all the necessary materials and tools required to complete assigned tasks. With regard to reloading materials, crews are required to restock the truck from a central inventory as part of the mobilization process.
- To ensure effective project planning, this research assumes that crews are indivisible, and therefore allocates identical crews depending on the specific work type, given the varying
- skill levels of workers for different types of work.

1.4.3. Planning Scope

- It is deemed more fitting and effective to govern the project planning process from a project-level perspective instead of focusing on the activities level. This decision is based on the projects' logical independence relationship and project-level crew requirement, made after thorough discussion with industry specialists.
- Tailored models are developed to suit various project constraints that are based on the actual terms and conditions of construction projects.
- The models do not incorporate the distance between sites since crew members return to their homes at the end of each day and commute to the specific project site at the beginning of each working day. However, the models do consider the crew members' commuting time within the city limits, which is regarded as part of their preparation time before the start of each workday.
- Despite project durations being estimated as integer intervals, the ratio of crew transition time to project duration is minimal. Even if the model had accounted for the fractional number of durations to include crew transition time, the number of required travels between allocated sites is negligible. As a result, crew travel time between projects can be effectively disregarded. This approach avoids routing optimization and its associated computational challenges while ensuring sufficient consideration of the essential elements. It’s worth noting that while crew allocation plans are barely modified due to the travel time between sites, the plan is visually presented on Google Maps as a tool for construction managers review (this is further explained in section 4.3.2). If there arise any necessary adjustments, they can be made accordingly based on the map.

- Construction on site is planned to start and continue in several working days non-preemptively, i.e., in a single continuous interval without interruption that matches the actual situation due to the public inconvenience that the site mobilization/access imposes on the community traffic or business around the site location. Also, since mobilization is a significant portion of the time required to complete the work, preemption of crew work for allocation to a different project is not allowed.

It is to be noted that projects prioritization follows risk analysis processes consisting of risk/hazard identification, analysis, and evaluation processes. The processes, in general, define risk criteria with likelihoods and consequences related to (1) health and safety (public and employees); reputation (credibility as a trusted utility service provider); (3) environment (including public health), (4) regulatory compliance, (5) business interruption (reliability), and (6) financial impact (operating loss/extra expenses/asset damage) (Grigg 2012, Shahata and Zayed 2016). The processes entail taking systematic analytical procedures to rate the event's likelihood or consequence effectively and producing a project priority index, which is not the focus of the current planning problem definition but serves as one input factor in the optimization formulation described in the corresponding chapter. Separating the prioritization process from the planning process can be beneficial in preventing conflicts and tensions among crews since it eliminates the possibility of crews competing for access to specific projects and prioritizing them over others, which can result in communication breakdowns and decreased cooperation.

It should be noted that the project prioritization process does not consider the respective due dates, deadlines, or timelines associated with each project. These factors are not considered when determining the priority of projects.

1.5 Magnitude Of The Problem

Budget restrictions leave managers in charge of infrastructure management organizations, such as utility companies and highway administrations, with few resources to maintain and improve the infrastructure/facilities. Given the resources and projects' restrictions, the high volume of projects, and the pressure from authorities to conduct these projects in a timely and cost-effective fashion and with minimum service interruption to the public demands efficient usage of resources and constant attention to project planning and control. However, as illustrated, the conventional project planning methods and tools are insufficient for this complex multi-concurrent project planning problem. Therefore, the current practice to address the problem is a trial-and-error approach, which can be tedious, given the number of ongoing, planned, newly added projects and the imposed constraints. The resultant solution is far from the optimum but practically feasible at best, which may not correctly align with all the project deadline constraints. In reality, this potentially leads to completion delays, large backlogs of projects, clients' dissatisfactions, business and social costs, and inefficiencies in limited resource utilization that affect infrastructure and facilities' long-term health. Therefore, it is crucial to establish a suitable methodology and system that can aid infrastructure and facility project managers in allocating limited resources effectively while planning projects. Such an enhanced allocation and planning system will lead to the timely completion of projects, optimal utilization of resources, and, ultimately, a reduction in long-term maintenance costs while enhancing the service level of infrastructure and facilities.

1.6 Sources of Uncertainties

Based on the defined features of the problem, this section aims to present the sources of uncertainty by reviewing relevant literature and consulting subject matter experts. The subsequent chapter will delve into the common approaches utilized to address the identified uncertainties and discuss their applicability in tackling the problem at hand.

As defined by (Meredith et al. 2017), uncertainty refers to having "only partial knowledge of the outcome and the situation." Uncertainty is unavoidable in decision-making, and lack of information causes making decisions more complicated. In many realistic settings, planning decisions must be made in uncertain situations. For instance, after deciding on a schedule, a resource may unexpectedly become unavailable, different and unknown site conditions may lead to longer or shorter durations than expected, or there might be an unexpected release of high-priority projects.

It is important to distinguish between uncertainty and risk, as they are not interchangeable terms. Uncertainty pertains to the unknowns, while project risk can be described as "an uncertain event or condition that, if it occurs, may have a positive or negative impact on one or more project objectives" (Lester 2006). Another essential distinction is that the risks are usually expressed in terms of the impacts of the realization of events, usually on project task durations and/or costs. In contrast, uncertainty might or might not have a known effect, concerns all aspects of the work on projects, and is present in all stages of project life cycles (Ulusoy and Hazır 2021).

Simply put, risk refers to a situation in which we don’t know what will happen next, but we do know what the distribution looks like. In contrast, uncertainty is when we don’t know what will happen next, but we don't know what the possible distribution looks like. In project risk management (PRM), as defined in the Project Management Body of Knowledge Guide (PMBOK®), the concept of known unknowns is commonly understood as risks (PMI 2021). Conversely, unknown unknowns are deemed inconceivable, and PRM does not attempt to account for them. It is important to note that this research focuses on the uncertainty that arises during the planning and execution of projects under the conditions outlined in sections 1.2 and 1.3; this is due to the limited risk associated with this type of project which is mitigated through buffer time incorporated in the project deadline.

Project uncertainty is mainly classified in the published literature by the source or impact (Pich et al. 2002). At the conceptual design stage of modeling and managing uncertainties, it is more critical to determine the significant sources of uncertainty than to determine and quantify them since some defined uncertainties may be insignificant (Thunnissen 2005). In construction projects, several sources of uncertainty can affect project outcomes. These uncertainties can arise from various factors and impact project schedules, costs, and overall project success. The following categorization is based on common themes found in the project planning recent literature such as (Atkinson et al. 2006; Hazır and Ulusoy 2020; Siraj and Fayek 2019; Zhong et al. 2018). Various studies have attempted to categorize sources of uncertainty in construction projects from different perspectives, including external and internal classifications. It is worth noting that the categories may overlap across multiple sources of uncertainty. However, for this research, the following list has been compiled based on standard industry terminology.

1. *Design Uncertainty*: Uncertainties associated with the project's design can arise due to incomplete or defective design information, conflicting specifications, or changes in design

requirements during the project lifecycle. Design uncertainties can lead to rework, design modifications, and schedule delays.

2. *Scope Uncertainty*: Uncertainties related to the project scope may arise from requirements ambiguities, client expectations changes, or evolving project objectives. Scope uncertainties can result in scope creep, disputes, and increased project costs.
3. *Cost Uncertainty*: Construction projects are prone to cost uncertainties due to various factors such as inaccurate cost estimation, fluctuations in material prices, unforeseen site conditions, and changes in project scope. Cost uncertainties can lead to budget overruns and financial risks for project stakeholders.
4. *Schedule Uncertainty*: Project scheduling uncertainty can arise from inaccurate activity duration estimates, delays caused by weather conditions, unforeseen events, resource constraints, or coordination issues. Schedule uncertainties can result in project delays, penalties, and disruptions to subsequent project activities.
5. *Technical Uncertainty*: Uncertainties associated with the project's technical aspects can emerge from using new technologies, complex construction methods, or unfamiliar site conditions. Technical uncertainties may lead to performance issues, quality problems, and the need for additional resources or expertise.
6. *Environmental Uncertainty*: Construction projects can be affected by environmental uncertainties, including weather conditions, natural disasters, regulatory changes, and environmental risks. Environmental uncertainties can disrupt project activities, cause safety concerns, and impact the project schedule and cost.
7. *Stakeholder Uncertainty*: Uncertainties arising from stakeholders' actions, decisions, or conflicting interests can influence project outcomes. Stakeholder uncertainties can result

from changes in project requirements, disputes, communication breakdowns, or unforeseen stakeholder actions.

8. *Legal and Regulatory Uncertainty*: Uncertainties related to legal and regulatory aspects can arise from changes in building codes, permits, zoning regulations, or environmental regulations. Legal and regulatory uncertainties can lead to compliance issues, delays, and additional project costs.
9. *Market Uncertainty*: Construction projects can be affected by market uncertainties such as economic fluctuations, changes in market demand, or fluctuations in material and labor costs. Market uncertainties can impact project financing, resource availability, and the viability of the project.
10. *Organizational Uncertainty*: Uncertainties related to project organizations and management practices can arise from changes in project leadership, organizational restructuring, inadequate communication, or conflicts between project participants. Organizational uncertainties can affect project coordination, decision-making, and team performance.

Furthermore, regarding project goals' impacts, (Zhu et al. 2017) divided project uncertainty into two main groups: minor deviations and disruptions.

- Deviations are commonly encountered due to random variations, particularly in the duration of activities.
- Contrarily, disruptions are infrequent unexpected events that are considerably more complicated to handle. The authors classified disruptions as follows based on their effect on the project structure.

- *Project network disruptions*: new activities or precedence relations may be added to the network or deleted.
- *Activity disruptions*: Activity times or resource demands of the activities may change.
- Resource disruptions: Resource availability may change.

The above-developed list was presented to the department's managers and field practitioners, and with their collaboration in a brainstorming session, the following source of uncertainties concluded as the main sources of uncertainty in the undertaken problem.

1. *Multi-Project network disruptions:* The lack of a technological network at the planning stage distinguishes this type from regular construction projects. Further, after deciding on a plan, the construction order can alter at the execution stage due to the new project arrivals (emergency projects) or client cancellations. A new project arrival increases the number of projects in the multi-concurrent project pool, causing more severe disruption than the variation of duration or resource availability. The new project can be started before all the ongoing projects in the multi-project plan are finished. However, the new multi-project plan is no longer optimal since the new make-span is prolonged, and the resources may already be fully utilized. The original optimal baseline plan typically becomes suboptimal or irrelevant in the new project execution environment when the new project starts directly.
2. *Emergency projects uncertainty:* another significant uncertainty lies in the unpredictability of emergency projects in terms of their overall quantity and time of arrival.
3. *Resource constraint changes:* A crew availability calendar may change and unexpectedly become unavailable after a plan has been finalized.
4. *Project duration estimation uncertainty:* some projects may take longer to finish than

anticipated due to inclement weather or a complication during excavation (e.g., soil condition variations). Nevertheless, this uncertainty is deemed insignificant since the projects are typical and have short durations estimated by the experienced practitioner at the time near construction. Therefore, the execution condition can be foreseen with higher predictability, and duration is estimated with high accuracy.

5. *Legal and Regulatory Uncertainty:* As mentioned earlier, in construction projects, uncertainties in classification, changes in building codes, permits, zoning regulations, or environmental regulations may occur in this type of project as well.
6. *Uncertainty of Project deadline:* refers to the lack of certainty or predictability regarding the specific date or time when a project will be completed. In the undertaken problem, each project's deadline is associated with a specified time window on a work permit or a temporary road closure order. Notably, the department considers a certain amount of buffer time to account for perceived risks that are generally very limited when setting the project completion date with the client.

The above list categorizes the main uncertainties in this type of project in this research.

1.7 Research Objectives

Now that this thesis has clearly and comprehensively stated the problem, it aims to develop an adequate planning and scheduling methodology to address the resource allocation and scheduling problem of multiple concurrent scattered projects. The following criteria are considered to accomplish this goal.

- *Simplified and efficient development*: while models should capture and formulate all the realistic conditions and constraints of this class of projects, they should be simplified and straightforward to be comprehended and communicated in construction terms and conditions. This is a crucial criterion to keep the models alive and updated with constraints or other model changes over a longer time. Furthermore, efficiently providing solutions is essential due to constant changes in this dynamic multi-project planning problem.
- *Linearity of the models*: formulating the constraints and conditions of the problem as linear models is very challenging but paramount to reaching optimal yet practical solutions in an iterative fashion or agile approach while avoiding the need for metaheuristics that add complexity to the methodology.

These two mentioned criteria are aligned and prepare the foundation for the following criterion.

- *Flexible and adaptive framework*: A flexible framework is necessary to put the optimization analytical models into practice. At the same time, the framework needs to be adaptive to the dynamic conditions of the studied problem and provide a base for continuous improvement and the foundation for just-in-time revisions of the plans as required by the real-world situations.
- *Cost-effective platform*: computing platform and tools should be practical and suitable for the intended application setting while exhibiting cost-effective purchasing and low-cost maintenance. This factor should be considered, as it is important for successful implementation.
- Once all the above measures come together acts as a decision support system that caters to real-world applications, such as infrastructure /facility managers, municipalities/ private

utility providers, and construction trades, that in today's competitive market, are under pressure to maximize the number of completed projects on time as practically possible, the utilization efficiency of their limited available crew resources, the work continuity of their crew resources, thus retaining satisfied clients and building a long-term business reputation.

1.8 Research Methodology

This section thoroughly describes the process and methods used to conduct this research.

1.8.1. Introduction

According to a study developed at the Center for Integrated Facility Engineering at Stanford University called CIFE method (Fisher 2006), research methods for new projects can be divided into three categories.

1. Research projects exploring a new terrain in two different ways:
    a. In practice, through conducting on-site observations or participating in pre-construction, construction planning, and construction work to identify, document, and quantify a particular problem as best as possible.
    b. In the lab, researchers determine the technical feasibility of a particular envisioned system or method through rapid prototyping and using test cases from past projects or textbooks.
2. Pilot projects that test a new method to learn about its practical value and identify necessary improvements to address the challenges encountered by engineers and constructors.

3. Research efforts to expand successful methods from pilot projects for broader implementation.

It is to be noted that formalizing construction projects in model-based problems is demanding, mainly because lab experiments cannot replicate the situations in practice where formal methods must be applied. As a result, construction sites and project offices become research labs, which makes it difficult to isolate a particular factor and study its effect on the outcomes. To overcome this challenge, researchers need to combine field observations with theory in related literature, predictions and insights from experts, and models developed from the observations, theory, and expert opinions (Creswell and Creswell 2017; Fisher 2006).

1.8.2. Summary

A research methodology was adopted to achieve objectives within the research scope. The researcher with professional experience in the construction industry was engaged in the industry partner's daily business to explore the problem in practice.

As depicted in Figure 1.3 and then detailed in Figure 1.4, the primary step of this research process is defining and formulating the problem. Indeed, this is the most crucial phase of the entire process, as it establishes the groundwork for all subsequent steps, necessitating comprehensive and explicit attention. The problem must be articulated with the greatest clarity and concision to ensure that all subsequent steps are based on precise information. Consequently, the research was conducted through an iterative process, wherein the problem and models underwent progressive refinements.

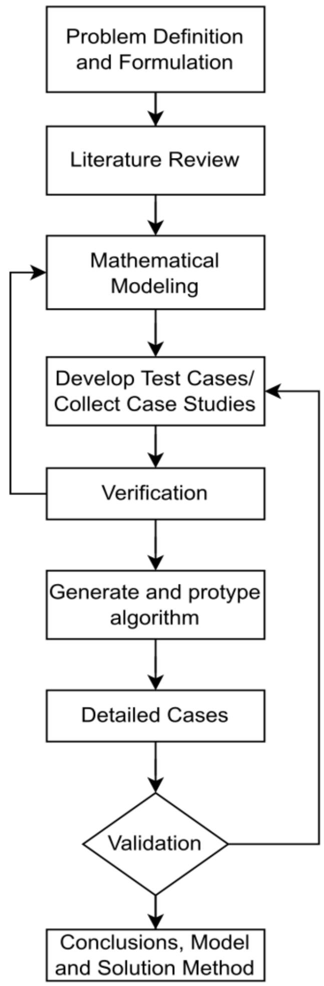


Figure 1.3: Research methodology overall process

For instance, beginning with a very general model of the multi-project resource allocation problem, the initial model was refined and revised several times during the course of this research. The refinements made it possible to conduct more thorough investigations, ultimately enhancing and fine-tuning the models.

Following this iterative process, the general problem was derived from investigating the current and typical industry practice, several discussions with the department's managers and experts, and similar cases reviewed in the pertinent literature.

1.8.3. Detailed Process

As stated in the summary subsection, the problem and models were progressively defined and formulated through an iterative process. As depicted in Figure 1.4, in an engaging work environment with the industry partner, I was actively involved in current processes.

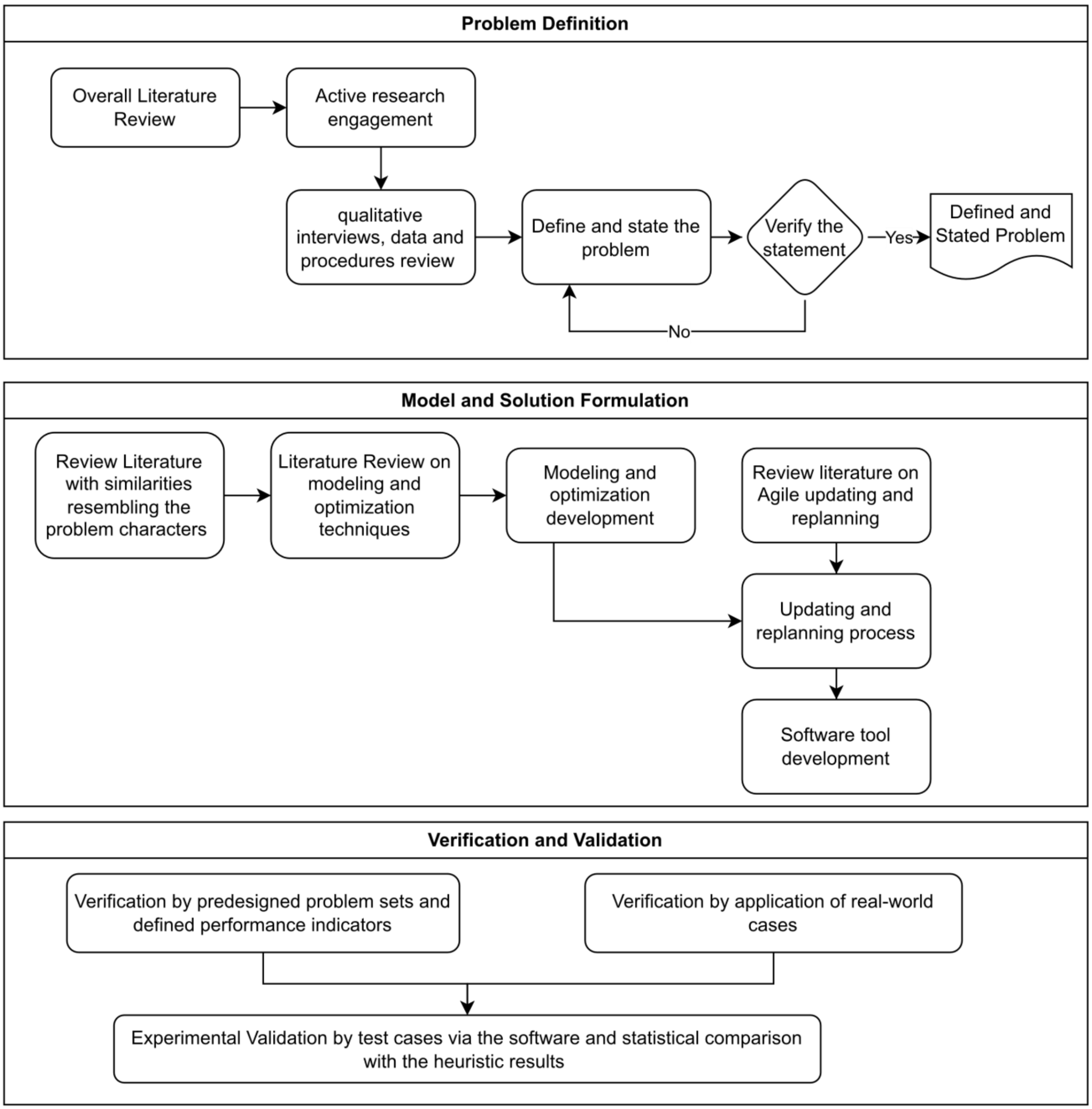


Figure 1.4: Research methodology detailed process

This involvement ranged from receiving work orders and completing preconstruction requirements to planning and distributing projects between site supervisors. Subsequently, site visits were conducted at various locations to oversee the construction activities. In addition, several interviews (more than 50) with practitioners and subject matter experts were conducted during this stage. The participation of several foremen and construction managers was solicited to ensure that meaningful problems and realistic assumptions were formulated regarding the domain.

The *qualitative interview method* was chosen because the participants' opinions were partially or fully unexpected, which made the researcher unable to put all response alternatives in closed-ended questions. A particular analysis of comparable problem areas was conducted, followed by a subsequent narrowing down to resource-constrained scheduling problems, inclusive of both single and multi-projects.

In a nutshell, the three main components of the research methodology are interconnected and interactive, as shown in Figure 1.5. Findings from the literature review shed light on areas to be explored in the field study process. Field studies provide empirical data and real-world context of the problem, while literature reviews offer theoretical foundations and insights. The data collected during field studies are used to validate and refine the problem model.

At the same time, the literature review informs the choice of modeling techniques and identifies relevant parameters and assumptions for the model. Combining the two approaches with insights from industry professionals results in a comprehensive and well-informed problem-solving process, leading to more effective and robust solutions. Multiple iterations and adjustments were undertaken to ensure realistic and more precise formulation and modeling.

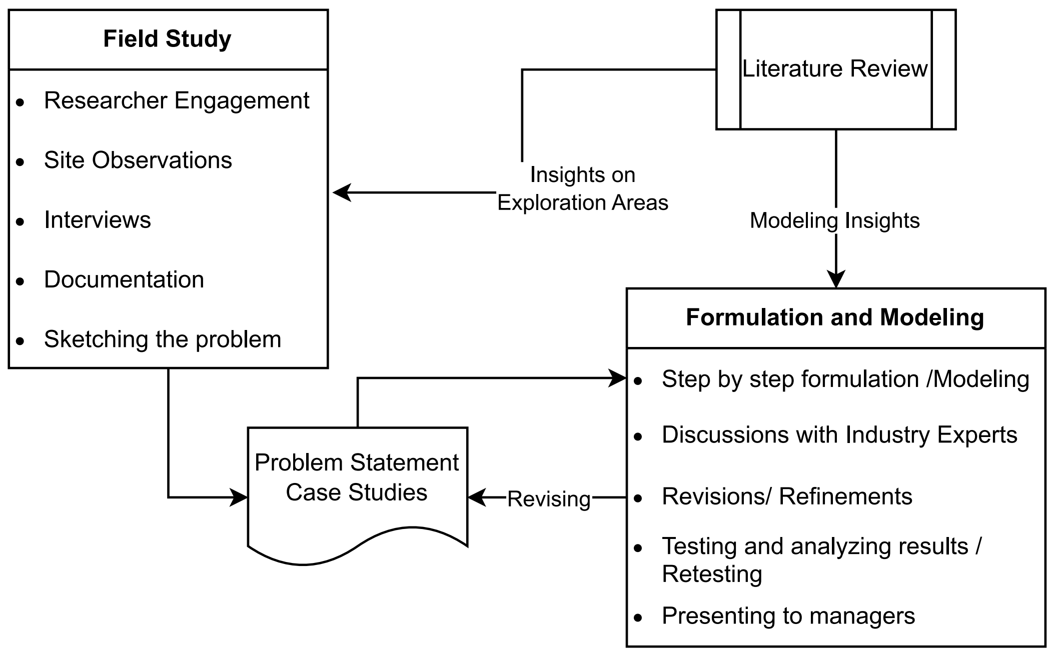


Figure 1.5: Main Components of the Research Methodology

The focus was on the model's linearity and simplicity while elucidating all the practical definitions and formulations required.

The upcoming chapter provides a summary of the research areas reviewed. Chapter Three summarizes the examined concept of agile project management, along with justifications for why it was considered appropriate for addressing the proposed problem solutions. As the problem definition and model became more precise during the course of this research, so did the created optimization models. For example, the first modeling concept evaluated the routing of assigned crews based on crew availability. However, after careful consideration in discussion with subject matter experts, it was concluded that the commuting times were insignificant and would not justify the complexity added to the models if routing optimization were considered. Ultimately, Chapter Four will unveil the development of adequate integer linear programming (ILP) and zero-one (binary) models consistent with agile project management.

Then, I determined the technical feasibility of the envisioned system by prototyping it utilizing data and test cases collected from the industry partner. Several experiments on real-world test cases, rather than bench testing alone, verified that the models were performing as expected. Ultimately, after extensive code debugging, the prototyped system was successfully completed in Excel VBA along with Analytical Solver as the optimization engine.

1.9 Thesis Organization

The dissertation is composed of seven chapters, with each chapter featuring a detailed breakdown of its contents. Detailed contents of each chapter are listed as follows.

First Chapter comprehensively analyzes the problem, highlighting its specifications and underscoring its significance. Additionally, it identifies the primary uncertainties surrounding the problem and outlines the research objectives and methodology to be employed.

Second Chapter summarizes previous studies and literature reviews relating to the problem. It also highlights their similarities and differences with the current research.

Chapter Three briefly introduces agile project management and outlines the reasons for adapting the agile methodology to the problem. And it also covers some of its relevant topics utilized to address the problem.

Chapter Four describes mathematical models for addressing the problem and presents exact and heuristic model solutions, along with real-world case studies and performance metrics to evaluate the effectiveness of the developed plans.

Ali Bayesteh and Ming Lu (2021) "*Analytical decision support to dispatching finite crews to service jobs at customers' premises: case of municipal drainage network repair*", *In Proceedings of ASCE Computing in Civil Engineering Conference, September 12-14, Orlando, Florida.*

Ali Bayesteh and Ming Lu (2022) "*Short-Term Planning of Municipal Drainage Infrastructure Maintenance Operations: Problem Statement and Optimization Solution*", *Journal of Civil Engineering and Management* (under review).

Ali Bayesteh and Ming Lu (2024) *"Short-Term Planning of Municipal Drainage Infrastructure Maintenance Operations: Problem Statement and Optimization Formulation", CI & CRC Joint Conference 2024, Iowa State University and ASCE (under review).*

Chapter Five introduces an agile framework for planning multi-projects and details the steps to implement the framework. It also presents case studies with corresponding results to validate the method. A part of this chapter has been published as:

Ali Bayesteh and Ming Lu (2023) "*Agile Project Planning Framework and Method for Allocating Limited Crews to Drainage Construction Projects* " *In Proceedings of ASCE Computing in Civil Engineering Conference, June 25-28, Cornville, Oregon State University.*

Chapter Six explores approaches to tackle the uncertainties related to the problem at hand. It presents a novel method of addressing these uncertainties.

Bayesteh, A., Pourrahimian, E., Lu, M., AbouRizk, S., (2022). "*Integrated Dematel and Anp-Based Framework to Model Construction Labor Productivity*", *Construction Research Congress 2022, pp. 370-380.*

I was responsible for conceptualization, methodology, data curation, formal analysis, validation, writing original draft, and editing. Elyar Pourrahimian contributed to data analysis, editing and validation part analysis, Dr. Ming Lu was the supervisory authority and was involved with the conceptualization, methodology, and manuscript review and editing, Dr. Simon Abourizk was responsible for proofreading and final review.

Finally, **Chapter Seven** summarizes the conclusions, contributions, limitations, and recommendations for future development.

Chapter 2: Literature Review

This chapter explores other research areas that share similarities with the context and conditions of the current study. The following section provides an essential review of the area of research related to the problem being investigated, which sets the stage and background for the proposed research. The traditional CPM method is initially evaluated to see if it can be used or modified to address the problem, as it is commonly used in project scheduling. Other fields with some similarities are also examined and outlined in subsequent sections.

2.1 Critical Path Method Scheduling

As far as human formative history is categorized, since the early beginnings of (the 1950s-1960s) when critical path method (CPM) scheduling was developed by Kelley and Walker (1959), project managers have relied on critical path analysis to schedule projects. Although the development of CPM brought significant advancement in project management, allowing for more efficient planning, scheduling, and control of complex projects, its drawbacks or shortfalls concerning the problem under investigation are highlighted as follows.

Birrell (1987) disclosed that CPM is incompatible with the fundamental nature of the engineering phases, including feasibility study, design, and contracting. Birrell pointed out that if CPM is imposed upon such cyclic, iterative, and interactive processes, it can jeopardize the quality of their output, which is reflected in the project's flawed life cycle cost profile.

More specifically, CPM requires discrete differentiation of detailed tasks, in which one task must end before others can begin. There can be parallel streams of this in a CPM diagram, but the fundamental requirement of CPM is that each stream, with nodes at the start and finish of each task, follow the order of the arrow diagram. That intercepts the continuous, simultaneous, independent parallel flows of the natural disposition of the efficient construction process. Furthermore, CPM ignores the limited resources availability, calendars' constraints, and zonal constituents in defining tasks. Hence, it considerably reduces or compounds the use of construction plans for deliveries with an efficient flow of resources and the efficiency of the actual construction process. These vital ingredients cannot be and are not expressed in CPM, and hence if CPM is adhered to in construction, an actual construction process that is less efficient than the natural disposition model is created (Birrell 1980; Kim and de la Garza 2005; Lu 2006).

Besides the critiques above of CPM, it is essential to note that the projects involved in the problem are independent with no precedence or logical relationship. As a result, it is not possible to construct a project network, and subsequently, a CPM-based schedule cannot be developed to allocate resources. In other words, a network model cannot be formed to govern the scheduling logic. Therefore, CPM scheduling was not recognized as a suitable method for addressing the current problem.

2.2 Job Shop Problem

The operations research community has devoted considerable attention to the problem of allocating resources in factory settings. These problems are commonly referred to as "job shop" problems. Since the optimization of resource allocation is a central objective of job shop scheduling, it is reviewed as an affiliated area to the problem in this research.

Factory environments are often represented by job shop problem variations, which involve workpieces moving between machines. These products in progress may need varying equipment, order, and batch sizes. As determined by (Stevenson et al. 2005), job shop problem can be distinguished as a process that utilizes machines and facilities with similar functions (i.e., cells or workstations such as cutting, drilling, etc.). The products pass through the functional units according to the required technological sequence (Stevenson et al. 2005). As stated by Kuhpfahl (2016), a unique set-up, alongside its process steps, is required to meet the level of customization that this process offers, and the workstations are utilized to perform various tasks during the manufacturing process. Once customization is completed, the process is fixed unless a new development is required in the long term (Kuhpfahl 2016).

Job shop problems involve organizing the flow and sequencing of raw materials and parts for processing through various manufacturing workstations. In such a context, jobs are scheduled first, and machine timetabling is adapted to cover the machine loads (Kuhpfahl 2016; Pinedo 2009). The following factors explain the differences between the job shop problems and the undertaken problem based on reviewed literature (e.g., (Abourizk and Mohamed 2002; Lu and Wong 2007) and comparative remarks with the problem at hand.

1. In a job shop environment, each job typically follows a specific routing, which specifies the sequence of operations required to complete the job. This predefined ordering in a job shop problem represents a set of task dependencies that are often organized by the production flow or machines capabilities. Whereas, as identified earlier in chapter one, section 1-2, there is no predefined relationship between the projects in the undertaken problem.
2. Job shop production is a process-oriented setting that runs from the beginning of the first task to the end of the last through a chain of workstations, regardless of the number of

machines executing operations. However, in the problem at hand, projects are independent and situated at particular locations, each assigned to one crew in a project-oriented setting.

3. The job shop process is formed in an enclosed, indoor setting with machinery and workforce resources deemed relatively stationary, either fixed at a specific location or moving locations in such a relative closeness that the resources' travel times are negligible in modeling the system. In contrast, the construction projects under the identified problem land in an open-air, outdoor environment (site) with various site conditions, scattered in discrete locations in a wide geographical area. Allocated crews must travel to the sites to perform the projects, additionally the outdoor environments and site conditions may considerably affect their productivity rate.
4. Another main difference is that in a job-shop problem, work input and flow are set based on the production plan, meaning a constant stream of work is scheduled and managed in a production management environment. This contrasts with the problem on hand, which involves discrete projects that are planned and scheduled based on the laid-out constraints in a project management profession.

Based on the evidence presented, it is apparent that the current problem at hand is distinct from the job shop problem encountered in manufacturing. Consequently, the models and solutions proposed for job shop scheduling cannot be applied to the case of this problem.

2.3 Simulation Based Models

A simulation model serves as an approximation of reality and outlines the calculations that offer valuable insights into the potential behaviors of the system being modeled (AbouRizk 2010). Simulation models have been utilized for various scientific objectives, such as prediction and explanation, and applied to the scheduling of limited resources in construction projects, particularly those that involve modular or repetitive construction (Hegazy and Kassab 2003; Lu et al. 2008; Lu et al. 2006; Mahdavian and Shojaei 2020). In other cases, simulation has been combined with other methods for resource allocation. For instance, Liu and Mohamed (2012) presented a model based on a multi-agent resource allocation structure implemented within an agent-based simulation environment developed for a real case of assembly operations of industrial construction modules.

Simulation models can be conceptualized through a three-part structure consisting of input, mechanism, and output conditions (Hassannayebi et al. 2014). And as Tekin and Sabuncuoglu (2004) described, simulations are descriptive models of the system, meaning they represent possible outcomes without explaining how to achieve them. Furthermore, simulation modeling for complicated problems demands critical observation or examination of the problem's features and model necessities, which may also increase the problem's complexity. The purpose here is not to criticize the simulation models, which hold many established advantages as an applied science when employed for suitable problems. Nonetheless, based on the following grounds, simulation modeling does not appear to be a fitting solution for addressing the problem being explored.

- First, it has been recognized that empirical data often do not fully determine causal structure. Even when the available empirical data align with input and output structures, creating and implementing the causal mechanism within a simulation can be complicated and might not accurately reflect the true causes present in the real-world problem (Grim et al. 2011).

- Second, it is less probable to draw actual conclusions from simulation models when accurate measures or setups for relevant input conditions are vague or when the simulation mechanism does not sufficiently regulate the problem's complexity(Eason et al. 2007).
- Third, simulations are sometimes used to obtain intermediate results, but they are primarily utilized for modeling mathematically intractable problems (Tekin and Sabuncuoglu 2004). Given that the problem under investigation can be mathematically modeled tractably, the effectiveness of simulation modeling for this problem is arguable.
- Forth, simulation models don't optimize efficiently; thus, they are often coupled with metaheuristics (e.g., Genetic Algorithms) for optimization, leading to models that are not computationally efficient and straightforward.
- Lastly, due to the dynamic nature of the problem, the planning and updating process may occur regularly on a daily or weekly basis. Due to these frequent updates, simulation modeling may not be the most suitable method as it demands advanced technical skills and knowledge of the simulation algorithm to manage the system and adapt to changes effectively. Furthermore, the process can be time-consuming, which limits its efficiency as a solution.

Consequently, as a result, this study departs from using simulation modeling as the solution to the undertaken problem.

2.4 Operations Research (OR)

Various models can be found in the literature considering diverse factors for project planning that significantly impact the efficiency of construction processes (Sarker et al. 2012). Most of these models originate from operations research, a multidisciplinary field of applied mathematics that employs mathematical modeling, statistics, and algorithms to make optimal or sensible choices in intricate problems (Salvendy 2001). Given the intricate nature of the problem at hand, which involves various variables such as project and crew variables, it is imperative to consider utilizing models from the field of operational research as a potential solution.

In this regard, the vehicle routing problem, a prominent topic in operations research, deals with optimizing routes for a fleet of vehicles to transport goods or provide services to multiple locations, which may share similarities with the problem at hand. Consequently, this topic is explored next to determine if it could be employed or adapted to address the current problem.

2.4.1. Vehicle Routing Problems (VRPs)

In the vehicle routing problems, $\underline{m}$ identical vehicles located initially at a depot are to deliver discrete quantities of goods to $\underline{n}$ customers. Each customer has a demand for goods, and each vehicle has a capacity. A vehicle can make only one tour starting at the depot, visiting a subset of clients, and returning to the depot. Time windows define an interval for each client within which the visit must be completed. A solution is a set of tours for a subset of vehicles such that all clients are served only once, and time window and capacity constraints are respected. The common objective is to minimize the distance traveled and, sometimes, reduce the number of vehicles operated (Bräysy and Gendreau 2005; Laporte 1992). Upon analyzing the characteristics of the problem under investigation and comparing them with the classes for the Vehicle Routing Problem (VRP) literature presented in two recent review articles by Braekers et al. (2016) and Lahyani et al. (2015, it can be determined that the problem at hand differs substantially from VRPs due to the following reasons.

1. The classic VRPs are heavily focused on route characteristics, and related extensions of the VRP in the literature are related to inventory routing, location routing, production routing, and vehicle and driver scheduling in the context of supply chain management. At the operational level, short-term and daily decisions are driven by each vehicle route. In contrast, the problem under this research does not rely on the routing of the crews nor considerate routing as part of the decision process.
2. Time window constraints impose the service schedule for each client based on the client's availability and allow early arrival (i.e., idle vehicle) but not late arrival. In the case of a soft time window, penalties are considered for services starting after the allowed time window. The time window determination at the depot implies that each vehicle's earliest departure and the latest arrival times lie within the interval time associated with the depot. However, in the undertaken problem, the crew schedule is entirely different from the client availability; additionally, no depot is allocated for crews to depart or return.
3. In VRPs, the total customers demand on each route is tied to the vehicle capacity constraint so that it can stay within the capacity. On the contrary, in this study, the total work to be completed in each planning horizon is tied to the crews' availability constraint.

Therefore, based on the main reasons mentioned above, the problem in this research varies thoroughly from VRPs. Moreover, the techniques used in operations research primarily emphasize the theoretical development of models and unique solution procedures specific to that field (Jörg Kalcsics 2008; S.Hiller and J.Leberman 1999). In contrast, models designed for problems within the construction domain should concentrate on the significance of planning, scheduling, applications, and control strategies tailored specifically for construction projects, ensuring comprehensibility and applicability to the construction industry.

2.5 Resource Constrained Scheduling Problems (RCSP)

During the 1960s, the rise of industrial processes and complex production and consumption lines sparked an interest in planning and controlling projects with limited resources. Resource-Constrained Scheduling Problems (RCSP) refer to scheduling problems that occur when project activities are allocated to a resource or group of resources with limited capacity or availability, as explained by Christodoulou et al. (2009). Since the proposition of the RCSP by Dike (1964) resource-constrained project scheduling has been a significant challenge in the field of construction project management. It requires the assignment of dates to project activities and the matching of necessary resources with project tasks over time while considering resource availability constraints and leveling them throughout the duration of the project to meet a fixed deadline (Harrison and Lock 2004).

The RCPSP has been the subject of extensive research since Pritsker et al. (1969) developed a mathematical model for this problem. While the model presented in that paper was powerful, it was limited in its ability to cover situations that can arise in practical applications. As a result, researchers have developed extensions of this problem, typically using the standard RCPSP as a starting point. Various operation research techniques have been extensively studied to address this problem.

At its simplest, the problem involves finding a schedule of activities that does not exceed the available resources at any given time. This is achieved by calculating the total resource hours required for parallel activities over time and generating resource profiles based on the earliest start times, latest start times, or within the total float of each activity, as outlined by Willis (1985).

The RCPSP can be formulated as follows:

A set of activities *N*, numbered from a dummy start node 0 to a dummy end node $n + 1$, is to be scheduled without pre-emption on a set *R* of renewable resource types. Each renewable resource $k \in R$ has a constant availability a_k per period. Each non-dummy activity $i \in N$ has a deterministic duration d_i and requires $r_{i,k}$ units of resource type $k \in R$. The start and end dummy activities 0 and $n + 1$ represent the start and completion of the project, in which their duration and renewable resource requirement equal to zero. A project network is represented by a topological ordered activity-on-node (*AoN*) format where *A* is the set of pairs of activities between which a *finish-start* precedence relationship with time lag 0 exists. A schedule *S* is defined by a vector of activity start times and is said to be feasible if all precedence and renewable resource constraints are satisfied.

The objective of the problem type is to find a feasible schedule within the lowest possible *project makespan*. Therefore, based on the classification scheme of Herroelen et al. (1999), the problem type can be denoted as $m,1 \mid cpm \mid C_{max}$, or following classification scheme of Brucker et al. (1999) as $PS \mid prec \mid C_{max}$. The problem is known to be a generalization of the job shop scheduling problem and involves scheduling project activities while adhering to finish-start precedence constraints with no time lag and constant renewable resource constraints. The objective is to minimize the overall project duration (Herroelen et al. 1999). However, there are other objectives considered in the literature that are categorized to the following groups according to Ulusoy and Hazır (2021).

Time-Based Objectives: The makespan or project duration C_{max} is a single project's most frequently considered time-based objective. Other time-based objectives include the lateness L = (Cmax - D), where D is the project's due date. Depending on the relative magnitudes of C_{max} and D, L can be zero, positive, or negative. When L= 0, the project is said to be on time. When L > 0, the project is said to be tardy, with tardiness T= max (0, L). When L < 0, then the project is early. Earliness is denoted by E= max (0, -L): L and T are both regular measures, whereas E is not. Here a regular performance measure defined as non-decreasing tasks completion times (Błażewicz et al. 2007).

Cost-Based Objectives: these performance measures deal with the cost related objectives such as cash flows associated with the activities and/or events, e.g., the maximum cash balance, defined as the maximal gap between cumulative cash inflow and outflow in any period, representing the maximum amount of cash (operating capital) required in any period over the project duration. An objective reflecting this necessity is minimizing the maximal cumulative gap between the project's cash inflows and outflows. Another cost-related objective considered is minimizing the cost of the resources required to complete the project by a pre-specified due date. This objective is only relevant for project scheduling problems with multiple modes since this provides the project manager with several alternative combinations of duration and cost for each activity, among which the most advantageous combination can be selected.

Quality-Related Objectives: A widely employed measure of quality in both industry and services is conformance to customers' requirements. Considering the three dimensions of duration, cost, and quality in project management, project managers seek to exceed customer requirements while completing the project on time and within budget. Hence an appropriate objective for maximizing quality would be minimizing the cost and time required for rework to remediate quality problems arising from failure to meet customer specifications. A specific function of this type proposed by

(Kim et al. 2012) which involves minimizing the sum of the direct cost of the time-cost trade-off and the non-conformance cost of rework and modification.

Resource-Based Objectives: they are typically associated with the resource levels employed. One such objective, resource leveling, seeks to minimize the fluctuations in resource usage over time. Another problem variant, the Resource Availability Cost Problem (RACP), aims for a feasible project schedule that does not exceed the deadline and minimizes the total cost, expressed as a function of the peak resource demand. However, it assumes constant renewable resource availability over the project duration.

Over time, a significant body of literature has emerged that describes various methods for addressing the RCSP. These methods can be broadly classified into two categories: exact and heuristic approaches. Exact methods, such as integer programming and constraint programming, are based on mathematical programming techniques and aim to find an optimal solution to the problem. In contrast, heuristic approaches use rules of thumb and approximation algorithms to generate feasible solutions quickly, but these solutions may not be optimal. Additionally, metaheuristic approaches, such as genetic algorithms, simulated annealing, and tabu search, have been developed to address this problem. Some researchers have also explored combining discrete event simulation approaches with particle swarm optimization to develop more effective solutions (Lu et al. 2008; Zhou et al. 2017).

Some researchers tried to address RCSP shortcomings. For example, Kong and Dou (2021) introduced a new approach for RCSP under multiple time constraints, which combined three types of time constraints, including a duration constraint of activity, temporal constraint, and resource calendar constraint. The authors developed a constraint programming optimization model for the new problem and use the IBM ILOG CPLEX-CP version 12.9.0 optimizer to provide a near-optimum solution to instances with hundreds of activities. He et al. (2021) discussed the challenge of RCSP in the construction industry, where project managers need to balance conflicting objectives such as time, cost, and energy consumption. The authors proposed a multi-objective optimization framework based on the quantum genetic algorithm (QGA) to find the best trade-off relationship among these goals. The proposed model considered the allocation of resources in each construction activity, which ultimately determined its execution time, cost, and energy consumption. The QGA was used to find the best combination of time, cost, and energy consumption and the optimal scheme of resource arrangement. In another paper, Zhu et al. (2017) discussed handling disruptions in an ongoing project, focusing on the RCSP with finish-start precedence constraints. The authors proposed a classification scheme for different types of disruptions. They defined the constraints and objectives that comprise the recovery problem to get back on track as soon as possible at minimum cost, where cost was considered as a function of the deviation from the original schedule. Cheng et al. (2015) identified a new set of RCPSPs that allowed non-preemptive activity splitting, where each activity can be processed in multiple modes and renewable and non-renewable resources are considered. The multi-mode RCPSP with non-preemptive activity splitting was shown to be a generalization of the RCPSP with calendarization, and activity-ready times and due dates were considered to study the impact them on project makespan. Computational experiments were conducted to compare optimal makespans under three different problem settings: RCPSPs without activity splitting, RCPSPs with non-preemptive activity splitting, and preemptive RCPSPs.

For more detailed information on the past and recent developments of the RCSP, I refer to the most recent article reviews by (Franco-Duran and Garza 2019; Habibi et al. 2018; Hartmann and Briskorn 2022). These articles provided comprehensive overviews of the various methods and approaches that have been developed to address this problem. However, before describing the suitability of the RCSPs with the problem on hand, the resource constraints scheduling method on the multiple projects is explored, in the next subsection.

2.6 Resource Constrained Multi-Project Scheduling Problem (RCMPSP)

Lova et al. (2000) conducted a survey across companies in the areas of construction, textile, computers and information systems, and public administrations; they concluded that 84% of the companies worked with multiple concurring projects, which was consistent with the findings by Payne (1995) reported that 90% of projects by value was executed in a multi-project environment. In such environment, multiple projects compete for limited resources with one another in order to meet diverse clients' needs, therefore rendering resource allocation in a multi-project environment to be a critical decision process in which managers are faced with critical decisions to maintain competitiveness in the market (Laslo and Goldberg 2008). These decisions include selecting which projects to pursue, allocating resources effectively, and scheduling multiple projects, that challenge and force the management to a continuous firefighting mode, leading to reactive behavior and short-term problem solving as described by Engwall and Jerbrant (2003).

To address the last two challenges, the Resource Constrained Multi-Project Scheduling Problem (RCMPSP) has gained significant attention in both academic research and practical applications. The RCMPSP focuses on optimizing the desired outcome by scheduling multiple projects while considering available resource capacities and ensuring that precedence constraints are met.

As reviewed in the literature and according to Lova et al. (2000), RCMPSs are generally solved as follows.

1. **Single-project (SP) approach**: All projects are artificially cumulated by combining their networks into an extensive super- AoN network, with one common dummy source and sink

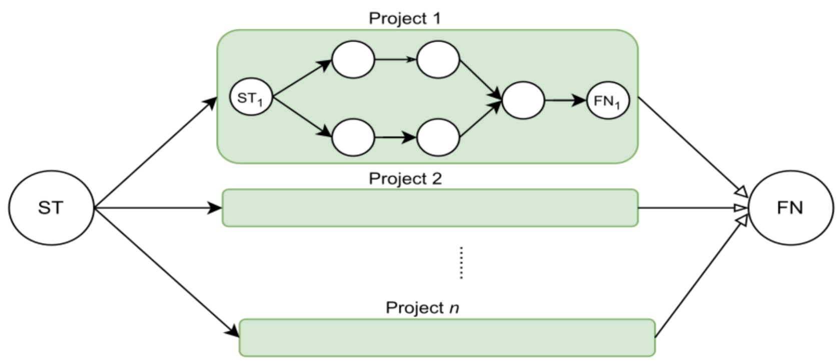


Figure 2.1: Super-Project Network for SP approach

node as displayed in Figure 2.1. Meaning that RCMPSP is a generalization of the RCPSP and it combines multiple projects into a large project, and all projects are scheduled uniformly based on shared goals and resources by the multi-project manager (Cheng et al. 2016; Van Eynde and Vanhoucke 2020).

The single-project approach is commonly adopted for solving the multi-project scheduling problem in the construction project management domain. For instance, Sonmez and Uysal (2015) proposed a hybrid algorithm integrating the backward-forward scheduling method, generic algorithms, and simulated annealing for solving resource-constrained multi-project scheduling problems. In another article, Liu and Lu (2019) presented a dual-level multi-project scheduling framework for optimizing resource allocation decisions and minimizing resource dependencies among multiple concurring prefabrication projects.

2. **Priority rules**: in this approach, various priority rules are usually adopted for allocating resources to activities in multiple projects. Commonly implemented heuristic rules include the minimum slack rule, minimum latest finish time rule, shortest activity from the shortest project first, and maximum total work content (Browning and Yassine 2010; Kim et al. 2005; Lova et al. 2000). However, the performance of heuristic rules is problem-dependent with no consensus on which rule works best (Browning and Yassine 2010; Cohen et al. 2004).

For more detailed review on RCMPSPs, I refer to (Gómez Sánchez et al. 2023; Issa and Tu 2020) that provided a comprehensive review of the evolution of the RCMPSPs by analyzing various problem features, objective functions, proposed solution methods, benchmarks, and their connection to practice. The available research on managing multiple construction projects at the same time is limited. According to a study conducted by East and Liu (2006) the resource allocation problem in construction projects has been categorized into four distinct classes, as depicted in Figure 2.2. This research concluded that there is still a need for further study of multi-project resource allocation. Another study by Zhou et al. (2017) also confirmed the research gap in resource constrained multi-project scheduling.

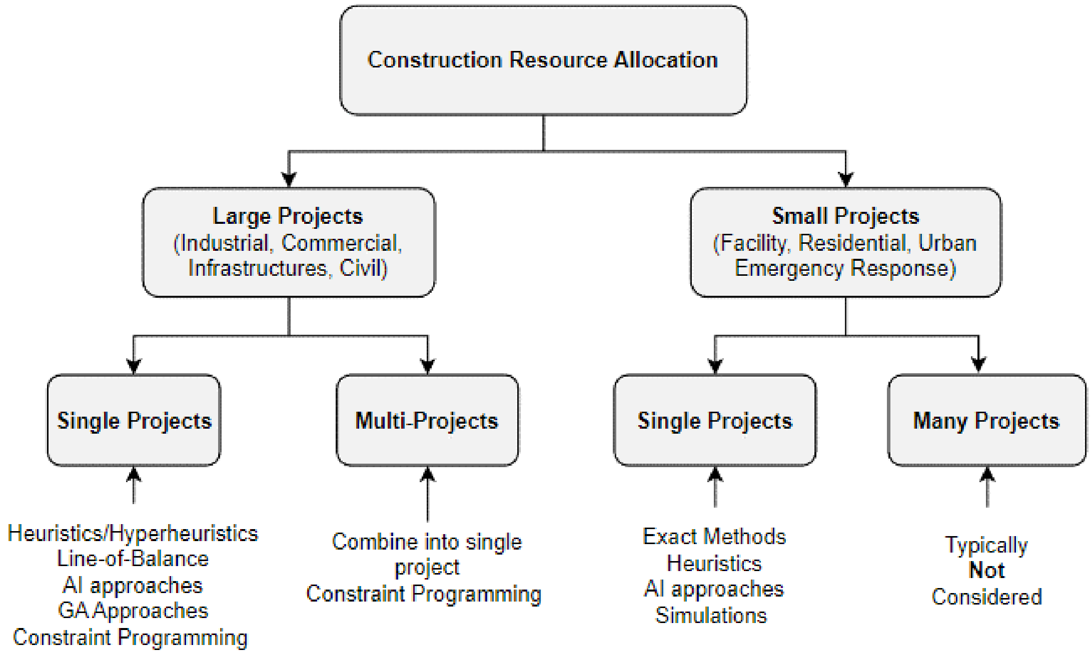


Figure 2.2: Construction Resource Allocation Problem Domain

Furthermore, the methods and solutions used to tackle RCPM/RCMPSPs have been found to have some drawbacks that can have negative impacts on project performance and outcomes. Some of the downsides have been illustrated as follows.

1. ***Unidentified Resource Links in Multiple Calendars***: When an activity is scheduled during the nonworking days of its predecessor due to a delay, the RCPM fails to recognize the resource links associated with it. For instance, (Franco-Duran and Garza 2019) discussed the lack of dynamic resource links in the development of scheduling algorithms for projects by reviewing related literature. The articles that were reviewed did not discuss the use of resource links to update project schedules. During the control phase of a project, an update or delay event can alter the priority order of scheduled activities designated by the scheduling heuristic. As a result, the resource links identified before the update may no

longer be necessary, and new resource links can be identified after the update. The initial resource links should be removed from the schedule before updating it because they were identified based on different project conditions. Keeping the resource links during the update can constrain the schedule, and for that reason, resource links are considered temporal or dynamic. Incorporating dynamic resource links in RCPM is challenging because it requires knowing how to handle and keep track of the links that have been created, removed, and/or updated as each update may change the sequence of activities (Kim 2009). Given that the induced resource links are crucial to the problem at hand, the aforementioned drawback could have significant negative impact on the projects scheduling and crews planning, if RCPM/RCMP methods are utilized to address the problem.

2. ***Precedence based formulation:*** In RCSP /RCMSP, precedence constraints between pairs of activities call for each such pair to be conducted in a predetermined order. In contrast, in the undertaken problem, no predetermined order of projects is recognized in advance.
3. ***Encoding and decoding methods*** for the RCSP /RCMSP schedule activity as early as possible, which may lead to inadequate resource utilization (Li et al. 2017). The proposed solution does not apply to this particular problem, as postponing a project while still adhering to the project deadline could yield a higher value for the objective function.
4. ***Resource transfer times and associated costs*** are essential prerequisites for formulating optimization models for multi-project scheduling in RCMSPs, as noted by Liu and Lu (2019). However, in the present problem, the impact of resource movements is not significant and has not been taken into account, as illustrated in chapter one.

5. ***Model complexity***: RCPSP is known as a NP-hard problem. Due to the complexity of its models, there is still a need to develop effective and efficient problem-specific heuristics to solve its various versions. Aggregating multiple projects yields very large problems in RCMPSPs, the models become even more challenging to solve, and their formulation is often not straightforward (Browning and Yassine 2010). As a result, the feasibility and execution of these models are impacted, not to mention the necessity for prompt response times to accommodate the frequent changes in the current problem.

2.7 Specific Case Applications

Moreover, several specific cases related to the current problem are reviewed. For example, Choo et al. (1999) claimed a database program called WorkPlan for scheduling work packages and allocating available resources to develop weekly work plans systematically by adopting the Last Planner methodology. WorkPlan was a process started a week before conducting work by spelling out work packages, identifying constraints, checking constraint satisfaction, releasing work packages, and allocating resources; then, at the end of the week, updating the plan from the field. Although the authors claimed that the weekly plan satisfies the constraint and allocates resources to the cleared work packages, their approach only prepared the work packages for construction on a weekly basis. Furthermore, WorkPlan received the work packages from a project master schedule and didn't possess any scheduling or allocation algorithm to satisfy resource or project constraints.

In another related study, Gomar et al. (2002) investigated and developed a linear programming model to help optimize the multiskilled workforce assignment and allocation process in a construction project. Their model suggests what type and how many workers to hire over time, when to switch them to another activity, and when to lay them off completely. However, they basically balanced the number of hires and fires by minimizing a weighted sum of the number of days workers are hired, switching costs, and firing costs. Lu et al. (2003) presented a simulation system for the resource provision planning and production planning of a ready mixed concrete plant to meet given demands at several sites for concrete over a working day. They simulated a simple process that was mainly machine (i.e., truck mixer) oriented and comprised of a few number (i.e., six) activities within a more stable environment than the current researched problem. Therefore, feasible methods of acquiring reliable operational data to support simulation modeling were adaptable. However, updating the input data in the simulated model and the code was nontrivial but complex to some extent, preventing practical applications.

In another study by Hegazy et al. (2004) a genetic algorithm (GA) optimization model was utilized to minimize the total construction cost to facilitate the planning and scheduling of resources for an extensive project network. They studied a project environment featuring repetitive tasks in large construction projects that involve multiple distributed sites. Their study determined the required number of crews for each activity to meet the project deadline based on the CPM calculations durations and floats. The problem studied in this research is distinguished from their research on the following grounds.

- This research scope includes multi-projects distributed in various sites with different deadlines, not one project with a specific deadline.
- No CPM calculations are applied to this problem, and no critical path schedule can be derived in advance to guide crew allocation. In contrast, the schedule has to be developed based on crew allocation to complete the projects within their deadlines.

- The number of available crews is fixed and determined in advance in this research, and predetermined crews are assigned to the sites, not the opposite.

Furthermore, in another paper, Hegazy (2006) discussed three common approaches owner organizations use to deliver infrastructure maintenance/repair programs that involved multiple distributed sites: using in-house resources, outsourcing to contractors, and combining both. (Fontecha et al. 2020) developed an operation routes optimization model for sewage lines' minor repairs in a set of geographically spread sites. Elmasry et al. (2019) offered an optimization model for inspecting deteriorated sewer pipelines using a multi-objective optimization approach for which time, cost, and the number of inspected sections were optimized utilizing mixed-integer linear programming (MILP). Dasović et al. (2020) presented a survey on the integration of optimization and project management tools that allow sustainable construction scheduling, particularly in terms of continuous optimal time and resource allocation throughout the project life cycle. Siu et al. (2015) developed a mathematical model to facilitate the scheduling and allocation of skilled trades at project and workface levels. Another study by Das and Bhattacharyya (2015) suggested a MILP formulated waste collection path optimization based on the traveling salesman problem (TSP) for the municipal solid waste collection and transportation system. Atef et al. (2012) presented an analytical framework to determine the right condition assessment technologies and intervals for buried water and sewer networks in facility-condition assessment methods. Additionally, with recent developments in artificial intelligence (AI), non-traditional optimization techniques such as simulated annealing (SA) and genetic algorithms (GAs) have been employed for schedule optimization in projects/networks. Nijland et al. (2021) utilized a combination of SA and dual simplex to solve a MILP model for the optimal design of the railway maintenance schedules, including train operators' restrictions and capacity constraints of maintenance crews in the design process. Osman et al. (2017) presented a simulation-based GA-based multi-objective optimization model to schedule water break repair crews in an urban setting. Halfawy et al. (2008) applied a GA-based multi-objective optimization technique to find a Pareto front of feasible solutions, each involving a set of sewer lines to be renewed each year in Regina, Canada. They discussed the application of the proposed solution to implementing a GIS-based decision support system for the renewal planning of sewer networks.

Based on the critical review presented in the above subsections of this chapter, the existing literature has not yet adequately addressed the planning of large sets of independent projects located in various sites subjected to project and resource constraints in the construction domain. Furthermore, it has yet to be adapted to the dynamic environment of this type of project, specifically at the execution stage, with the necessity for quick, adaptable responses to the changes and plan updates required.

The following last section of the literature review explores different fundamental approaches to address the uncertainty in a resource constraint multiproject environment.

2.8 Multi-Project Scheduling Under Uncertainty

Managing projects in the presence of uncertainty is a critical issue in project management. While there is a significant amount of research on project scheduling under uncertainty, most of it focuses on single-project problems. In multi-project scheduling, the influence of uncertainty factors on the scheduling scheme is more complex. However, there is a limited amount of literature available on multi-project scheduling under uncertain conditions as stated by (Hazır and Ulusoy 2020).

Stochastic programming, robust (proactive) optimization, and fuzzy programming are the fundamental optimization approaches that can be used to manage projects in the presence of uncertainty as reviewed in the literature, such as (Hazır and Ulusoy 2020; Herroelen and Leus 2005). In order to tackle uncertainty in the current project scheduling problem, I will briefly explore these approaches and reactive scheduling techniques that show potential. While some of these methods were originally designed for machine scheduling, my primary focus is on determining their appropriateness for scheduling projects in this research under uncertain circumstances.

2.8.1. Stochastic Scheduling

The stochastic resource-constrained project scheduling problem (SRCPSP) is an extension of the RCPSP that deals with stochastic or random activity durations. In this problem, the duration of each activity is modeled as a random variable with known probability distributions or other known information regarding the duration of each activity (Hazır and Ulusoy 2020). Typically, SRCPSP does not create a baseline schedule. However, it views the problem of scheduling projects under precedence and resource constraints as a multistage decision process that uses so-called scheduling policies (or scheduling strategies) that dynamically make scheduling decisions at stochastic decision points t, based on the observed past and the a priori knowledge about the activity processing time distributions. The two-stage stochastic model is a commonly used approach that divides decision variables into two sets. The first set of variables is independent of any uncertain parameters and must be determined before any random fluctuations occur. Once a specific realization of the parameters takes place, the second set of variables, known as recourse variables, can be determined with an additional cost to the objective function value of the first set of variables as demonstrated in the papers like (Dhaliwal 2011; Meredith et al. 2017).

The stochastic approach requires the specification of probability distributions for all random variables involved for accurate and reliable project planning. Additionally, The project scheduling literature, specifically stochastic scheduling, has concentrated on the variability in activity durations (Ulusoy and Hazır 2021). However, as illustrated in chapter one, projects' durations are not deemed as a significant source of uncertainty; contrarily, other uncertainties, such as those in resource availabilities and scope changes, significantly impact the schedule performance.

2.8.2. Fuzzy Programming

Fuzzy programming has gained popularity as an alternative approach to addressing project scheduling problems with uncertainty. A principal difference between the stochastic and fuzzy approaches is in the way uncertainty is modeled. Instead of using random variables and modeling uncertainty through discrete or continuous probability functions, uncertain parameters are modeled as fuzzy numbers, and constraints are defined using fuzzy sets and membership functions (Sahinidis 2004). Membership functions can allow for some constraint violations and measure the degree of satisfaction with the constraints. Proponents of the fuzzy activity duration approach argue that probability distributions for activity durations are often unknown due to the lack of accurate historical data. They also argue that activity durations estimated by human experts may be more accurate than those estimated by other methods (Herroelen and Leus 2005; Ulusoy and Hazır 2021). For instance, Wu et al. (2004) proposed a fuzzy rule-based system to assist the dispatchers in crew management in case of large-scale multiple outages happen. In another study, Bakry et al. (2016) offered an algorithm for optimized scheduling and buffering of repetitive construction projects. The algorithm used fuzzy numbers to help users model uncertainties associated with quantities, productivity rates, and costs. The buffer building process utilized fuzzy inputs to assess the uncertainties affecting each activity and uses artificial intelligence to capture different users' required confidence levels in the schedule produced. This approach could be valuable for helping project managers better manage risk and uncertainty in construction projects. One potential issue with using fuzzy numbers in project scheduling is the concept of degree of satisfaction, as it can be unclear which solution is optimal. Additionally, it can be challenging to find a real-world analogy to help understand the concept of fuzziness. Using a probabilistic approach, on the other hand, can allow the development team to determine the likely completion time and make more informed decisions as elaborated by Logue and McDaid (2008).

2.8.3. Reactive Scheduling

Reactive scheduling involves modifying or re-optimizing schedules in response to disruptive events that render them suboptimal or infeasible. Project managers typically prepare a baseline schedule for the entire project life cycle or construct the schedule dynamically during project execution. The first approach is called predictive-reactive scheduling, whereas the second is called dynamic scheduling. Rescheduling may be performed when an unexpected event occurs (event-driven approach) or at preset intervals to assess and modify the schedule (periodic approach). In both instances, either the current schedule is partially updated (partial rescheduling), or all remaining activities are rescheduled (complete rescheduling) according to (Chakrabortty et al. 2021; Ulusoy and Hazır 2021). Ma et al. (2015) and Deblaere et al. (2011) demonstrated that reactive scheduling involves optimizing the scheduling process, random interferences were found, and a response scheduling plan was proposed, which affects the normal baseline scheduling with a fixed time scale or time drive so that scheduling continuity and stability are maintained.

2.8.4. Robust(proactive) scheduling

In contrast to the reactive approach, robust scheduling employs a proactive strategy. Variability is incorporated into the models, and schedules that are less susceptible to disruptions are sought. Herroelen and Leus (2007) examined schedule robustness in solution robustness (stability) and quality robustness. Stability refers to the insensitivity of activity start times to variations in input data. In contrast, quality robustness refers to the insensitivity of schedule performance measures, such as project completion time, to the input data. In the context of CPM, increasing total slacks enhanced quality robustness, while free slacks improved stability. Therefore, slack analysis is essential in robust project planning, as it supports project managers to identify and focus on critical activities. However, identifying the slacks in resource-constrained projects is ambiguous because the outcome is not unique but depends on the resource allocation rules utilized in scheduling (Wiest 1964). The activities ' late start/finish and early start/finish times must be determined to find the slacks. In resource-constrained settings, the early and late times are calculated by establishing left and right justified schedules. A schedule generation mechanism and a priority rule are required to construct these schedules. Left and right justified schedules; thus, activities' early and late times depend on the schedule generation rule applied (Adeli and Karim 2001). Even in a simple resource-constrained project network, alternative resource allocations are often possible, resulting in a choice of schedules with identical project durations but different activity slacks as illustrated by Meredith et al. (2017).

2.8.5. Sensitivity Analysis

Compared to other aforementioned approaches, there has been relatively little attention paid to sensitivity analysis in the literature. An exception is the study by Gálvez and Capuz-Rizo (2016) who applied different sensitivity analysis techniques to identify the parameters that had the largest effect on project scheduling. *Sensitivity analysis* is a powerful tool that enables project managers to predict how risk items can impact project goals. This commonly used quantitative analysis tool can be applied in various areas. By analyzing risk items individually, sensitivity analysis helps identify those that require frequent monitoring and determine their tolerance intervals, showing the level of changes that can be tolerated. While sensitivity analysis primarily considers one variable at a time, real-life situations often demand the consideration of several variables simultaneously. Monte Carlo simulation can be used to model the impacts of multiple variables and their interdependencies, allowing for testing alternative action plans. However, it is essential to estimate the probability distributions of uncertain variables correctly (Mavromatidis et al. 2018).

Moreover, some studies have investigated the impact of uncertainty and risk on resource constraint multi-project scheduling. For example, Zayed et al. (2018) proposed a stochastic optimization model that considered the uncertain duration of tasks and resources to minimize the expected project completion time and cost. Similarly, Gao et al. (2020) developed a risk-based scheduling model that incorporated the risk factors of different projects and resources into the scheduling process.

With this brief overview of the most common fundamental approaches to address uncertainty, chapter six further elaborates on this review and present a suitable method to tackle the uncertainties associated with the current problem effectively.

Chapter 3: Agile Project Management in Construction

Throughout history, humankind has undertaken various projects, ranging from massive accomplishments like the Great Wall of China to technological breakthroughs like the printing press or the Internet. Despite this, formal project management, as we understand it today, only emerged in the mid-twentieth century. In 1970, a computer scientist, Winston Royce, published an article titled "Managing the Development of Large Software Systems" which outlined the phases of the waterfall methodology (Royce 1970). Although the term "waterfall" was coined later, the phases remain consistent with Royce's original definition as displayed in Figure 3.1. The waterfall model is straightforward and linear approach, where work cascades down in a specific, organized, sequential order: Initiation and scoping, contracting, design, construction, procurement, testing and commissioning, and handover, as an example in construction.

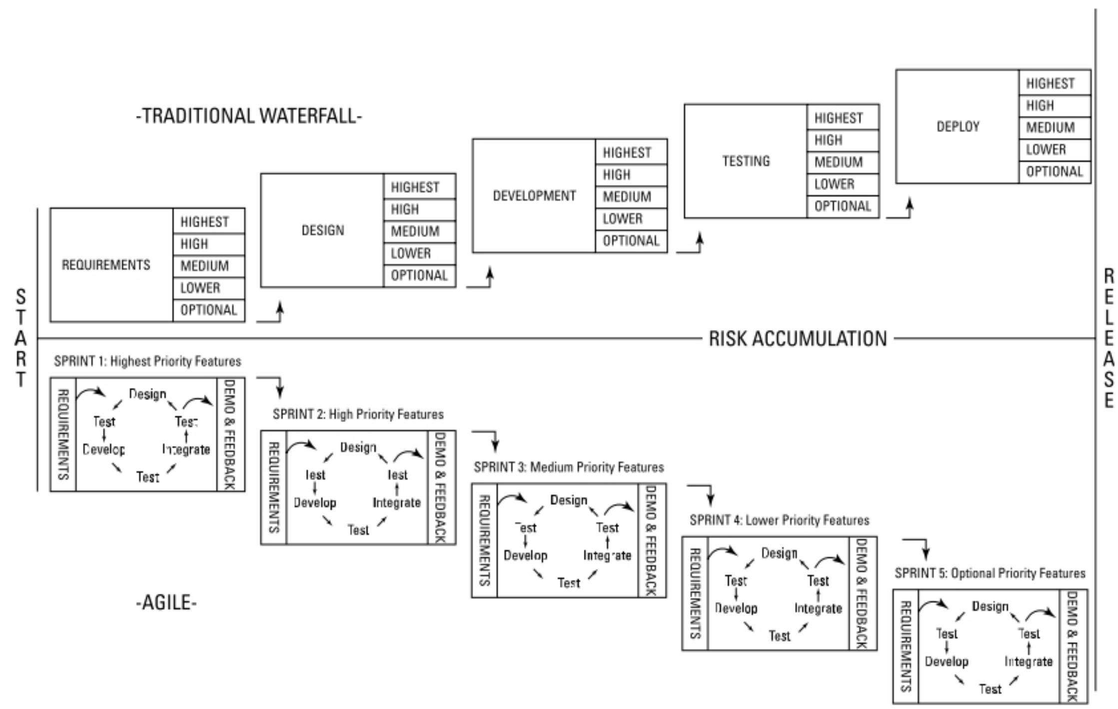


Figure 3.1: Waterfall vs Agile adopted from (Layton et al. 2020)

Each phase resembles completed in this methodology before proceeding to the next so that stages of a project resemble a waterfall, hence the name waterfall. As seen in Figure 3.1, when undertaking a project, whether it be through an agile management model or a classic waterfall mode, the same type of work must be accomplished. However, the agile management model breaks down the project into smaller iterations, known as sprints, rather than tackling all the steps for all product features at once. This allows for a more manageable and efficient process.

It is to be noted that fully completing each step before moving on is not what Royce intended. Indeed, he recognized the inherent risks of such an approach and proposed developing and testing within iterations to create more refined products. Unfortunately, many organizations overlooked this crucial aspect of the waterfall methodology, leading to potential setbacks and challenges in the project management process (Layton et al. 2020).

Thereafter, the Agile Manifesto was created back in 2001 by a team of software and project experts (Fowler and Highsmith 2001). This manifesto outlined a set of values that were essential for successful software development. Additionally, the creators of the Agile Manifesto also established 12 principles to support those values. As per the Agile Manifesto, the principles include prioritizing the satisfaction of customers, adaptability to changing requirements, frequent delivery of work (iterative development), simplicity, self-organizing teams, emphasizing collaboration, motivation of individuals, face-to-face communication, measuring progress through working software, maintaining a sustainable development pace, continuous technical excellence, and regular reflection for improvement.

Over recent years agile project management has evolved and adapted to embrace changes, promoting iterative and incremental development, and breaking projects into smaller, manageable parts (Jin 2017; Sohi et al. 2016; Wysocki 2019). Hence, the agile project management concepts and methods hold great potential to inform the development of cost-effective solutions to the present application problem.

The agile management model was originally developed for software development; since then, different industries, such as biotech, manufacturing, aerospace, marketing, and finance have adopted agile to their business. Major companies like Apple, Microsoft, and Amazon have led this transformation (Layton et al. 2020). The State of Scrum 2017-2018 report quoted a Scrum Alliance board member who said, "Any organization that does not go through an Agile transformation will die. It is the same as a company refusing to use computers(Alliance® 2017)."

3.1 Scrum Methodology

The roots of Scrum can be traced back to 1986, with the publication of an influential article called "The New Product Development Game" in the Harvard Business Review by (Takeuchi and Nonaka 1986). This article emphasized the importance of self-organizing teams and the role of management in the development process, and it laid the foundation for Scrum as is known today.

One of Scrum's key strengths is its focus on delivering working, tested, and business-valuable features in a timely manner. This is achieved through short iterations, typically lasting from a week to a month. During each iteration, a cross-functional team takes on all aspects of the work required to produce fully functional features that can be put into production.

However, the amount of work in the product backlog can often be overwhelming, so the team must carefully select which high-priority items to work on during each iteration. Figure 3.2 displays an elegant representation of the Scrum approach.

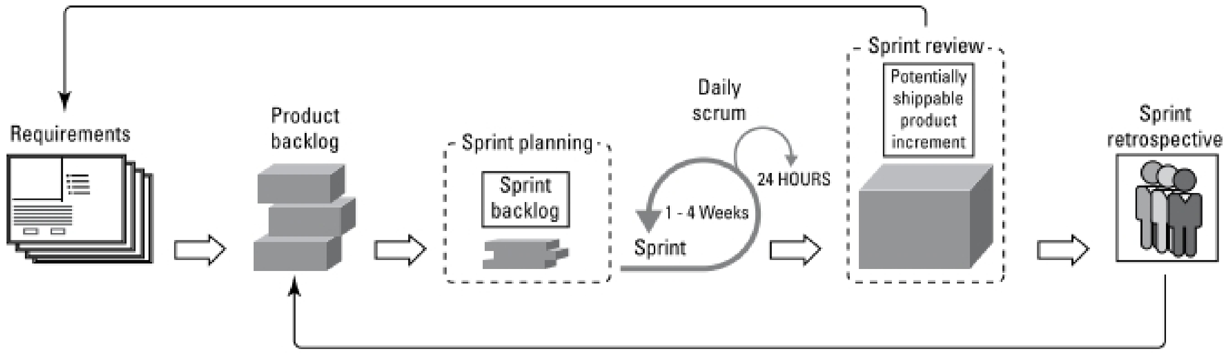


Figure 3.2: The Scrum Approach reference to (Layton et al. 2020)

At the end of each iteration, the team reviews the completed features with stakeholders for feedback. This enables the product owner and team to adjust their plans for the next iteration based on what they have learned. As each iteration concludes, the entire process begins anew with planning for the next one. Overall, Scrum offers a robust framework for teams to work collaboratively and effectively, delivering high-quality products that meet the needs of stakeholders (Rubin 2012).

According to Digital.ai's 14th annual State of Agile Report 2020 (digital.ai 2020), Scrum is widely considered to be the most popular agile framework. At its core, Scrum is an iterative approach centered around the sprint (the scrum term for iteration). Scrum practices consist of different roles, activities, artifacts, and rules, which are outlined in Figure 3.3 and explained, according to Rubin (2012) and Layton et al. (2020).

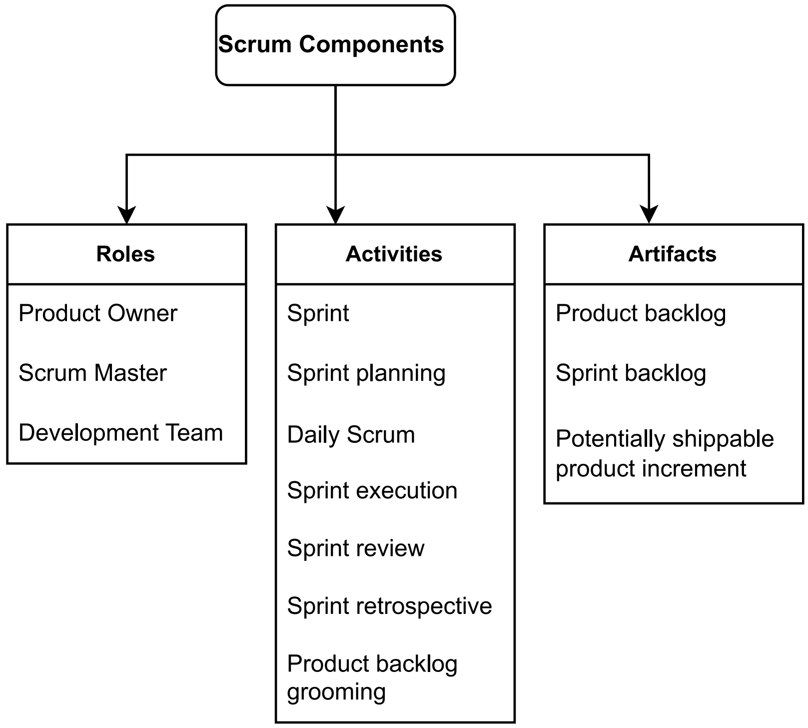


Figure 3.3: Scrum practice components

As listed in Figure 3.3, in Scrum development, it is common to have one or more Scrum teams, with each team consisting of three key roles: the product owner, Scrum master, and the development team. The product owner holds the responsibility of deciding what should be developed and when it should be developed.

On the other hand, the ScrumMaster guides the team in creating and following its own process, which aligns with the broader Scrum framework. The role of a scrum master is to provide support to the development team while ensuring that organizational roadblocks are cleared, and processes remain true to agile principles. While similar to a facilitator or team coach in non-scrum environments, the scrum master's responsibilities are unique to agile product development.

The role of a scrum master is distinct from that of a project manager. While a project manager oversees and manages a project, a scrum master serves as a servant-leader peer to the team. This means that the scrum master's role is enabling rather than one of accountability. By supporting the team to be fully functional and productive, the scrum master empowers them to achieve their goals successfully.

With agile product development, the scrum master will:

- Act as a process coach and agile champion, helping the team and the organization follow scrum values and practices.
- Help remove impediments reactively and proactively and shield the development team from external interferences.
- Work with the product owner to foster close cooperation between stakeholders and the development team.
- Facilitate consensus building within the scrum team.
- Protect the scrum team from organizational distractions.

To be effective, scrum masters must possess strong communication skills and enough organizational clout to secure the conditions for success. However, it's important to note that clout differs from authority. Organizations need to empower their scrum masters so they can influence change in the team and organization without formal authority over others. Empowering scrum masters to influence change in the team and organization without formal authority over others is crucial to their success. This clout is earned through success and experience, and it allows scrum masters to negotiate for the right environment, protect the team from distractions, and remove restrictions. Ultimately, the development team is responsible for determining the best approach to delivering what the product owner requires (Layton et al. 2020; Rubin 2012). It is necessary to note that the Scrum framework only defines certain roles that pertain to Scrum and not all positions that may exist within an organization that utilizes Scrum.

Scrum also includes three distinct artifacts that are physical deliverables that are transparent to the scrum team and are used for continuous inspection and adaptation. These three tangible deliverables are the product backlog, sprint backlog, and product increment.

The *product backlog* is a comprehensive list of requirements that define the product and are documented from the end user's perspective regarding business value. It is a dynamic document that evolves throughout the product lifecycle. The product owner is responsible for managing the product backlog and deciding what goes into it and the priority of each item.

On the other hand, the *sprint backlog* is a list of requirements and tasks essential for achieving a specific sprint goal. The product owner and development team select the requirements for the sprint during sprint planning. The development team breaks down these requirements into tasks. Unlike the product backlog, the sprint backlog tasks can only be changed by the development team to ensure they can achieve the sprint goal.

Finally, the *product increment* is the working functionality that is potentially shippable to the customer. It includes requirements that have been elaborated, designed, developed, tested, integrated, documented, and approved to meet the customer's business needs. It should be complete enough to demonstrate its working functionality, regardless of whether the product is a website or a new house. After enough shippable functionality has been verified to meet their business goals, the product increment is released to the customer. It may take more than one sprint to generate enough valuable functionality to ship to the customer.

Additionally, scrum consists of five events, each of which is essential to the overall process.

The first event is the *sprint,* which is essentially a short iteration that allows the scrum team to create potentially shippable functionality. The sprint is the container for each of the other scrum events, and it helps the team make immediate adjustments for continuous improvement rather than at the end.

The second event is *sprint planning,* which occurs at each sprint's start. During this meeting, the scrum team decides on the business goal, scope, and support tasks that will be part of the sprint backlog. This helps to ensure that everyone is on the same page and that the team is working towards a common goal.

The third event is the *daily scrum,* which takes no more than 15 minutes daily. During this meeting, development team members inspect their progress, adjust their plan to achieve their sprint goal and coordinate the removal of any impediments with the scrum master. This helps to ensure that the team works efficiently and that any issues are dealt with quickly.

The fourth event is the *sprint review,* which takes place at the end of each sprint. During this meeting, the development team demonstrates the accepted parts of the product that the team completed during the sprint to the stakeholders and the organization. The key to the sprint review is collecting feedback from the stakeholders, which informs the product owner how to update the product backlog and consider the next sprint goal.

The fifth event is the *sprint retrospective,* which takes place at the end of each sprint. This is an internal team meeting in which the team members (product owner, development team, and scrum master) discuss what went well during the sprint, what didn't work well, and how they can improve for the next sprint. This action-oriented meeting ends with tangible improvement plans for the next sprint.

As seen in Figure 3.4, it becomes apparent that the diverse components of the scrum methodology work together to promote a streamlined and effective team dynamic. Through strict adherence to the five scrum events, teams can remain focused on a shared objective, make consistent progress, and continually refine their processes in preparation for future sprints. This approach allows teams

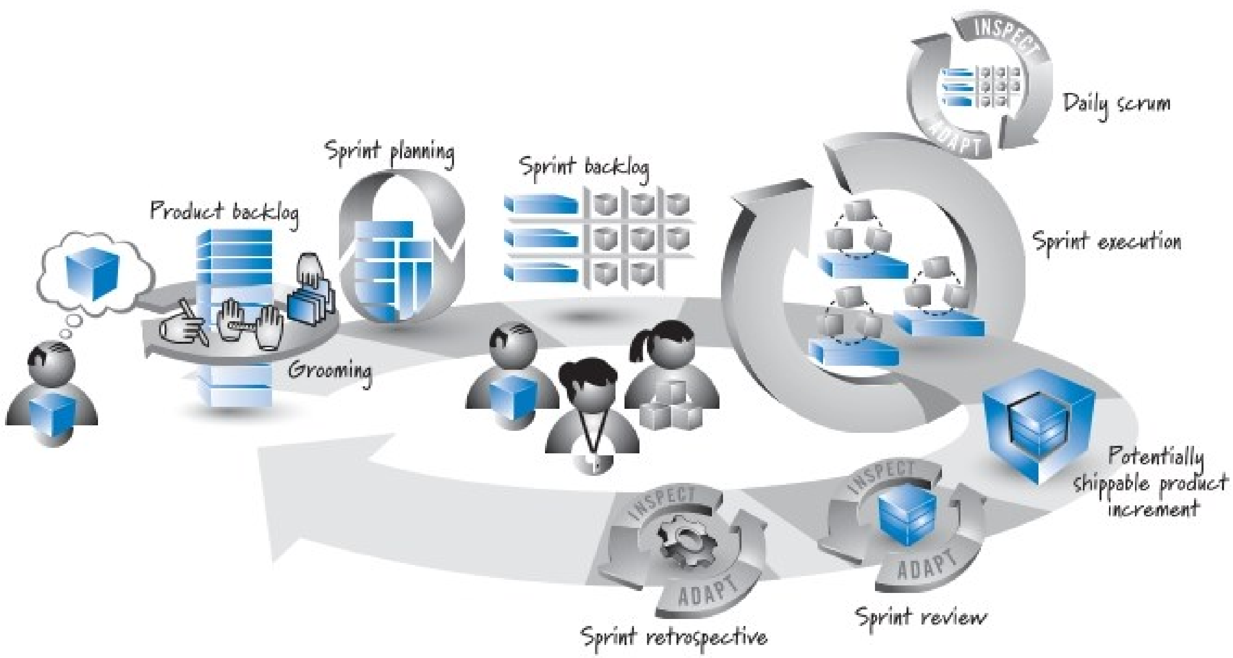


Figure 3.4: Scrum process overview adopted from Rubin (2012)

to optimize their performance and enhance their chances of success collaboratively and efficiently (Cole and Scotcher 2016; Rubin 2012).

3.2 Why Agile-Scrum?

As explicated in Chapter 1, the problem at hand pertains to planning multiple concurrent projects with varying deadlines, priorities, and resource constraints, coupled with constant alterations in scope. In line with the research objectives outlined in section 1.7, the proposed solution model must be sufficiently adaptable and efficient to facilitate timely plan modifications while upholding simplicity. Considering these criteria, the following rationales are presented for addressing the problem.

Shrnhur et al. (1997) categorized projects across two dimensions and concluded that management style should be tailored to specific differences in project type. These dimensions were the level of technological uncertainty and the level of system complexity. Later, Pich et al. (2002) modeled a project as a payoff function influenced by the state of the world and a sequence of actions. The impact of actions on the state of the world was represented by a causal mapping, which may not be fully known to the project team. The state of the world was described by an underlying probability space that reflects the available information. Interactions between actions and states of the world determine the complexity of the payoff function. Activities within the project are determined by a policy that maximizes the expected project payoff.

The concept of information adequacy plays a crucial role, representing the sufficiency of available information about states of the world and action effects. The appropriate strategy depends on the type of uncertainty present and the complexity of the project's payoff function. Information inadequacy can arise from both ambiguity and complexity. Ambiguity refers to a lack of awareness of the project team about particular states or causal relationships (Schrader et al. 1993). Project complexity refers to when many different actions and states of the system parameters interact, making it difficult to assess the effect of actions (Priemus et al. 2013; Simon 1969), . In complex projects, an adequate representation of all the states significantly influencing the project payoff or causal relationships may be beyond the project team's capabilities.

Existing project management approaches advocate partially conflicting approaches to the project team, such as executing planned tasks, triggering preplanned contingencies based on unfolding events, experimenting, and learning, or exploring multiple solutions simultaneously. The Waterfall methodology, for instance, requires the team to fully understand all the requirements from the outset to ensure accurate time, budget estimations, and adequate resources and team members. However, such planning and estimations may pose challenges and require significant expertise, experience, and effort (Layton et al. 2020). As previously mentioned in Chapter One, the projects being studied have tight time frames, and the high frequency of receiving concurrent projects makes complex planning and estimation demanding expertise and effort nearly impossible.

On the other hand, the Agile methodology and Scrum, as its most favored method, control the process flow, provide flexibility and adaptability, and enable incremental, iterative planning (Arefazar et al. 2019; Cole and Scotcher 2016). In Scrum, the duration consistency of sprints throughout the project provides a predictable and regular rhythm of work (Goncalves and Heda 2010; Schwaber and Sutherland 2022). Moreover, as important as it is to start with a plan, we typically have minimal knowledge about what will be required at the beginning of a project. Therefore, Agile project management recommends a just-in-time approach to planning what is needed to support the overall product vision and roadmap. By modifying the plan as it goes, teams can avoid wasting time on unnecessary features and deliver products that delight customers. That means the product development teams do not plan less than Waterfall teams; they plan as much or more differently (Layton et al. 2020).

Furthermore, for reasons explained in the subsequent section, I have found the Agile methodology to match the uncertainty conditions concerning the present problem. All the rational explanations have led to the selection of Agile methodology and Scrum as the strategy and foundation to address the current problem in this research.

3.3 Agile perspective to uncertainties

Based on the literature reviewed so far, I can conclude that the classical waterfall processes prioritize the elimination of all uncertainties by fully defining the project from the outset and only then addressing any uncertainties that arise. These linear, plan-driven processes mandate full requirements and a complete plan, assuming that everything can be determined upfront. However, this approach is not realistic, as it is unlikely that all the requirements and detailed plans can be determined correctly from the beginning. Moreover, when requirements change or due to execution stage varied circumstances, the baseline requirements and plans must be modified to reflect the current situation (Sahinidis 2004). This linear approach to uncertainty reduction is not well-suited to complex problems, where construction team actions and project environments constrain each other (Pich et al. 2002).

Scrum, on the other hand, takes a more holistic approach by focusing on reducing all uncertainties simultaneously. This approach facilitates the simultaneous reduction of multiple types of uncertainty through iterative and incremental development, guided by constant inspection, adaptation, and transparency. This way, the project team can identify and learn about all types of uncertainties, including the unknown unknowns (things that they do not yet know that they do not know) as they emerge(Meredith et al. 2017; Ulusoy and Hazır 2021).

Scrum acknowledges that it is not possible to capture all the requirements or plans upfront. Attempting to do so could be hazardous because important knowledge may be missing at that stage, leading to low-quality plans and creating the illusion that uncertainties have been addressed, only to realize later that it was a waste of time and energy (Rubin 2012).

It is important to note that Scrum is not against planning. On the contrary, Scrum still produces some requirements and plans upfront, but only to the extent necessary, with the assumption that the details of the plans will be filled in as the team learns more about the product being built. Simply put, while the waterfall method places great emphasis on detailed upfront requirements and planning before moving on to later stages, Scrum believes upfront work should be helpful without being excessive. Scrum is about striking a balance between up-front predictive work and adaptive just-in-time work. Being overly predictive requires making many assumptions in the face of great uncertainty, whereas being overly adaptive can lead to constantly changing requirements, making the work feel chaotic and inefficient(Cole and Scotcher 2016; Layton et al. 2020).

Chapter 4: Models and Solutions

4.1 Opening Remarks

Before exploring the various models developed for distinct practical conditions of the problem, it is essential to clarify the considerations taken to align the optimization models with the research objectives, as outlined in Chapter One, section 1.7.

Agility in Optimization Models: It is of paramount importance to consider that all the optimization models were developed in a way that is compatible with the agile-based planning framework, as outlined in Chapter Five. For instance, the models take into account the fact that crews are self-organized and plan the assigned project activities themselves during the daily scrum meeting. Consequently, the models do not deem it necessary to schedule projects at the activity level. Another crucial aspect to note here is the dynamic project set condition of the problem, which is further explained below.

Dynamic Project Set: The dynamic nature of the appearance of projects in this problem was addressed as the underlying benefit of adapting agile project management. This was accomplished by considering the fact that projects first require preconstruction tasks as they arrive so that as they become ready for construction, a static set of them can be planned in small iterative periods of time, as prescribed in the agile planning framework. Additionally, the status of each project and its identified resource can be determined at any given time. Given a snapshot of new initial-state information, a new plan can be developed based on the status when new projects arrive. The just-in-time revisions in the plan can be achieved through the developed system. Given the rapid evolution of ubiquitous technology applications, real-time revisions can be available in no time.

Simplicity: As explained in the research methodology section 1.8, through an iterative and progressive approach by reviewing pertinent literature and careful discussions with practitioners, subject matter experts, and managers in the partner company, optimization models were categorized as follows and effectively simplified to reflect the actual conditions of the projects in practice without sacrificing their practicality and usefulness in real-world situations. For instance, as Chapter One Subsection 1.1.5 illustrated, route optimization was deemed unfitting in this problem setting. It is imperative to note that the natural deductions in the formulation are necessary to simplify the problem without compromising the practice's essential details.

Linearity: considerable effort has been dedicated to maintaining linearity and avoiding complex, intricate nonlinear models while accurately capturing the system's behavior. As was set in the research objectives, this criterion has been met in all developed models and yields tractable mathematical models. This approach significantly simplifies analysis and computation, resulting in analytical solutions for the resultant models.

Agile approach in dealing with uncertainties: as it is described in Chapter Six, this research models an agile approach to dealing with the uncertainties conceived in the problem.

4.2 Plan Performance Metrics

As stated in Chapter One, performance metrics are devised to evaluate resultant project plans and to measure the "goodness" of the plan. This section outlines these metrics. Additionally, these metrics can be used to compare different plans resulting from each model.

The first metric is the *Plan Performance Index* (PPI), which is valuable for evaluating the goodness of the optimized plan in this research. PPI allows for comparison between different plans being developed, as well. Given the available resources, PPI is calculated by comparing the number of planned projects from the model to the estimated number of projects that could be completed as displayed in Eq. (4.2.1).

$$\text{PPI} = \frac{\text{Total number of projects planned}}{\text{Potential project completions estimation}} \tag{4.2.1}$$

Where, the total number of projects planned results from the running the model. And the number of potential project completions is estimated as follows.

$$\text{Potential project completion estimation} = \frac{\text{Total crew days available}}{\text{Sample mean of project durations}} \tag{4.2.2}$$

Note that the numerator in Eq. (4.2.2) represents the sum of the crews' availability within the planning horizon, and the denominator is the mean value of the project duration factoring in the projects in the pool ready to be planned. The result represents a reasonable estimation of the number of projects that can be allocated.

The *Client Satisfaction Index* (CSI) is the second crucial measure devised to evaluate the goodness of plans resulting from models. It is meant to match the plan's details with client satisfaction (this factor aligns with the agile project management concept) and serves as a valuable indicator of client satisfaction regarding meeting project deadlines. CSI is based on whether the project's completion date falls within the promised deadline. Since all projects adhere to regulatory and quality standards, clients typically focus on meeting deadlines and minimizing construction disruptions. As such, CSI is an essential metric in ensuring client satisfaction. A CSI of 100% is assigned if the planned project completion date falls within the deadline and zero otherwise. Indeed, the purpose of defining this metric is twofold. First, it highlights the correlation between planning outcomes and client satisfaction. Second, it incentivizes the completion of projects within their deadlines and without any undue delays.

Calculating *crew utilization planned* (CUP) is necessary to ensure that crew members are effectively utilized while considering their availability. The process involves measuring the CUP for each crew according to Eq. (4.2.3). It is worth noting that a CUP over 100% indicates over-allocation. In comparison, a CUP under 75% indicates under-allocation. The ultimate goal is to achieve 100% CUP for optimal crew utilization. However, it is essential to note that CUP only assesses the crew's idle time between allocated projects and does not factor in non-working time while executing projects.

$$\text{Crew utilization planned (CUP)} = \frac{\text{Crew working days planned}}{\text{Crew working days available}} \qquad (4.2.3)$$

Hence, CUP here in this research corresponds to the crew work continuity. Implementing crew work continuity presents an opportunity to optimize resource allocation by reducing idle crew time. Interruptions in the workflow can lead to increased direct costs, as crew members are left idle and should therefore be minimized. It is to be noted that crew work continuity can be determined by calculating idle times for each crew by subtracting the planned start date of each allocated project from the planned finish date of the precedent allocated project. It was then dividing the sum of the idle times by the crew availability. For example, if project i and j were assigned to crew n, project j followed i in the order assigned. Ide time = Project j planned start date - Project i planned finish date = Project j planned start date - Project i planned start date - Project i duration. Then, the idle times needed to be summed up and divided by crew availability. However, the formula (4.2.3) yields the same results in a more straightforward way, so it was selected as the better alternative.

The goodness of each plan is evaluated by the performance metrics described above. However, if an overall score is desired, an overall score is computed through the equation (4.2.4) as follows. The overall score (Sc_p) represents the combined performance metrics (PPI, CSI and CUP), and can be computed using the decision-maker-specified weights that reflect the relative significance of each metric.

$$Sc_p = W_{PPI} \times PPI_p + W_{CSI} \times CSI_p + W_{CUP} \times CUP_p \qquad (4.2.4)$$

The significance assigned to each performance metric depends on the organization's specific objectives and preferences. Consequently, the weighting of these metrics can vary from one organization to another. Nonetheless, conducting diverse assessments like the novel model presented in Chapter 6, section 6.3 or sensitivity analysis can determine the most attainable weightings for metrics based on the company's goals.

4.3 Model for Projects with Deadline and Priority

This section outlines the optimization model that has been developed for resource-constrained multi-concurrent projects with strict deadlines and assigned priority. The model was formulated using the defined research methodology in chapter one and is presented below.

4.3.1. Model Formulation

As stated in chapter one, section 1.2, the model must consider a set of *n* independent projects to be constructed by a limited *m* number of crews. Each crew can handle one project at a time; therefore, each project can be assigned at most to one crew. The mathematical formulation is based on Integer Linear Programming (ILP) and solved by Analytic Solver, resulting in an optimal crew allocation plan. Note that Frontline Systems Inc markets the Analytic Solver, an Excel-based optimization tool that utilizes branch and bound algorithms to reach the optimal solution.

When faced with complex combinatorial problems, the branch and bound algorithm is often the most effective means of generating optimal solutions while minimizing computational effort (Hillier and Lieberman 2001). By intelligently enumerating portions of the solution space, the algorithm avoids needing to examine every potential solution individually. This reduces the computational time required to identify the optimal solution, making it a valuable tool for solving complex problems like the constrained multi-project scheduling problem. (Hillier and Lieberman 2001) and (Brucker and Knust 2006) highlighted the effectiveness of this implicit enumeration algorithm for solving combinatorial optimization problems to optimality.

Analytic Solver mathematical optimization engine is the more advanced version featuring state-of-the-art optimization algorithms in contrast with the known free version of Solver available in MS Excel. The model is set up in Excel-based spreadsheets that provide a simple, user-friendly interface to feed the project and crew data to the model. Projects data included site index, unique project number (i.e., work order), location, type, released (received) date, estimated duration, and priority index; crew attributes comprised crew availability within the planning horizon, calendar, and non-working days. The model assumptions include a fixed finite number of available crews with determined availabilities, deterministic but not equal project durations, and no pre-emption of projects (details related to these assumptions, can be found in chapter one).

Before discussing the model formulation, it is important to define two key factors.

The first is *slack time*, which is the amount of time between when a project is received and the project-specific deadline after deducting the expected project duration (as displayed in Figure 4.1.

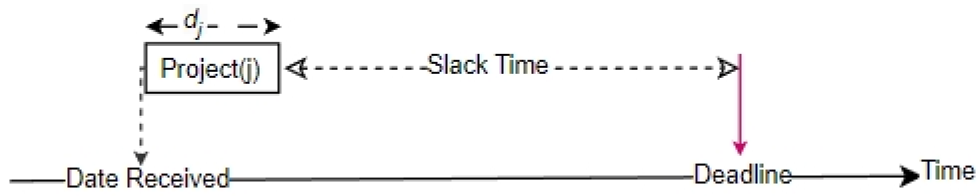


Figure 4.1: Schematic View of Slack Time

This buffer accounts for necessary planning and administrative work, such as obtaining permits and preparing and mobilizing crews. The second factor is priority indices, which rank projects in order of importance. Considering these factors, the optimization model can be effectively applied to real-world construction projects, ensuring efficient allocation of resources and timely project completion. The slack time is calculated as per Eq. (4.3.1).

$$ST_j = dl_j - dr_j - d_j \,, j = \{1,2,..,n\} \qquad (4.3.1)$$

The second factor is the *priority index* (PI) as one of the model components where high-priority projects are evaluated based on a formal risk analysis procedure at the project manager's discretion, as stated in the problem statement section in Chapter One. However, for generalization purposes, PI is simplified and scaled on the range [0.1, 0.5] to denote various priority grades from low priority to emergency projects.

Below, we outline the notations used in the model with their explanations.

T: length of the planning horizon, usually defined as one or biweekly plan period

n :total number of projects to be scheduled

m :total number of crews

$(d_j \,, dl_j \,, dr_j)$ denotes

(construction duration, deadline, date received)respectively , for project j

$i\,,j$: crew and project indices respectively

PI_j: priority index project j

And the model is formulated as follows.

$$Maximize\ z = \sum_{i=1}^{m}\sum_{j=1}^{n} \mathrm{PI_j}\ (1\text{-}\ (\mathrm{ST_j}/\sum_{j=1}^{n}\mathrm{ST_j}\,))\ .\ x_{ij} \qquad (4.3.2)$$

Subject to:

$$\sum_{i=1}^{m} x_{ij} \quad \leq 1 \qquad \text{where } \ \mathrm{j} = \{1,\ldots., \mathrm{n}\} \qquad (4.3.3)$$

$$\sum_{j=1}^{n} d_j.\ x_{ij} \leq \mathrm{a}_i \qquad \text{where } \ i = \{1,\ldots,\mathrm{m}\} \qquad (4.3.4)$$

$$x_{ij} \in \{0,1\}, \qquad i\ =\ \{1,\ldots,m\}, j\ =\ \{1,\ldots.,n\} \qquad (4.3.5)$$

Where $\mathrm{x}_{ij}\ = 1$ if crew i is allocated to project j, and $\mathrm{x_{ij}}\ = 0$, otherwise. To avoid trivial cases, it also the model parameters have to be bounded as follows:

$$\underset{i=1,\ldots m}{\mathrm{Min}}\ a_i \geq\ \underset{j=1,\ldots n}{\mathrm{Min}}\ d_j\,, \sum_{j=1}^{n}\mathrm{d_j} \geq\ \underset{i=1,\ldots m}{\mathrm{Max}}\ a_i\,, \sum_{j=1}^{n}\mathrm{d_j} \geq\ \sum_{i=1}^{m} a_i \qquad (4.3.6)$$

The main goal of the model is to optimize the number of projects with higher priority and less slack time over a specific planning horizon. The objective function (4.3.2) comprises two factors: the priority index and the normalized project's slack time. The latter is calculated by subtracting one from the project's slack time divided by the total slack time of all projects. This factor aims to identify projects with less slack time to meet project deadlines as much as possible. The set of constraints (4.3.3) ensures that no more than one crew can be assigned to each project. The set of constraints (4.3.4) restricts each crew's utilization to its availability, meaning that each crew can be assigned within its total availability. Constraint (4.3.5) defines the type of decision variables. Finally, in the set of constraints (4.3.6), the first assumption ensures that each crew's availability exceeds the minimum project durations. If this inequality is violated, we may remove the corresponding crew from the optimization model for that specific planning horizon. Also, the second assumption avoids a trivial solution where all projects can be performed by one crew. Additionally, the last inequality in the constraints (4.3.6) denotes that the summation of the project durations is greater than or equal to the total crews' availability. If this inequality is violated, the model still generates the solution but with crews idling time which is not desired.

It is worth noting that the simplified model shares some characteristics with the Multiple Knapsack Problem (MKP), the well-known NP-hard combinatorial optimization problem. However, the model is designed to solve a project scheduling problem under specific constraints, such as resource availability, priorities, and deadlines. The main difference between this problem and MKP is that the former deals with allocating crews to projects specifically no more than one crew can be assigned to each project, while the latter is concerned with packing items in knapsacks with different capacities (Fréville 2004). Furthermore, in the context of the problem at hand, it is essential to note that no project duration can exceed the maximum crew availability, and that is an inherent requirement that does not necessitate additional constraints. Conversely, it is essential that the sum of the project durations must be at least equal to the crews' total availability.

4.3.2. Case Studies

Several case studies have been conducted to validate the results in collaboration with the industry partner. Table 4-1 presents a sample of the project input data used in the conducted studies.

Table 4-1: Projects input data in the optimization model

Site index	Work Order	Received	Deadline	Priority	Duration
1	207823.1	21-07-06	21-07-25	0.3	2
2	207843.2	21-07-07	21-07-25	0.4	2
3	206905.1	21-07-07	21-07-26	0.1	3
4	208061.3	21-07-07	21-07-29	0.3	2
5	208412.5	21-07-08	21-07-30	0.2	3

All the cases consider eight crews, each of which was employed full-time and worked five days a week, except for statutory holidays, as depicted in Table 4-2. This Table served as a template for biweekly registering crew availability. It is worth noting that Crew "Cr-215" had one workday off over the two-week project planning window, which differed from the other crews and was factored into the optimization solution.

Table 4-2: Crews availability in two weeks

Crew code	Availability	Crew code	Availability
Cr-214	10 d	Cr-230	10 d
Cr-215	9 d	Cr-231	10 d
Cr-217	10 d	Cr-232	10 d

As to be noted, the model was executed using Frontline Solvers Excel Analytic Solver (Analytic Solver Optimization V2017: 020ASOPTIM), resulting in optimal solutions. One of the sample solutions selected for illustration purposes is presented herein. The optimization was set to run 100 times and utilized the standard LP/Quadratic Engine from the Analytical Solver package to execute the optimization. On a desktop Intel(R) Core (TM) i7 computer, the CPU time was recorded to be less than one minute for all samples with fewer than 100 projects and less than two minutes for samples ranging from 100 to 250 projects. Table 4-3 summarizes the results of applying the optimization model to some case studies, along with their statistics.

Table 4-3: Samples Results of Optimization Model with 8 crews and 100 runs

Samples Elements				*Optimization Results Statistics*					
No	**#Projs**	**Capacity**	**Horizon**	**Time (S)**	**#Planned**	**#Delay**	**PPI**	**CSI**	**CUP**
1	45	77 d	2 w	11.25	40	0	1.05	100%	100%
2	62	79 d	2 w	16.78	42	0	1.10	100%	100%
3	85	116 d	3 w	19.38	66	0	1.13	100%	100%
4	100	118 d	3 w	65.23	67	0	1.12	100%	100%
5	200	120d	3 w	91.84	81	0	1.33	100%	100%
6	250	156d	4 w	95.47	104	0	1.32	100%	100%

Table 4-3 shows that consistently across all cases, the PPI is greater than one, indicating that the optimization results outperform manual planning practices based on heuristic rules. This starkly contrasts the time-consuming and error-prone nature of manual procedures. Upon obtaining an optimized plan at any point of time, the resulting crew allocation plan can be visualized through Gantt chart, detailed plan in Excel spread sheets, and communicated to field supervisors.

For instance, utilizing the sample with 45 projects, Figure 4.2 displays a portion of the Gantt chart, showcasing the allocated crew across multiple sites and project start and completion dates. The graph's vertical axis represents Site ID, while the bar chart visualizes project start and finish times with the allocated crew. These color-coded bars distinguish the projects distributed among various crews, with each crew's work continuity easily traced through their assigned color.

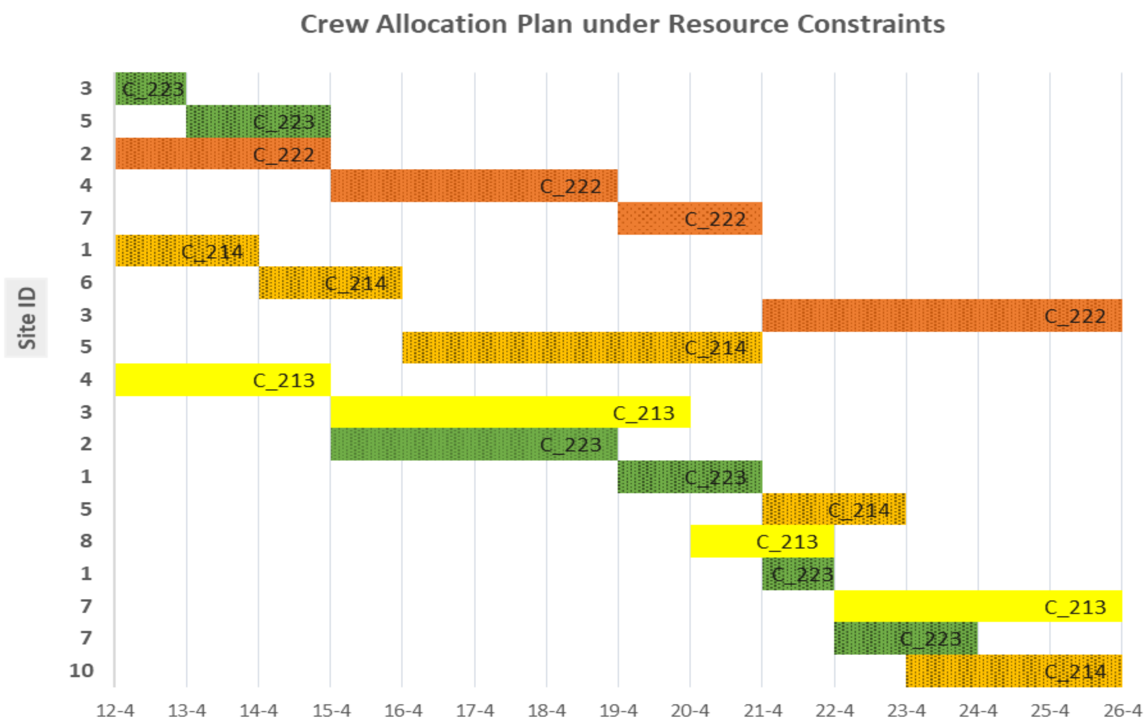


Figure 4.2: Snapshot of Gantt Chart based on the Optimization Solution

Multiple case studies were assessed with the industry company to validate the model's effectiveness. For example, in another case examined, out of 55 projects 28 projects were allocated to six crews over a two-week period as the results depicted in Table 4-4 below.

Table 4-4: two week-plan for case of 55 projects

Crews Availability and Utilization		
Crew ID	Availability	Utilization
C_213	10	10
C_214	10	10
C_217	9	9
C_218	10	10
C_222	10	10
C_223	10	10

Number of Jobs Planned	28
Total Number of Jobs	55
Total Work Crew Planned	472 CH

Crew Utilization	100%
Pool Percent Planned	50.9%

Bi-Weekly Detailed Crew Site Plan: April_12 to April_26									
Site No.	WorkOrder	Site_Location	Date Created	Deadline	Duration	Start Date	Finish Date	Crew	Criticality
3	221056	7530 34 Street NW	2021-03-25	2021-04-28	1	2021-04-12	2021-04-13	C_223	10
5	220615	7809 93 Ave NW	2021-03-22	2021-04-26	2	2021-04-13	2021-04-15	C_223	7
6	219407	10825 83 Ave NW	2021-04-01	2021-05-06	3	2021-04-12	2021-04-15	C_222	13
7	218498	7912 93 Ave NW	2021-04-08	2021-05-13	2	2021-04-15	2021-04-19	C_222	14
8	206547	8011 93 Ave NW	2021-03-18	2021-04-22	2	2021-04-19	2021-04-21	C_222	2
9	209412.1	9711 93 Ave NW	2021-04-12	2021-05-14	3	2021-04-12	2021-04-15	C_217	15
11	208532.1	10014 105A Ave NW	2021-03-23	2021-04-27	2	2021-04-12	2021-04-14	C_214	8
13	208512.3	9322 105 Ave NW	2021-03-22	2021-04-26	2	2021-04-14	2021-04-16	C_214	6
16	207577.1	2123 & 2127 49 Street NW	2021-04-12	2021-05-16	3	2021-04-21	2021-04-26	C_222	12
17	206848.1	11745 83 Ave NW	2021-03-23	2021-04-27	2	2021-04-12	2021-04-14	C_218	8
18	206801.3	721 Cain Blvd SW	2021-04-05	2021-05-10	3	2021-04-16	2021-04-21	C_214	11
19	206709.3	2541 Bell Court SW	2021-03-19	2021-04-23	3	2021-04-12	2021-04-15	C_213	5
20	206800.9	1023 Canighane SW	2021-03-23	2021-04-27	3	2021-04-15	2021-04-20	C_213	4
25	206211.425	16301 - 87 Ave NW	2021-03-22	2021-04-23	2	2021-04-15	2021-04-19	C_223	3
26	206389.9	106 Street Sask. Drive	2021-03-30	2021-05-03	2	2021-04-19	2021-04-21	C_223	7
31	206749.4	17305 82 AVE NW	2021-03-29	2021-05-03	2	2021-04-21	2021-04-23	C_214	6
33	206269.4	3644 116 AVE NW	2021-04-02	2021-05-07	2	2021-04-14	2021-04-16	C_218	13
35	206706.7	42 AV and 126 ST NW	2021-04-05	2021-05-10	2	2021-04-15	2021-04-19	C_217	13
39	206885.4	10413 31A Ave NW	2021-04-09	2021-05-14	2	2021-04-16	2021-04-20	C_218	14
40	206354.5	10125 108 ST NW	2021-04-07	2021-05-12	2	2021-04-20	2021-04-22	C_218	12
41	206794.1	11516 134 AVE NW	2021-04-08	2021-05-13	2	2021-04-20	2021-04-22	C_213	13
46	206701.7	8203 140 Street NW	2021-04-06	2021-05-11	2	2021-04-22	2021-04-26	C_218	10
49	206538.6	109 ST UNIVERSITY AVE NW	2021-04-08	2021-05-11	1	2021-04-21	2021-04-22	C_223	11
50	206752.4	10315 32A Ave NW	2021-03-31	2021-05-05	2	2021-04-19	2021-04-21	C_217	9
51	206741.2	6004 106Ave NW	2021-04-08	2021-05-13	2	2021-04-21	2021-04-23	C_217	12
52	206226.6	2345 106Ave NW	2021-03-22	2021-04-26	2	2021-04-22	2021-04-26	C_213	1
54	2062765.3	2567 University Ave.NW	2021-04-02	2021-05-04	2	2021-04-22	2021-04-26	C_223	5
55	206459.2	3675 University Ave.NW	2021-03-22	2021-04-26	1	2021-04-23	2021-04-26	C_214	1

Note that the criticality of a project is marked by its relative place between other planned projects through ascending order of the project float. Each project's float is calculated by subtracting its planned finished date from its deadline date. The project with the minimum float is the most critical one at the first place of criticality. In Table 4-4 the most critical projects (with site numbers of 55, 52, 8 and 25) have been highlighted. Next, Figure 4.3 displays the Gantt Chart that visualizes the project's start and finish dates with the color-coded crews assigned to the identified sites. This result shows no crew's idle time waiting to start the next project at any point in time. Total work continuity for all crews has been reached.

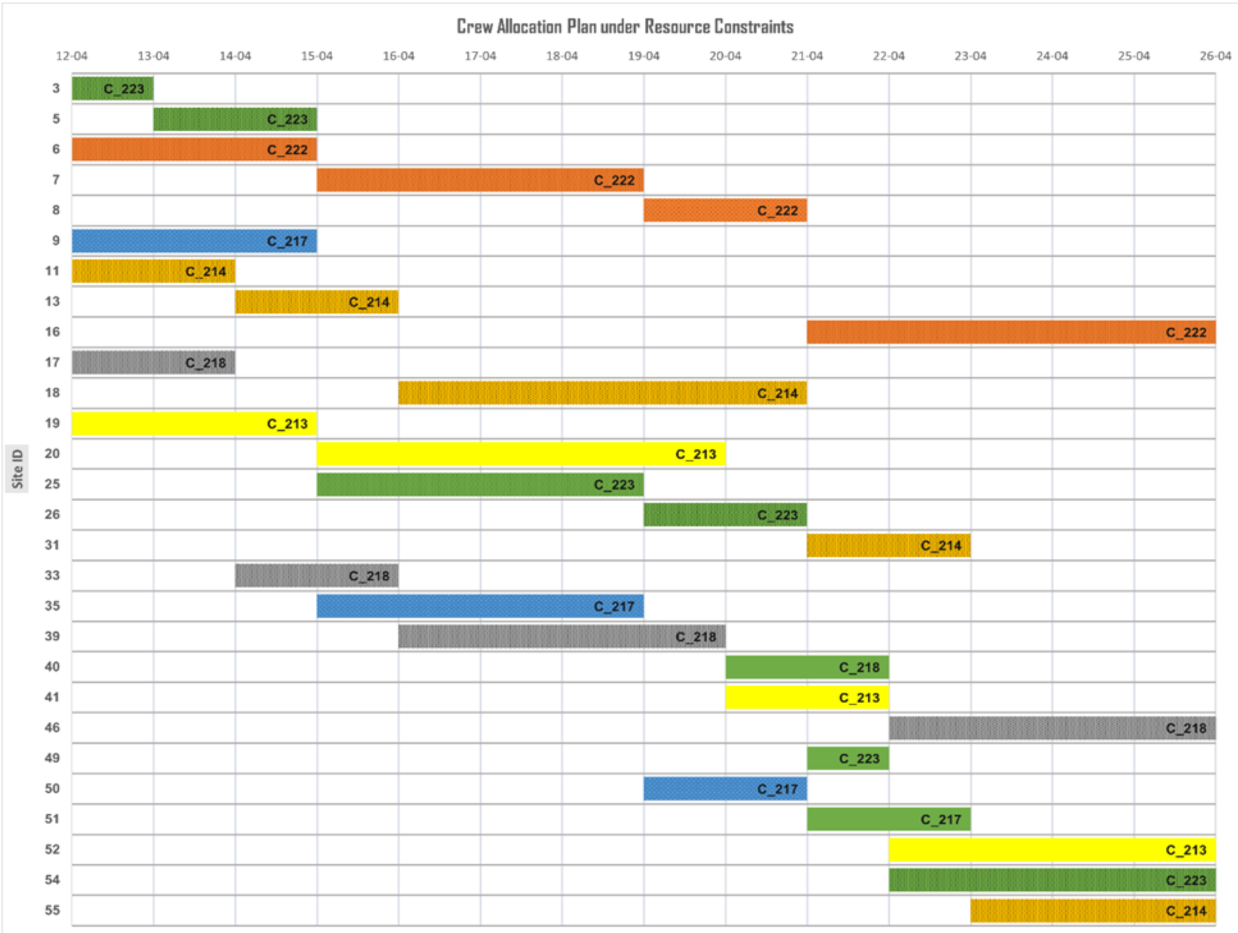


Figure 4.3: Gantt Chart for the Detailed Bi-Weekly Plan in Table 4-4

Moreover, all the project's completion dates comply with their deadlines' constraints. Based on the case study findings, it can be inferred that all projects were scheduled for completion prior to their respective deadlines, with a 100% success rate in meeting clients' deadlines.

As illustrated in chapter one, section 1.1.5, the route optimization aspect was excluded from the problem analysis. Although the travel time between sites does not significantly affect the crew allocation plans, the prototyped program develops a visual report using the locations of the sites and the assigned crew on Google Maps, as one case presented in Figure 4.4: case of visual report of crew allocation on Google Maps. This tool is intended for construction managers to review and make necessary adjustments based on the location of the allocated crews on the map.

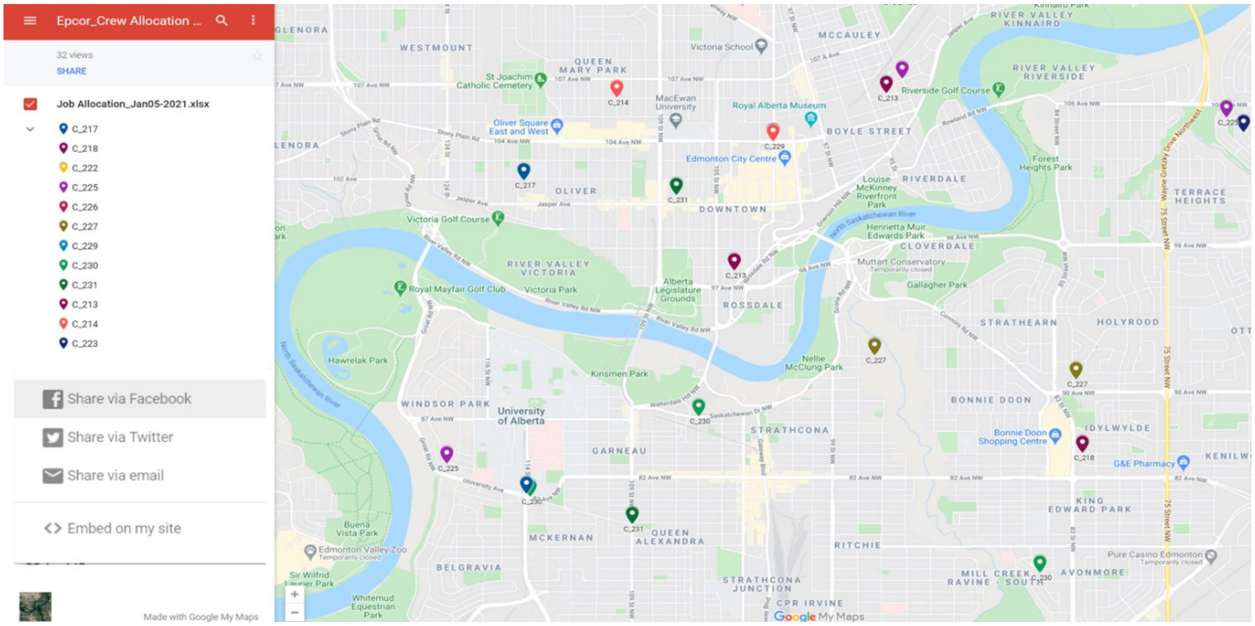


Figure 4.4: case of visual report of crew allocation on Google Maps

4.3.3. Model for standard projects

Since some projects are not prioritized (i.e., standard projects), a model needs to allocate resources to this kind of project. After careful investigation and applying different scenarios to cases conducted based on the data gathered from the industry partner company, it was realized that the same model could be modified to plan this type of project. This approach aligns with the research objectives of maintaining the simplicity and flexibility of the models and adequately responding to the problem conditions associated with this type of project.

Therefore, while planning standard projects, the developed model is modified by only changing the objective function, while the constraints remain the same. This modification allows the model to allocate resources to projects without priority assigned, ensuring that all projects are accounted for and efficiently planned.

$$\text{Norm.ST}_j = (\text{Max}(\text{ST}_j)\text{-ST}_j) + 1 \qquad j = \{1,\ldots, n\} \qquad (4.3.7)$$

$$Maximize\ z = \sum_{i=1}^{m}\sum_{j=1}^{n} (\text{Norm.ST}_j) \,.\, x_{ij} \qquad (4.3.8)$$

Equation 4.3.7 modifies the project slack times to be used as a criterion to maximize the number of planned projects. It is to be noted that one has been added to this equation to prevent the possibility of the project with the maximum slack time being overlooked in the optimization process since its Norm.ST would have equaled zero.

The objective function formulated in the equation 4.3.8 maximizes the number of projects to be planned subject to the constraints already explained in the model section 4.3.1.

4.3.4. Heuristic Method In Practice

The current practice for planning and scheduling a given problem has been streamlined and generalized into a heuristic method as a base for validating the mathematical model. This method consists of the following steps:

- Step (1): Sort the list of projects in ascending order based on their deadline, with projects with the shortest deadline appearing first.
- Step (2): For projects with the same deadline, sort them according to their priority, with higher priority projects taking precedence.
- Step (3): Assign projects from the resulting list from step (2) to the available crews arbitrarily.

- Step (4): Calculate each crew's remaining crew availability (RCA). Initially, RCA for each crew is equal to the crew availability within the planning horizon. After each project is assigned, the duration is deducted, resulting in an updated RCA for the crew.
- Step (5): Iterate through steps (3) and (4) until RCA equals zero. In the final iteration, it is essential to consider comparing the RCAs with the candidate projects' durations when matching and assigning projects to the crews.

4.3.5. Model Validation and Verification

Incorporating real-world case studies developed through a strong partnership with industry, Epcor Drainage Construction Services provides a solid layer of empirical validation to the proposed models. The industry partner company's experts reviewed and validated the results from the optimization model on many case studies. Specific quantitative comparisons through developed performance metrics highlight the substantial improvements in project crew allocation efficiency, customer satisfaction, the higher number of planned projects, and the number of delayed projects by optimized models in all the studied cases. Additionally, comparing the results obtained from the heuristic method, which is an enhanced method of the industry's current practice verifies the optimization model's superior performance.

It is worth mentioning that in every studied case, the developed model resulted in the optimum solution in quick turnaround time, while the company's professional planner time record for developing the plan in respective case studies remained hours at best. Also, it is to be noted that the heuristic model in practice was face-validated first with the experienced professional planner and construction managers.

A detailed comparison of the case of 85 projects conducted in both the developed optimization model and the heuristic method is presented to verify the optimization model's outcome.

Table 4-5 presents the crews' availability within a three-weeks planning horizon. Table 4-6 includes projects data in the planning pool. Table 4-7 represents the heuristic method's detailed results.

Table 4-5: crews' availability within a three-weeks planning horizon

Crew_ID	Cr1	Cr2	Cr3	Cr4	Cr5	Cr6	Cr7	Cr8
Availability	15	15	15	14	14	13	15	15

Table 4-6: Projects' input data

#Project	Site ID	Work Order	Duration	Date Received	Deadline	PI_j
1	3	210225.0	1	01-03-2022	15-03-2022	0.2
2	5	207823.1	1	01-03-2022	16-03-2022	0.1
3	6	210790.0	1	01-03-2022	16-03-2022	0.1
4	4	206683.1	3	01-03-2022	17-03-2022	0.4
5	3	210808.0	2	02-03-2022	17-03-2022	0.3
6	7	207843.1	1	03-03-2022	17-03-2022	0.2
7	3	206876.3	3	03-03-2022	17-03-2022	0.2
8	7	206317.5	1	03-03-2022	17-03-2022	0.1
9	4	210215.0	3	03-03-2022	17-03-2022	0.1
10	3	210682.0	2	03-03-2022	17-03-2022	0.1
11	4	210076.2	3	04-03-2022	18-03-2022	0.4
12	6	210754.0	2	04-03-2022	18-03-2022	0.3
13	4	210844.0	1	03-03-2022	18-03-2022	0.2
14	8	206701.2	1	01-03-2022	18-03-2022	0.1
15	6	206905.1	1	05-03-2022	19-03-2022	0.4
16	9	206848.1	2	04-03-2022	19-03-2022	0.4
17	9	210203.0	1	03-03-2022	19-03-2022	0.4
18	8	206741.2	2	04-03-2022	19-03-2022	0.3
19	10	210224.0	2	02-03-2022	19-03-2022	0.3

#Project	Site ID	Work Order	Duration	Date Received	Deadline	PI_j
20	7	210196.0	2	05-03-2022	19-03-2022	0.3
21	4	210628.0	3	05-03-2022	19-03-2022	0.3
22	1	207577.1	3	05-03-2022	19-03-2022	0.2
23	2	210412.0	1	02-03-2022	19-03-2022	0.2
24	5	210880.0	3	01-03-2022	19-03-2022	0.2
25	9	206226.6	3	04-03-2022	20-03-2022	0.4
26	7	202594.0	3	06-03-2022	20-03-2022	0.4
27	3	210358.0	2	06-03-2022	20-03-2022	0.4
28	6	210646.0	3	02-03-2022	20-03-2022	0.4
29	5	206801.3	2	04-03-2022	20-03-2022	0.3
30	2	210214.0	2	04-03-2022	20-03-2022	0.3
31	9	2062765.3	3	02-03-2022	20-03-2022	0.2
32	9	206768.5	1	01-03-2022	20-03-2022	0.2
33	1	219908.0	1	01-03-2022	20-03-2022	0.1
34	8	210504.0	3	01-03-2022	20-03-2022	0.1
35	9	210304.0	1	06-03-2022	20-03-2022	0.1
36	1	210430.0	1	03-03-2022	20-03-2022	0.1
37	10	208512.3	1	03-03-2022	21-03-2022	0.4
38	7	206459.2	3	01-03-2022	21-03-2022	0.4
39	10	210484.0	2	07-03-2022	21-03-2022	0.4
40	2	206800.9	3	01-03-2022	21-03-2022	0.3
41	10	206723.2	2	02-03-2022	21-03-2022	0.3
42	2	219526.0	3	07-03-2022	21-03-2022	0.3
43	5	210286.0	1	05-03-2022	21-03-2022	0.3
44	7	210466.0	1	06-03-2022	21-03-2022	0.3
45	6	210556.0	2	07-03-2022	21-03-2022	0.3
46	4	206701.8	2	05-03-2022	21-03-2022	0.2
47	3	210448.0	2	07-03-2022	21-03-2022	0.2
48	1	206752.5	1	01-03-2022	21-03-2022	0.1
49	1	210502.0	1	07-03-2022	21-03-2022	0.1
50	8	210664.0	3	05-03-2022	21-03-2022	0.1
51	3	210718.0	3	07-03-2022	21-03-2022	0.1
52	9	210520.0	1	07-03-2022	22-03-2022	0.4
53	7	210700.0	3	02-03-2022	22-03-2022	0.4
54	4	210934.0	3	05-03-2022	22-03-2022	0.3
55	3	208061.1	3	02-03-2022	22-03-2022	0.2
56	5	210610.0	2	03-03-2022	22-03-2022	0.2

#Project	Site ID	Work Order	Duration	Date Received	Deadline	PI_j
57	4	210340.0	2	05-03-2022	22-03-2022	0.1
58	7	207732.1	2	07-03-2022	23-03-2022	0.4
59	8	210598.0	1	03-03-2022	23-03-2022	0.4
60	3	206706.8	2	06-03-2022	23-03-2022	0.3
61	3	216990.0	3	06-03-2022	23-03-2022	0.3
62	7	206538.7	1	07-03-2022	23-03-2022	0.2
63	9	210916.0	1	05-03-2022	23-03-2022	0.2
64	6	206709.3	3	06-03-2022	23-03-2022	0.1
65	8	206724.1	1	04-03-2022	23-03-2022	0.1
66	4	210574.0	1	06-03-2022	23-03-2022	0.1
67	9	210736.0	3	07-03-2022	23-03-2022	0.1
68	8	210826.0	2	05-03-2022	24-03-2022	0.4
69	6	210862.0	2	04-03-2022	24-03-2022	0.4
70	10	208395.0	1	04-03-2022	24-03-2022	0.2
71	9	210250.0	1	04-03-2022	24-03-2022	0.2
72	7	210538.0	1	04-03-2022	24-03-2022	0.2
73	6	205954.1	3	07-03-2022	24-03-2022	0.1
74	6	210206.0	2	05-03-2022	24-03-2022	0.1
75	7	210592.0	3	06-03-2022	25-03-2022	0.3
76	8	210898.0	3	06-03-2022	25-03-2022	0.3
77	5	210772.0	1	08-03-2022	25-03-2022	0.2
78	4	210268.0	3	06-03-2022	26-03-2022	0.3
79	7	208412.1	2	08-03-2022	26-03-2022	0.1
80	2	210322.0	3	07-03-2022	26-03-2022	0.1
81	10	210477.0	1	07-03-2022	27-03-2022	0.4
82	1	210394.0	3	07-03-2022	27-03-2022	0.1
83	8	206723.8	1	08-03-2022	28-03-2022	0.4
84	10	210376.0	2	08-03-2022	28-03-2022	0.4
85	2	210232.0	3	08-03-2022	28-03-2022	0.1

Table 4-7: Heuristic method results for the case of eighty-five projects

Crew(1)					RCA1
Site ID	Job ID	d_i	C_i	dl_i	15
3	210225.0	1	09-03-2022	15-03-2022	14
4	210215.0	3	12-03-2022	17-03-2022	11
9	210203.0	1	13-03-2022	19-03-2022	10
9	206226.6	3	16-03-2022	20-03-2022	7
1	219908	1	17-03-2022	20-03-2022	6
10	206723.2	2	19-03-2022	21-03-2022	4
8	**210664**	**3**	**22-03-2022**	**21-03-2022**	1
8	210598	1	23-03-2022	23-03-2022	0

Crew(2)					RCA2
Site ID	Job ID	dj	Cj	dlj	15
5	207823.1	1	09-03-2022	16-03-2022	14
3	210682.0	2	11-03-2022	17-03-2022	12
8	206741.2	2	13-03-2022	19-03-2022	10
7	202594.0	3	16-03-2022	20-03-2022	7
8	210504	3	19-03-2022	20-03-2022	4
2	**219526**	**3**	**22-03-2022**	**21-03-2022**	1
1	**210502**	**1**	**23-03-2022**	**21-03-2022**	0

Crew(3)					RCA3
Site ID	Job ID	dj	Cj	dlj	15
6	210790.0	1	09-03-2022	16-03-2022	14
4	210076.2	3	12-03-2022	18-03-2022	11
10	210224.0	2	14-03-2022	19-03-2022	9
3	210358	2	16-03-2022	20-03-2022	7
9	210304	1	17-03-2022	20-03-2022	6
5	210286	1	18-03-2022	21-03-2022	5
3	210718	3	21-03-2022	21-03-2022	2
4	**210340**	**2**	**23-03-2022**	**22-03-2022**	0

Crew(4)					RCA4
Site ID	Job ID	dj	Cj	dlj	14
4	206683.1	3	11-03-2022	17-03-2022	11
6	210754.0	2	13-03-2022	18-03-2022	9
7	210196.0	2	15-03-2022	19-03-2022	7
6	210646	3	18-03-2022	20-03-2022	4
1	210430	1	19-03-2022	20-03-2022	3
7	210466	1	20-03-2022	21-03-2022	2
5	210610	2	22-03-2022	22-03-2022	0

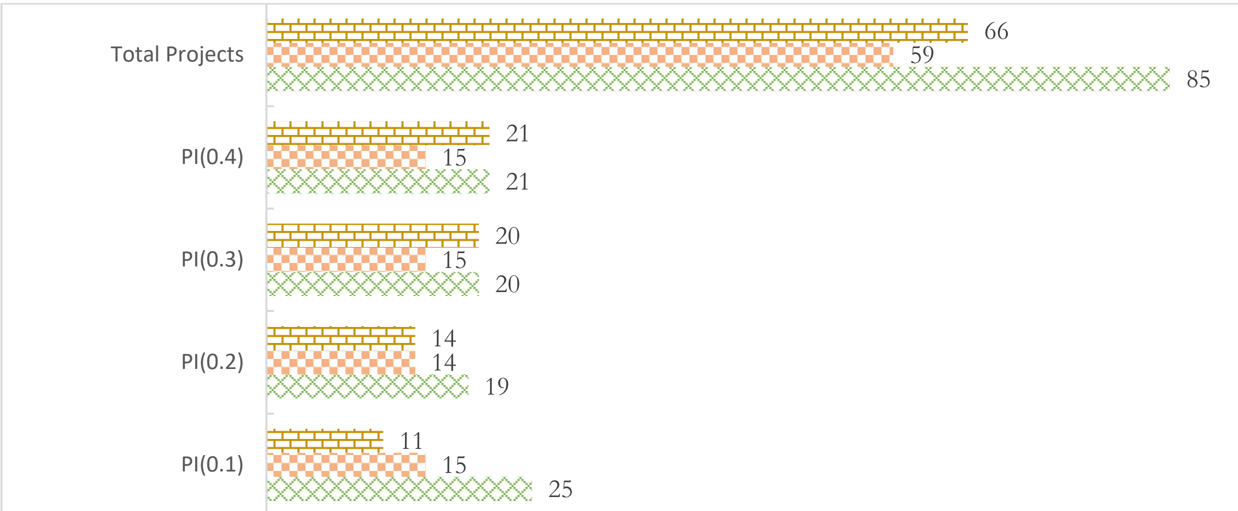
Crew(5)					RCA5
Site ID	Job ID	dj	Cj	dlj	14
3	210808.0	2	10-03-2022	17-03-2022	12
4	210844.0	1	11-03-2022	18-03-2022	11
4	210628.0	3	14-03-2022	19-03-2022	8
5	206801.3	2	16-03-2022	20-03-2022	6
10	208512.3	1	17-03-2022	21-03-2022	5
6	210556.0	2	19-03-2022	21-03-2022	3
7	210700.0	3	22-03-2022	22-03-2022	0

Crew(6)					RCA6
Site ID	Job ID	dj	Cj	dlj	13
7	207843.1	1	09-03-2022	17-03-2022	12
8	206701.2	1	10-03-2022	18-03-2022	11
1	207577.1	3	13-03-2022	19-03-2022	8
2	210214.0	2	15-03-2022	20-03-2022	6
7	206459.2	3	18-03-2022	21-03-2022	3
4	206701.8	2	20-03-2022	21-03-2022	1
9	210520.0	1	21-03-2022	22-03-2022	0

Crew(7)					RCA7
Site ID	Job ID	dj	Cj	dlj	15
3	206876.3	3	11-03-2022	17-03-2022	12
6	206905.1	1	12-03-2022	19-03-2022	11
2	210412.0	1	13-03-2022	19-03-2022	10
9	2062765.3	3	16-03-2022	20-03-2022	7
10	210484.0	2	18-03-2022	21-03-2022	5
3	210448.0	2	20-03-2022	21-03-2022	3
4	**210934**	**3**	**23-03-2022**	**22-03-2022**	0

Crew(8)					RCA8
Site ID	Job ID	dj	Cj	dlj	15
7	206317.5	1	09-03-2022	17-03-2022	14
9	206848.1	2	11-03-2022	19-03-2022	12
5	210880.0	3	14-03-2022	19-03-2022	9
9	206768.5	1	15-03-2022	20-03-2022	8
2	206800.9	3	18-03-2022	21-03-2022	5
1	206752.5	1	19-03-2022	21-03-2022	4
3	208061.1	3	22-03-2022	22-03-2022	1
7	206538.7	1	23-03-2022	23-03-2022	0

As displayed in the Table 4-7, the plan generated by applying the heuristic method scheduled fifty-nine out of eighty-five projects, whereas the optimization model scheduled sixty-six projects. The heuristic method resulted in five tardy projects that would miss deadlines, as highlighted in Table 4-7, whereas no tardy project resulted in the optimized solution.



	PI(0.1)	PI(0.2)	PI(0.3)	PI(0.4)	Total Projects
Optimization Solution	11	14	20	21	66
Heuristic Technique	15	14	15	15	59
Case Projects	25	19	20	21	85

Figure 4.5: Comparison of optimization results against the heuristic method results_ Case of 85 Projects

Out of the 59 clients to be served with the plan resulting from the heuristic method, five of them will have a CSI of 0%. This means that the average CSI for the remaining clients is 91.5%, compared to the 100% CSI achieved through the optimization solution with no client dissatisfaction (i.e., no delayed projects). Notably, both methods resulted in a crew utilization (CUP) of 100% in the current case.

Figure 4.5 depicts that the optimization model scheduled all higher-priority projects (i.e., with a PI of 0.3 and 0.4. In comparison, the heuristic method planned more projects with lower priority (i.e., fifteen "PI = 0.1" projects planned by the heuristic method, compared to eleven "PI = 0.1" projects in the optimization model). The solution obtained from the optimization model yielded a more significant number of planned projects with a higher priority level. In contrast, the heuristic method scheduled fewer total projects but more projects with a lower priority.

As seen in Figure 4.5, optimization results significantly outperform the current practice regarding the total number of planned projects and the number of projects with higher priorities.

The results from all the case studies demonstrated that the optimization model outperforms the heuristic method regarding scheduling more projects with the same crews' availabilities within the same planning window while ensuring that project deadlines are not exceeded, and higher priority projects are planned.

Furthermore, the time required to perform the heuristic method manually was significantly longer, taking hours to days, compared to the optimization model, which resulted in a quick turnaround time (a few minutes in large-scale cases with 250 projects).

The effectiveness and efficacy of the optimization models were further verified by subject matter experts, underscoring the reliability of both approaches.

4.3.6. Contributions of the model

The mathematical model and its results presented above have contributed to crew planning for multi-concurrent construction projects, mainly in the following academic and practical aspects.

From an academic standpoint, the model simplifies the crew planning problem for multi-concurrent projects scattered over distinct site locations. This is achieved by cutting down unnecessary constraints such as travel time between sites without compromising the sufficiency of the real-world problem definition, avoiding the complex computational burden of route optimization. Additionally, the model avoids the complexity of the scheduling models by simplifying the problem into a simple zero-one(binary) model, which is tractable and reaches the optimal solution with no need for metaheuristics. This simplification leads to solving the problem of practical complexity and size in a matter of seconds.

From a practical standpoint, our model offers optimal crew-project planning solutions formulated in a user-friendly Excel spreadsheet program. This program is simple for practitioners to work with and is not expensive. This program gives practitioners access to a streamlined crew-project planning model that provides optimal solutions quickly and efficiently.

Overall, this study provides a mathematical model that offers significant benefits to the crew planning process for multi-concurrent construction projects. The model's academic and practical contributions streamline the crew planning process by reducing unnecessary constraints and avoiding complex computational burdens while providing optimal solutions in a simple and user-friendly manner.

4.4 Model for Projects with Deadline and Delay Penalty

4.4.1. Significance of project deadline

The deadline is contractually obligated with special conditions for on-time or early completion bonuses and late penalties. The importance of deadlines cannot be overstated; it presents itself as both the goal and constraint in planning, scheduling, and project control. In practice, deadlines represent the most relevant piece of project planning information the project team perceives. In other words, the project team focuses on completing the given scope of work by the deadline.

Furthermore, the other crucial project success factor, the cost budget, is generally checked with deadline-related bonuses and penalties. All come together in the big picture as the invaluable reward of maintaining and boosting the reputation for being accountable for getting the project done by the deadline, which is even more influential in project closure accounting, bringing more value and benefits to the company.

As is typical in these types of projects, there are contractual obligations in place for late penalties (such as charges for delays in incentive contracts) and cancellation costs (such as damages for contract breaches, client and revenue losses, and damage to reputation) if completion time exceeds the maximum allowable delay. As a result, this study focuses on allocating limited renewable resources to multiple scattered projects while adhering to the maximum allowable tardiness to minimize delay penalties and prevent potential contract terminations.

4.4.2. Notations and assumptions

This section covers the mathematical model for an optimal crews-driven scheduling problem under maximum allowable delay subject to delay penalties and cancellation damage cost for multi-projects scattered in the various sites. The model decides the crew allocation (i.e., which crew is assigned to which project) and, simultaneously, the projects' schedule (i.e., determines start and finish dates for each project).

Based on the stated problem in Chapter 1, the model is summarized as follows.

Problem consists of a set $S^P = \{P_1, \dots, P_N\}$ of projects received at any point in time randomly with a unique site location; each has its predetermined obligated due date and deadline. Each project is bonded to a late penalty (i.e., a penalty charge per unit of time if the completion date passes its due date) and cancellation cost (i.e., a fixed damage cost for not delivering the completed project by its deadline). There is a set $S^C = \{C_1, \dots, C_m\}$ of construction crews at the disposal of the project manager, to construct the projects. Each crew has a distinct availability window within which they can only be assigned to a single project at any given time. Despite project independence, sharing resources creates a degree of interdependence between them. Moreover, in cases where projects are interdependent, delays in one project can have a ripple effect on others. This problem can be characterized as such.

1. Each crew can perform at most one project at a time when available. This assumption is in favor of the client and prohibits splitting work and multiple visits by various crews.
2. Each project can be constructed by only one crew at a time, with no interruptions allowed. This assumption is due to the high mobilization time relative to the construction duration, and also, as a project starts, it is better to be finished at the earliest due to road closures, interferences to the traffic access, and inconveniences for the businesses around the project location.
3. The travel time between sites is not considered as illustrated in chapter one section 1.1.5.

Next, the following notations to formalize the model for a set $S^R = \{P_1, \dots, P_n\}$ of projects ready for construction, is outlined in Table 4-8. S^R is a set of projects made ready for construction as a subset of S^P (i.e., $S^R \subset S^P$). Since the projects constantly keep arriving in the pools of S^P, the S^R holds multiple projects to be planned for construction.

Table 4-8: Model Notations

Symbol	Definition
	Parameters and indices
T, t =1,…,T	planning horizon, index for periods
S^R	set of projects made ready for construction: $S^R \subset S^P$
S^C	set f crews at the disposal of the project manager
$i, k \in S^R$	subscripts for projects in S^R *pool*
$j \in S^C$	index for crews
C_t	Total number of crews available for work on day t, where t $\in T$
c_{jt}	binary parameter specifies availability of crew j in time interval t
d_i	estimated duration to construct project i
$\bar{d}_i$	due date of project i
$\hat{d}_i$	cancellation deadline for project i
β_i	delay penalty cost per unit time for project i
δ_i	potential cancellation cost of project i
Sl_i	slack time for project i
$\hat{\tau}_i$	maximum allowable tardiness for project i
φ	denotes a large nonrestrictive value
	Variables
x_{ij}	binary decision variable that takes the value of 1 if project i is assigned to crew j , and 0, otherwise
y_{ijt}	binary decision variable that takes the value of 1 if project i assigned to crew j planned in the time interval t; and it takes value of 0, otherwise
z_{ikj}	binary auxiliary variable equal to one if projects i and k are assigned to the same crew j and the project projects k follows project i
St_i	decision variable that indicates earliest start date of project i
τ_i	possible delay for project i
v_i	binary variable that identifies potential cancellation of project i

All the parameters are non-negative and predetermined. Some are determined within the contracts or agreements (i.e.,$\bar{d}_i$, $\hat{d}_i$, β_i, δ_i), some are recognized at the time of planning such as S^R, S^C,C_t, c_{jt}. c_{jt} is a binary parameter that takes the value of 1, if crew j is available in time interval t; and 0, otherwise. Other parameters are calculated as follows at the planning state and fed to the model as inputs.

- d_i is estimated at the planning stage according to Eq. (4.4.1) in which Q_i is the quantity of work; P_r denotes the typical production rate for the crews involved, similar to the Means approaches (RSMeans 2023); and f_{it} denotes the productivity factor (0 to 100%) depending on the work conditions in site i during time interval t in which the project is planned. Both of these factors can be computed based on the method described in chapter six.

$$d_i = \frac{Q_i}{P_r \times f_{it}} \qquad (4.4.1)$$

- Sl_{it} is defined as the maximum available time to delay the completion of the project without violating its due date. Slack time at any interval is calculated as per Eq. (4.4.2).

$$Sl_i = \bar{d}_i - d_i - t \qquad (4.4.2)$$

- Project delay is based on project due dates and computed as defined in Eq. (4.4.3).

$$\tau_i = \bar{d}_i - d_i - St_i \qquad (4.4.3)$$

- Maximum allowable tardiness for project i (i.e.,$\hat{\tau}_i$) is calculated as follow.

$$\hat{\tau}_i = \hat{d}_i - \bar{d}_i \qquad (4.4.4)$$

- φ is a large positive constant value like "Big M" in operations research that is used to formulate and solve linear programming (LP) problems, particularly when dealing with conditional constraints or when it's necessary to enforce binary or integer decisions(Solvers 2023). This value, incorporated into the prototyped program as ($\varphi = 5.\sum_{i=1}^{n} d_i$) which was applied in many case studies and found sufficient to enforce the formulated constraints as determined below.

4.4.3. Model Objective Function

Formulating mathematical models is not straightforward, but rather a complex process that requires careful consideration of various factors, including conflicting objectives and the intended application (Oyetunji 2009). As described in the research methodology in chapter one, section 1.8, an iterative model development process is utilized. For example, after several discussions with subject matter experts in the partner company, the following objective function was finalized for modeling the projects with the conditions mentioned earlier. Two kinds of penalty costs are considered, delaying cost (i.e., $\beta_i.\tau_i$) and the potential cancellation cost (i.e., $\delta_i.v_i$). Accordingly,

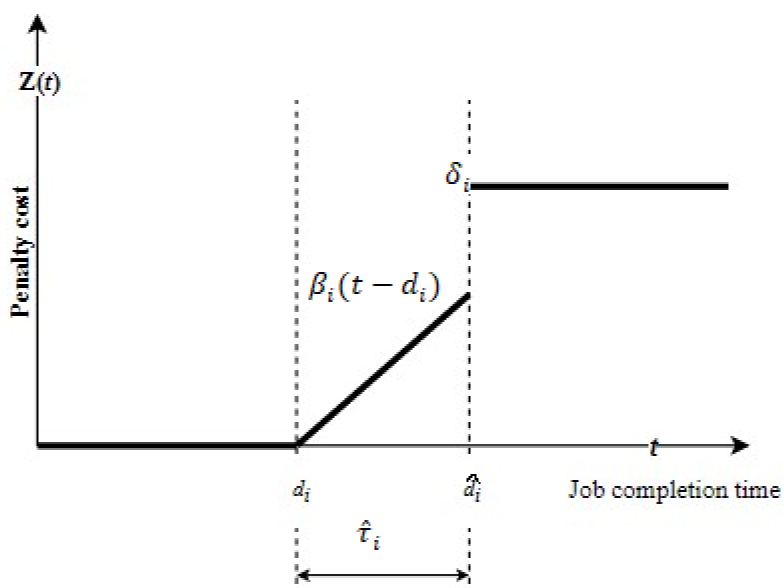


Figure 4.6: Penalty Cost Function

Figure 4.6 depicts the delay penalty cost as a piece-wise continuous non-negative function that increases linearly with tardiness and surges up to a fixed cancellation damage cost.

As the objective function in Figure 4.6 displays, at any specific time when a project completion date passes the due date, penalty charges accumulate by the slope of (β_i) until the maximum allowable delay is reached at the deadline when cancellation damage (δ_i) applies; $(\delta_i \gg \hat{\tau}_i . \beta_i)$. One objective criterion is minimizing the total delay and potential cancellation costs (i.e., $\sum_{i=1}^{n}(\beta_i . \tau_i + \delta_i . v_i)$.

Simultaneously, the number of projects scheduled within the planning horizon must be maximized while minimizing the project delays; therefore, the normalized slack time (NSl) and delay penalty are combined to accommodate this criterion. Combining the two factors was chosen because only relying on slack time might lead to higher potential delay charges. For example, suppose two crews, each five days available, and two projects, A and B, with 6 and 5 days of NSl and delay charges of 100 and 50, respectively. If the model schedules these two projects based on only the NSl criterion, Project B will be planned first, and Project A will have a one-day delay. Hence, projects with higher penalty charges also need to receive higher importance so that the cost of delay can be minimized.

Although the problem is addressed with a multicriteria objective, no degrading of any criteria is required while discovering the optimal objective value since the criteria in the objective function are not conflicting. However, it is noted that since raw data values may vary widely as if one of the features has a broad range of values, this particular element will govern the solution space, leading to flaws in the objective function evaluation. Therefore, the range of all features should be normalized so that each element contributes its approximate proportion to the objective function.

Therefore, all the criteria contributing to the objective function are normalized as follows, assuming projects have different slack times.

$$\overrightarrow{NSl_i} = \frac{Max(Sl_i) - Sl_i}{Max(Sl_i) - Min(Sl_i)} \;;\; \vec{\beta_i} = \frac{\beta_i}{Max(\beta_i)} \qquad \forall i \qquad (4.4.5)$$

Ultimately, the objective function was devised as displayed in Eq. (4.4.6); intends to plan as many projects as possible within the planning window while the projects' due dates are met as practically possible.

4.4.4. Model formulation

$$Max\Big(\sum_{i \in S^R} \big(\overrightarrow{NSl_i} + \vec{\beta_i}\big).x_i - \sum_{i \in S^R} (\beta_i.\tau_i + \delta_i.v_i) \qquad (4.4.6)$$

Subject to:

$$\sum_{j \in S^C} x_{ij} \leq 1 \qquad \forall\, i \in S^R \qquad (4.4.7)$$

$$\sum_{i \in S^R} y_{ijt} \leq c_{jt} \qquad \forall j \in S^C, \forall\, t \in T \qquad (4.4.8)$$

$$\sum_{t \in T} y_{ijt} = d_i\, .x_{ij} \qquad \forall i \in S^R, \forall j \in S^C \qquad (4.4.9)$$

$$x_{ij} \geq y_{ijt} \qquad \forall i \in S^R, \forall j \in S^C, \forall\, t \in T \qquad (4.4.10)$$

$$St_{ij} + d_i \leq St_{kj} + \varphi.\big(1 - z_{ikj}\big) \qquad \forall i > k \in S^R, \forall j \in S^C \qquad (4.4.11)$$

$$St_{kj} + d_k \leq St_{ij} + \varphi.z_{ikj} \qquad \forall i > k \in S^R, \forall j \in S^C \qquad (4.4.12)$$

$$St_i + d_i - \bar{d}_i \leq \tau_i + \varphi.(1 - v_i) \qquad \forall i \in S^R \qquad (4.4.13)$$

$$St_i + d_i \leq \hat{d}_i + \varphi.v_i \qquad \forall i \in S^R \qquad (4.4.14)$$

$$y_{ijt} \in \{0,1\}, x_{ij} \in \{0,1\}, z_{ikj} \in \{0,1\}, v_i \in \{0,1\} \qquad (4.4.15)$$

$St_i \geq 0 \; and \; \tau_i \geq 0 \;\; ; Both \; integers$ (4.4.16)

As seen in Eq. (4.4.6), the objective function loads as many projects to the crew calendar while maintaining crew availability constraints and avoiding tardy and overdue projects as practically possible. The following explanations clarifies each constraint in the model.

Project scheduling Constraints: the set of constraints in (4.4.7) ensure that each project in the S^{MRP} is scheduled at most once within T.

Crew Assignment Constraints: The set of constraints in (4.4.8) ensure that a crew is assigned to at most one project at any given time when available, that means when not available is not assigned to any project.

No-Interruption Constraints: the set of constraints in (4.4.9) and (4.4.10) articulate the ensure that a crew assigned to a project continues the work until it is finished with no interruptions. That means that firstly the duration of the project assigned has to be equal to the sum of the intervals that the project is scheduled (constraint 4.4.9). Secondly, the intervals are specifically required to be continuous starting from when the project starts (i.e., t) until end of its duration $(t + d_i + 1)$ (i.e., constraint 4.4.10).

Constraints on crew-induced precedence relationships: As mentioned earlier, projects are independent but interrelated due to shared resources. Nevertheless, their dependency type differs from logical precedence relationships in CPM since these dependencies are generated and merged during optimization runs, not present at the beginning of the optimization. Consequently, possible conditions must be accounted for as they are modeled, yielding constraints with IF functions, which are not linear and not even smooth nonlinear functions (Boer 1998; Frontline Systems

2023). Therefore, avoiding the nonlinearity constraints, sets of transformed linear constraints (4.4.11,4.4.12) devised to guarantee that projects assigned to the same crew do not overlap; in other words, a finish-to-start precedence relationship is imposed between two projects planned to be executed by a same crew. Constraints (4.4.13 and 4.4.14) track the potential delay units for each project and specify the possible project cancellation. Finally, constraints (4.4.15 and 4.4.16) define the range of decision variables.

4.4.5. Constraints clarifications

Referring to the recent point, constraints (4.4.11 to 4.4.14) model the problem's conditional statements. Nevertheless, their underline logic is convoluted and not straightforward enough to be represented as linear equations to constrain the objective function. Therefore, a clear explanation of their logic is presented next.

The mentioned constraints generally apply to scheduling and correspond to contractual conditions in project management. Therefore, their formulation in a logically valid, analytically elegant fashion constitutes part of the originality of this study.

To elaborate on constraints (4.4.11 and 4.4.12), let us enumerate the conditions for two projects*, i,* *k* have been assigned to the same crew. As displayed in Figure 4.7, six alternate conditions can be pictured between two projects assigned to the same crew. Section (A) in this Figure includes three possible situations when project *k* follows project *i* (i.e., z_{ijk}=1). The constraints (4.4.11 and 4.4.12) are applied to this section as follows.

$$\begin{cases} St_{ij} + d_i \leq St_{kj} + \varphi.\left(1 - z_{ikj}\right) \\ St_{kj} + d_k \leq St_{ij} + \varphi.z_{ikj} \end{cases} \xrightarrow{z_{ijk}=1} \begin{cases} St_{ij} + d_i \leq St_{kj} & (4.4.11) \\ St_{kj} + d_k \leq St_{ij} + \varphi\, St_{kj} & (4.4.12) \end{cases}$$

As seen in Figure 15, section (A), these two constraints are only satisfied together in situations (Section A.1 and A.2); since φ is a large number, constraint (4.4.12) is valid in all three situations, whereas constraint (4.4.11) is valid for section (A.1) when project k follows project i with a lag between them ($St_{ij} + d_i < St_{kj}$) and for section (A.2) when there is no lag between two projects ($St_{ij} + d_i = St_{kj}$). However, under no circumstance situation in Section (A.3) can satisfy the constraint (4.4.11) and consequently is rejected.

On another side of Figure 4.7, Section (B) comprises three other possible situations for when project i follows project k (i.e., $z_{ijk} = 0$). The constraints (4.4.11 and 4.4.12) are written in this section as follows.

$$\begin{cases} St_{ij} + d_i \leq St_{kj} + \varphi.\left(1 - z_{ikj}\right) \\ St_{kj} + d_k \leq St_{ij} + \varphi.z_{ikj} \end{cases} \xrightarrow{z_{ijk}=0} \begin{cases} St_{ij} + d_i \leq St_{kj} + \varphi & (4.4.11) \\ St_{kj} + d_k \leq St_{ij} & (4.4.12) \end{cases}$$

The same statement holds for the situations in this section as was for Section (A), with the difference that Section (B.3) can violate the constraint (4.4.12). Therefore, the two sets of constraints (4.4.11 and 4.4.12) together reject the situation (3) in which the two projects overlap.

It is worth noting that one can define two variables representing possibilities for which project follows the other, as stated below.

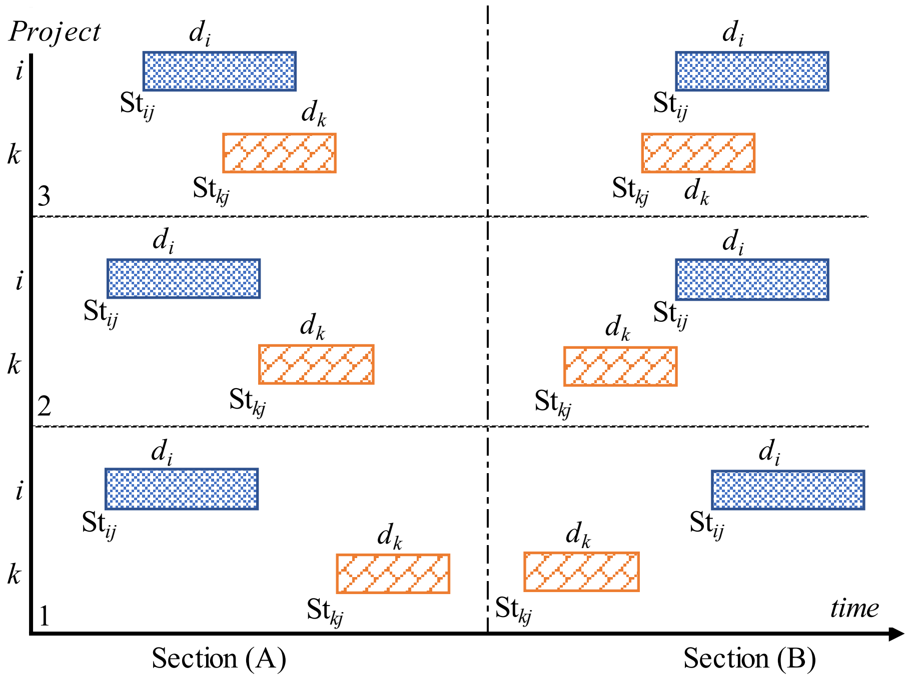


Figure 4.7: Section (A): Project *k* follows project *i*; Section (B): Project *i* follows *k*

$$\begin{cases} z_{ikj} = 1 & \text{if project } k \text{ follow project } i \\ z_{kij} = 1 & \text{if project } i \text{ follow project } k \end{cases}$$

However, since the two variables represent mutually exclusive conditions, $z_{ikj} + z_{kij} = 1$, in the form illustrated, sets of constraints (4.4.11 to 4.4.12) are expressed with one project pairing variable, which allows for higher efficiency in the model to a certain extent.

Given the above elaboration, desired conditions of allocating any pair of projects assigned to a same crew are enforced with the sets of constraints (4.4.11 to 4.4.12), which are the two embedded inequalities that are linear and guarantee the crew precedence relationships in contrast to the literature, e.g.,(Liu and Wang 2012) utilized if-then constraints making the optimization model nonlinear and challenging to solve.

Constraints on project tardiness and cancellation: Constraints (4.4.13) and (4.4.14) track the possible project delays and identify whether a delayed project is conceivably canceled. The underlying rationale of these restrictions is interpreted as follows according to the probable conditions depicted in Figure 4.8. As seen in this figure, both constraints (4.4.13 and 4.4.14) are satisfied as the corresponding variables are substituted with values for state (1).

$$\begin{cases} St_i + d_i - \bar{d}_i \le \tau_i + \varphi.(1 - v_i) \\ St_i + d_i \le \hat{d}_i + \varphi.v_i \end{cases} \xrightarrow{(1)} \begin{cases} St_i + d_i - \bar{d}_i \le \varphi \\ St_i + d_i \le \hat{d}_i \end{cases} \rightarrow \begin{cases} St_i + d_i \le \varphi + \bar{d}_i \\ St_i + d_i \le \hat{d}_i \end{cases}$$

For the second condition, the following is applied.

$$\begin{cases} St_i + d_i - \bar{d}_i \le \tau_i + \varphi.(1 - v_i) \\ St_i + d_i \le \hat{d}_i + \varphi.v_i \end{cases} \xrightarrow{(2)} \begin{cases} St_i + d_i - \bar{d}_i \le \tau_i + \varphi \\ St_i + d_i \le \hat{d}_i \end{cases}$$

$$\rightarrow \begin{cases} St_i + d_i - \bar{d}_i \le \bar{d}_i - d_i - St_i + \varphi \\ St_i + d_i \le \hat{d}_i \end{cases} \rightarrow \begin{cases} St_i + d_i \le \bar{d}_i + \varphi \\ St_i + d_i \le \hat{d}_i \end{cases}$$

Therefore, both conditions (1 and 2) satisfy the constraints (4.4.13) and (4.4.14). Finally, the third condition is proven to satisfy both constraints (4.4.13 and 4.4.14) as follows.

$$\begin{cases} St_i + d_i - \bar{d}_i \le \tau_i + \varphi.(1 - v_i) \\ St_i + d_i \le \hat{d}_i + \varphi.v_i \end{cases} \xrightarrow{(3)} \begin{cases} St_i + d_i - \bar{d}_i \le \tau_i \\ St_i + d_i \le \hat{d}_i + \varphi \end{cases} \rightarrow \begin{cases} St_i + d_i \le \tau_i + \bar{d}_i \\ St_i + d_i \le \hat{d}_i + \varphi \end{cases}$$

I replaced the constraint (4.4.14) with the below modified version using Eq. (4.4.4) for better efficiency in model spreadsheet layout and calculations.

$$St_i + d_i \le \hat{d}_i + \varphi.v_i \rightarrow St_i + d_i - \bar{d}_i \le \hat{\tau}_i + \varphi.v_i \qquad (4.4.14)$$

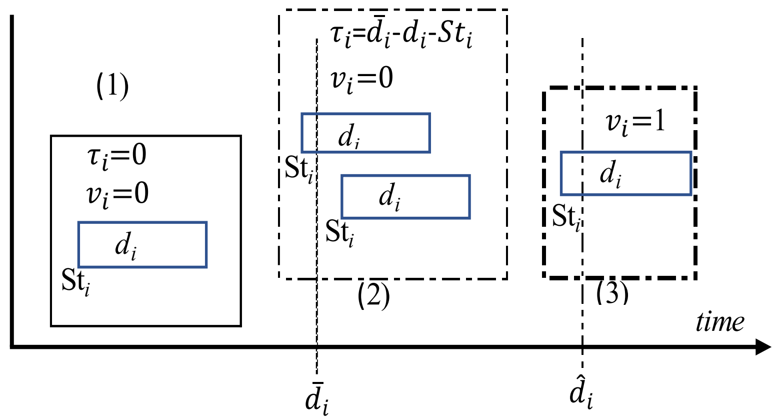


Figure 4.8: possible project delay conditions

This modification leads to a same left hand side expression for both constraints (4.4.13 -4.4.14), and lesser effort in setting up the model spreadsheet and avoiding extra calculations.

As illustrated above, the developed linear constraints (i.e., sets of (4.4.11- 4.4.14) perfectly capture conditional statements in the problem leading to avoiding IF conditions in the model. Additionally, the constraints validate adequate scenarios; invalid scenarios are excluded from the solution space by imposing the constraints. That is a significant contribution to this study; as the number of projects and crews increases, the number of conditions snowballs so that even programming them takes lots of effort and is prone to many errors.

Despite substantial time and effort dedicated to solving case studies with the developed model and multiple interactions with the support team from Frontline Solver, the optimization engine could not deliver a feasible solution for any of the cases. The reason for the unsuccessful experience lies in the incapability of the optimization engine to interact with VBA. Building the model in Excel spreadsheets requires forming several matrices as intermediate calculations of the optimization process, which requires coding with VBA for efficient and accurate calculations. However, due to the optimization engine's lack of ability to connect to VBA, feasible solutions could not be attained.

Nonetheless, an alternative version of the model is devised so that can be evaluated with a superior optimization engine.

When faced with multiple decisions in resource constraints modeling, it is customary to represent each decision with a separate variable. However, this approach becomes impractical when dealing with larger batches of projects and crews, as finding an optimal or even satisfactory solution can become time-consuming with existing optimization engines. The model is improved by combining two decisions into one variable to address this issue, resulting in a more efficient approach. The enhanced method modifies certain constraints and transforms the model into a binary ILP model. As a result, the improved model can be utilized for large-scale problems with better optimization engines.

Modifications are as follows. Constraints (4.4.8) and (4.4.9) have been modified, while constraint (4.4.10) is no longer required. In addition, since construction projects only consider whole units of time in estimating project duration and all the variables are binary, constraint (4.4.16) - which implies non-negativity - is intrinsic. These adjustments convert the model to a binary (0-1) ILP model instead of MILP, which the upgraded model's simplicity allows for more efficient solving techniques, such as branch and bound with binary partitioning or specialized binary optimization algorithms like the branch and cut method (Papadimitriou and Steiglitz 1998).

Modified: $x_{ijt} = \begin{cases} 1, & if\ project\ i\ allocated\ to\ crew\ j\ begins\ at\ the\ start\ of\ time\ t \\ 0, & Otherwise \end{cases}$

- Constraints (4.4.8 and 4.4.9) adjusted as:

$$\sum_{i \in S^R} x_{ijt} - c_{jt} = 0 \qquad \forall j \in S^C, t \in T \qquad \text{New}(4.4.8)$$

$$\sum_{\bar{t}=t}^{t+d_i-1} x_{ij\bar{t}} \geq d_i . x_{ijt} \qquad \forall i \in S^R, \forall j \in S^C \qquad \text{New(4.4.9)}$$

The new constraint (4.4.9) bands the work interruptions (e.g., preemption). If $x_{ijt} = 1$, constraint yields to $\sum_{\bar{t}=t}^{t+d_i-1} x_{ij\bar{t}} - d_i \geq 0$, that means at any interval that project i starts, it has to be continued until it is completed. If $x_{ijt} = 0$, constraint yields to $\sum_{\bar{t}=t}^{t+d_i-1} x_{ij\bar{t}} \geq 0$, which is always true. Suppose project three with two days duration, assigned to crew one at the start of day 2 (i.e., $x_{312} = 1$). This constraint implies that $x_{312} + x_{313} - 2 \geq 0$, meaning that the project's has to continue over intervals two and three.

4.4.6. Case Study

The following case study demonstrates the application of the model for projects with delay penalties and cancellation charges. As seen in Table 4-9, projects' input data required for the model includes projects' duration, due date, deadline, rate of delay penalty per day, and potential cancellation charges. The case study represents a two-week planning horizon, working five days a week. Also, the crews' availability within the biweekly planning horizon is shown in

Table 4-10.

Table 4-9: Projects Input Data

Project Id.	1	2	3	4	5	6	7	8	9	10
Duration (Day)	4	5	2	3	4	2	2	3	2	2
Due Date (Day)	7	8	9	10	10	10	10	9	8	8
Deadline (Day)	9	10	11	12	12	13	13	12	10	10
Delay Penalty/Day ($K)	1.00	1.50	1.00	1.00	1.10	0.90	0.90	1.00	0.90	0.90
Cancellation Charge ($K)	12.5	18.8	11.3	12.5	15.0	12.5	12.5	13.8	12.5	12.5

Table 4-10: Crews Availability Within Two-Week Planning Horizon

Crew ID	Crew1	Crew2	Crew3
Availability (Day)	9	10	10

In this small case study, Table 4-11 presents the detailed plan, and Figure 4.9 provides the crew-by-crew project allocation and schedule resulting from the optimization model. The optimal plan was achieved using the Analytic Solver optimization engine in a mere 58.06 seconds by implementing the prototype Excel program. This outcome demonstrates the efficiency and effectiveness of the optimization model utilized.

Table 4-11: Resultant Plan Information_10 Projects Case Study

Project Id.	1	2	3	4	5	6	7	8	9	10
Start_Date	0	2	0	7	4	4	8	6	2	0
Assigned_Crew	1	2	3	2	3	1	3	1	3	2
Delay_Charges	0	0	0	0	0	0	0	0	0	0
Cancelation_Charge	0	0	0	0	0	0	0	0	0	0

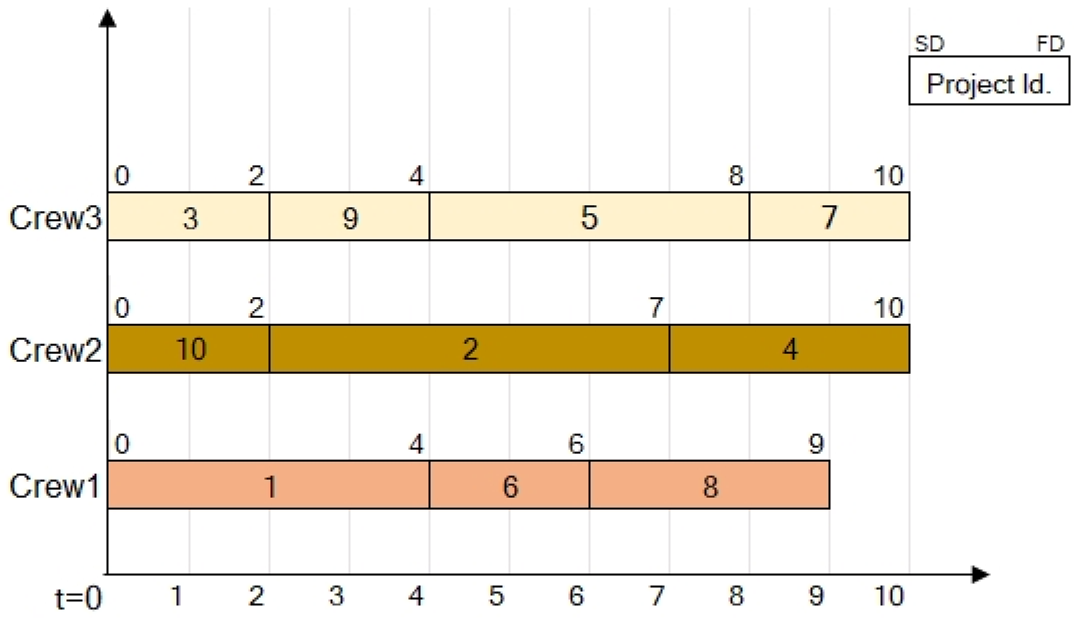


Figure 4.9: Crew-by-Crew Project Plan_10 Projects Case Study

In the above figure, the SD abbreviation stands for start date, and FD stands for finish date.

As depicted in Figure 4.9 and Table 4-11, each crew has been allocated to only one project at a time, enforced by constraints 4-4-7; each crew utilized its availability, resulting from constraints 4-4-8. There is no preemption in the schedule enforced by constraints 4-4-9 and 4-4-10. The sequence of projects assigned to each crew has been determined with no overlap, as enforced by crew-induced precedence relationship constraints (i.e., constraints 44-11 and 4-4-12). All projects have been planned to be completed before their due dates with no potential delay or cancellation, enforced by constraints 4-4-13 and 4-4-14. Overall, the resultant plan efficiently schedules projects by the allocated crew while maintaining the highest number of planned projects and meeting the projects' due dates and crews ' availability. Additionally, the maximum number of projects has been efficiently planned with no potential delay penalty or cancellation charges, validating the objective function.

The industry subject experts validated the model, and this small case study was performed to cross-validate the model formulation. Nonetheless, the Analytic Solver's optimization engine does not allow scaling up to the cases with more projects. The testing of the formulations based on a larger, more practical dataset is reserved for the near future when the Analytic Solver is upgraded.

Chapter 5: Agile-Based Framework

The previous chapters of this work have delved into the problem of resource-constrained multi-project scheduling and have applied scientific knowledge in mathematical programming to address the issue at hand. This chapter, in particular, aims to provide a complete framework for the planning and execution of multi-projects, with the necessary forms and detailed explanations. As illustrated in Figure 5.1, the developed framework is presented in the form of a flow chart.

It is worth noting that while the computer program was prototyped initially for a specific industry partner company, it is highly adaptable to similar business industries with some modifications and minor adjustments. Attachment B includes some program forms and the VBA code that can be utilized for this purpose. However, it is essential to emphasize that the framework and its process have been generalized to cater to all projects of this nature.

Following, the steps of the developed framework and associated forms will be presented in detail.

Step 1) The commencement of the process involves the registration of project data, encompassing the project index, site location, date received, priority, deadline, and other pertinent information. The project data can be entered manually, as displayed in Figure 5.2 or imported in bulk from an Excel file as displayed in Figure 5.3. It is important to note that certain modifications have been made to the presentation of forms herein in order to comply with confidentiality requirements.

Upon receipt, all projects are entered into the project backlog, which corresponds to the product backlog utilized in the Scrum methodology. The ever-changing project backlog is a dynamic collection of all the upcoming projects awaiting construction.

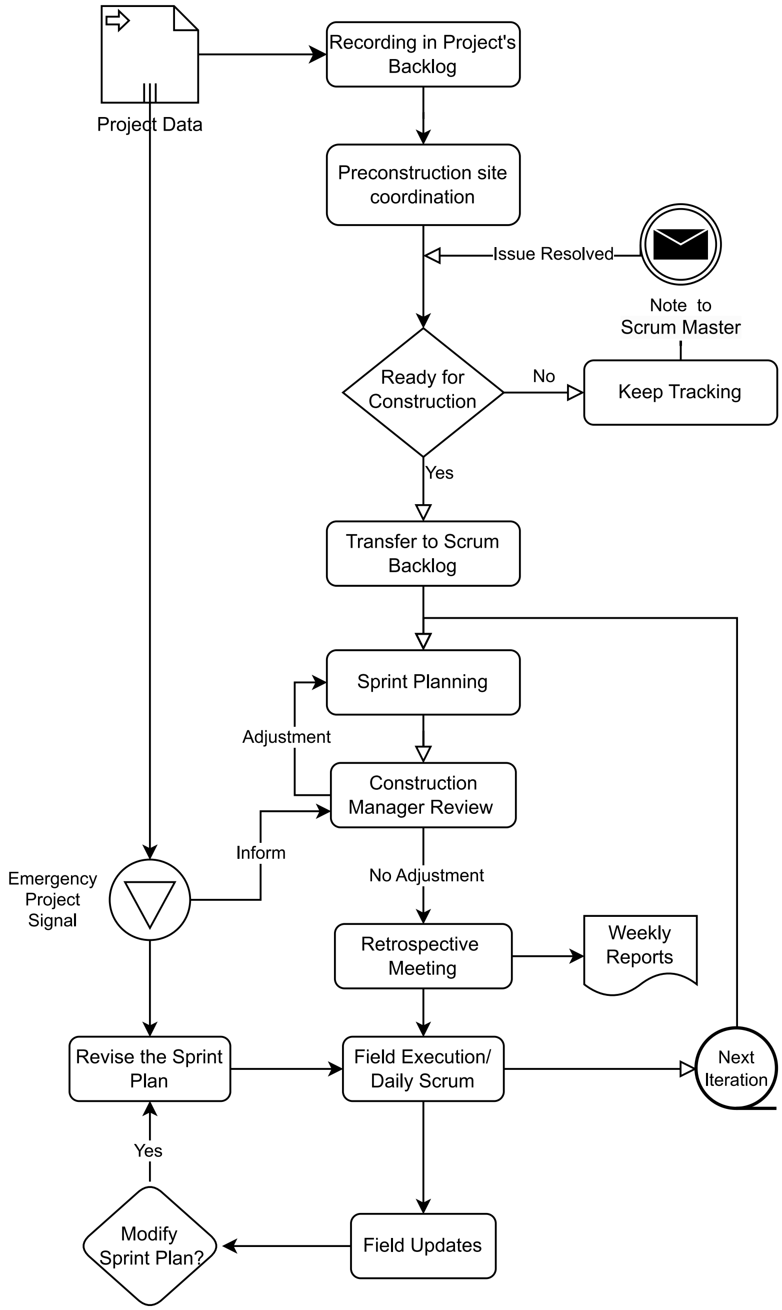


Figure 5.1: Agile Planning Framework Flowchart

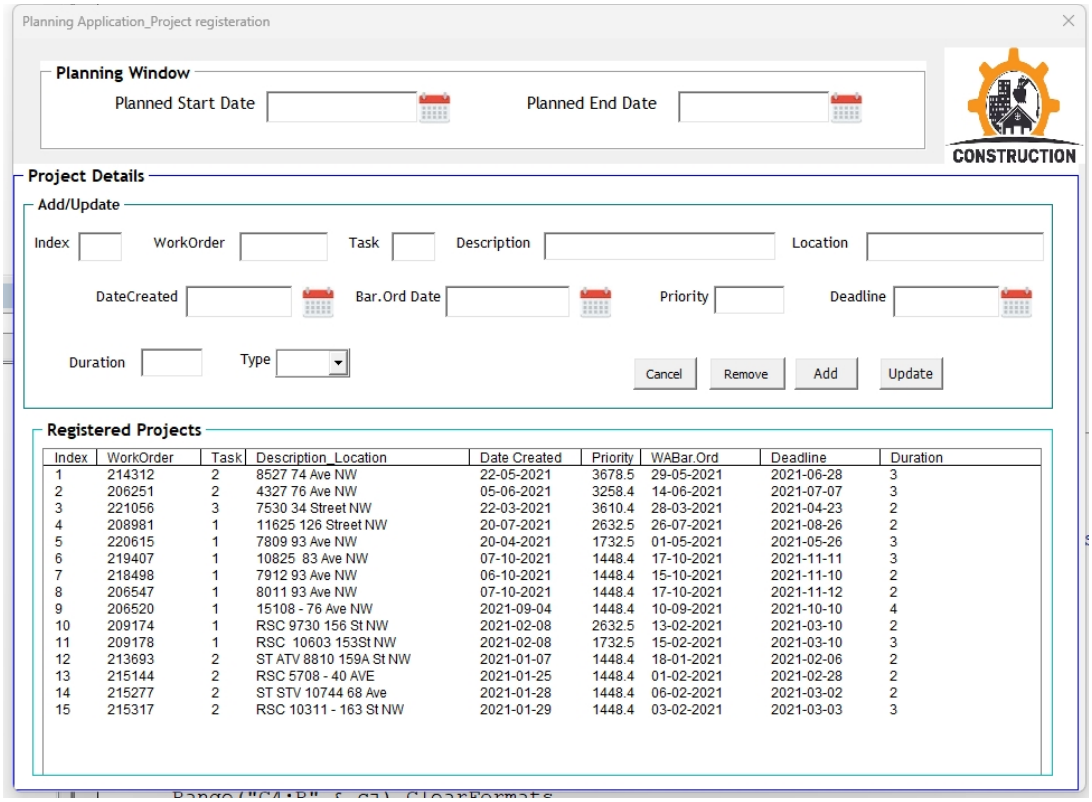


Figure 5.2: Project Registration Form

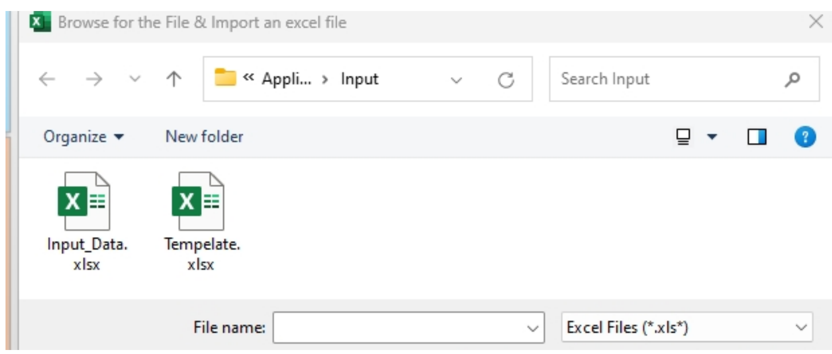


Figure 5.3: Import from an Excel file

Step 2) Preconstruction site coordination

Anecdotal evidence suggests that at least ten percent (10%) of the resources available to the infrastructure manager are wasted due to workers arriving at the project site before completing prerequisite work. This is a crucial step aimed at preparing the construction site before mobilizing the construction crews. The inputs required for this step are the construction drawings, site location, and work order. It involves identifying and locating the buried utilities at the site, ordering barricades, and obtaining necessary permits based on the site's specific requirements or as needed. The output of this step is a well-prepared site ready for the construction crew's mobilization. Coordinating this step is carried out by the planner and supervisors, with the construction manager ensuring the step is executed correctly. If any complications arise during this stage, the planner is responsible for informing the scrum master and ensuring that the issue is resolved. For a more detailed understanding of the roles and duties involved in this framework, please refer to chapter 3 and subsequent subsection.

Step 3) Transfer to Scrum Backlog

At this stage, all the projects deemed ready for construction; they are subsequently transferred to the Scrum backlog. This backlog consists of all the projects ready to be constructed, and it is a segment of the project backlog that has been assigned to the current Scrum.

Step 4) Sprint Planning

It's time to take the next step and plan the upcoming sprint. This planning process considers the projects in the Scrum backlog and the crew's availability, as depicted in Figure 21. As illustrated in Chapter 3, each sprint is a timeboxed iteration with a fixed duration. The ideal length of the sprint varies based on the project requirements and the team's capacity. A well-designed sprint should allow the team to produce an increment of work that could potentially be released while maintaining a sense of urgency and flexibility. Therefore, the sprint duration should be tailored to the team's ability to deliver value. Based on these factors, the agile framework proposed in this research has established a standard period of four weeks for each Scrum and one week for each sprint when planning projects.

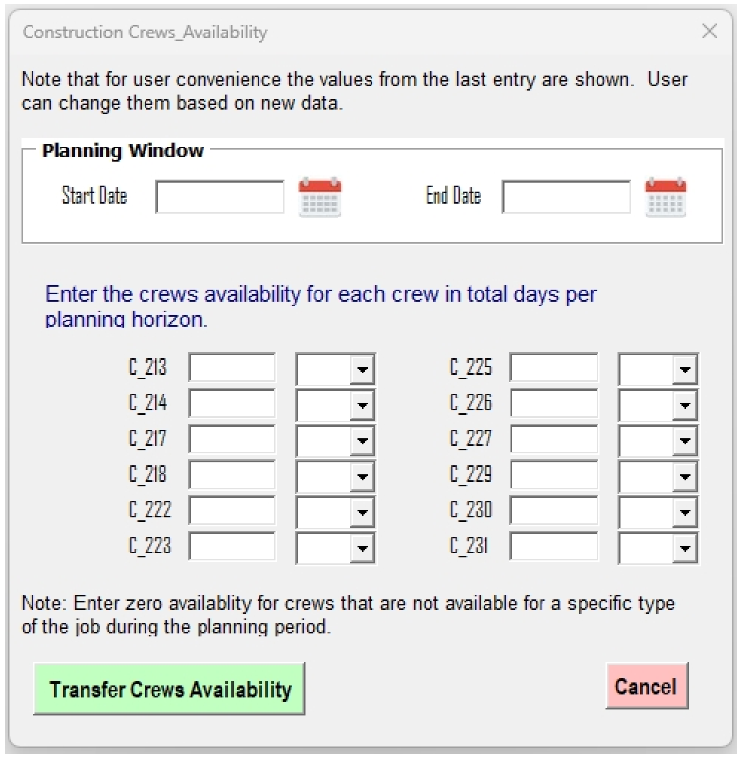


Figure 5.4: Crew Availability Determination for Sprint Planning

By the end of each week, specifically at the beginning of the last day of each week on Fridays, the planner prepares the sprint plan for the upcoming sprint by utilizing a coded program and selecting the suitable model, as demonstrated in chapter four. The model is then run, and the plan is ready in a matter of minutes. Once the plan is prepared, it is sent to the construction managers for review. If any adjustments are needed, the plan is modified accordingly. Otherwise, the plan is ready to be delivered to the supervisors during the retrospective meeting.

Step 5) Retrospective (or sprint review) meeting

This meeting is held at the end of each sprint; and includes a demonstration of work completed in that sprint and a retrospective review of the work undertaken to enable continuous improvement for subsequent iterations.

In the meeting, crews review and reflect on their last sprint's progress and outcomes. They discuss what went well and what could have gone better and identified areas for improvement in the subsequent sprints. It should be noted that retrospectives are not intended to blame sessions or endless discussions on why something did not go as expected. That is why retrospectives are kept restricted in timing (for instance, to an hour), avoiding the potential to become extended "think tanks," where crews spend ineffective amounts of time contemplating unrelated matters. Ideally, retrospectives are brainstorming sessions where issues (and resolutions) get identified, prioritized, assigned ownership, and actioned.

The progress of the Scrum backlog is communicated through monitoring and measurement tools, such as Kanban charts, burn-down charts, or some combination of a Gantt chart and a milestone chart is used (Goodpasture 2016).

Step 6) Field Execution/Daily Scrum

During the sprint, each crew gets together at the start of each day in a short stand-up meeting called the Daily Scrum. The purpose of the Daily Scrum is to summarize what was done yesterday, what will be done today, and what problems need resolution to achieve the sprint targets. In other words, a short update session is held each morning, enabling the team to review the required work and quickly address any hurdles. Then the crew start the work according to the sprint plan.

Step 7) Field updates/plan modification: the proper execution of sprint plans is a critical component in achieving desired objectives within a predetermined timeframe. In order to ensure adherence to the plan, dispatched crews provide daily progress updates to the planner. It is important to note that any project requiring a hold or cancellation must be communicated to the planner, who will adjust the plan to keep it updated.

Step8) revising the sprint plan: In situations where emergency projects arise, the planner will thoroughly review and revise the sprint plan and subsequently communicate any necessary changes to the construction manager. Following that, the revised plan will be distributed to supervisors and the construction manager as the new baseline plan.

It is worth mentioning that this process is not close ended; it iterates back to the next sprint. The practice of splitting planning and controlling missions into a sequence of iterations that must be achieved within a finite period ensures that the field supervisors consistently demonstrate progress. This, in turn, updates all stakeholders with the same determined parameters, thus ensuring that everyone is on the same page. Time-boxing is an essential tool that helps to achieve this goal and maintain the desired level of progress.

5.1 Agile Management Team

As elaborated in Chapter 3, essential personnel to the Scrum lineup are the product owner, Scrum master, and development team. These positions typically do not formally apply to most groups outside of the domain of software development. In this research, the functions of similar roles are taken from the existing construction management team in the industry partner company. For example, construction managers and planners versed in leadership and project management could be trained to serve as Scrum masters. Regarding the product owner, project managers, safety and quality officers in the company can be appointed to play this role as they are responsible for ensuring the timely delivery of projects to customers to project specifications and service requirements mandated by the City's bylaws and authorities.

5.2 Case Studies

In this section, two case studies are presented to further elaborate the agile based framework in practice. Both cases have been computed on Core (TM) i7-11th Gen Intel(R) processor with 16 GB RAM, and Frontline Analytic Solver for optimization models has been utilized, which its solutions are based on branch and bound algorithm.

Case_01: this case study was conducted for the planning period started on 01-April-2022 to 30-April-2022, it comprises of 52 Standard projects and 61 Prioritized projects at the beginning of planning. Attachment A lists all the projects records in this Scrum backlog (Scrum_2022_04). Table 5-1 highlights the changes to this backlog during periods of four sprints in April 2022.

Table 5-1: Records of Projects in Scrum_2022_04

Date	**Number Projects In Scrum Backlog**					
	Standard	Prioritized	Emergency	Added	Cancelled	Total
2022-04-01	52	61	1	0	1	113
2022-04-08	34	43	1	8	0	86
2022-04-15	30	23	2	5	0	60
2022-04-22	15	13	0	10	0	38
Total Processed in the Scrum Period						139
Transferred to the next Scrum						12

It is to be noted that the total number of processed projects in each scrum is calculated as follows.

Total Processed in the Scrum Period = Initial number of projects in the backlog + Newly added projects + Emergency projects - Cancelled projects

Additionally, the emergency projects are fed into the prioritized projects with the highest priority relative to the projects in the backlog at the time of arrival with deadline of 3 days after their arrival according to the company policy as the timeframe to address the emergency projects, their duration various between one to three days. Replanning occurs at the time they arrive and allocated crew from the optimization model is dispatched to the site. Further to be noted that the project slack time at any sprint is calculated by subtracting the sprint date from its deadline. Further details can be found in Chapter four.

Four sprints have been planned for the above-mentioned case study in the month of April 2022 as follows. Table 5-2 denotes the crews availability in number of days for each sprint categorized as the crews allocated to the Standard and Prioritized projects.

Table 5-2: Crew Availability In Each Sprint Planned for the Scrum_2022_04

Crew Availability (days) for Standard Projects						
Crew ID	C_213	C_214	C_217	C_218	C_222	C_223
Sprint_04_01	5	5	6	5	5	5
Sprint_04_08	5	5	5	5	5	4
Sprint_04_15	6	5	5	5	4	5
Sprint_04_22	5	6	4	4	4	4
Crew Availability (days) for Prioritized Projects						
Crew ID	C_225	C_226	C_227	C_229	C_230	C_231
Sprint_04_01	5	5	5	5	5	5
Sprint_04_08	5	5	5	5	5	6
Sprint_04_15	5	5	5	5	5	5
Sprint_04_22	5	5	5	6	5	5

Table 5-3 presents the outcomes of planning the Scrum backlog in the case mentioned above study. t is noteworthy that each optimization run was executed within a minute, demonstrating the efficiency of the process. However, it should be noted that the preparation time required for developing each plan - which entails feeding data to the model - takes less than an hour when utilizing the prototyped program.

Table 5-3: Sprint Plan Results for Case Study_01

#Sprint	Standard Projects				Prioritized Projects			
	Planned	PPI	CSI	CUP	Planned	PPI	CSI	CUP
Sprint_01	18	1.15	100%	100%	18	1.25	100%	100%
Sprint_02	14	1.02	100%	100%	23	1.42	100%	100%
Sprint_03	15	1.02	100%	100%	13	1.07	100%	100%
Sprint_04	13	1	100%	100%	13	1.04	100%	100%

Figure 5.5 displays the allocated crews to the projects in Gantt chart view for *standard* projects and Figure 5.6 depicts the plan for *prioritized* projects for sprint_01 in case study_01 as an example.

Index	WorkOrder	Description_Location	Assigned Crew	Start	Finish	4-Apr	5-Apr	6-Apr	7-Apr	8-Apr	9-Apr
1	204063	RSC 13540 126 STREET NW	C_218	4-Apr	5-Apr	C_218	C_218				
6	197817	RSC 7401A 151 STREET NW	C_223	4-Apr	5-Apr	C_223	C_223				
10	199434	RSC 11444 97 STREET	C_218	6-Apr	6-Apr			C_218			
11	199006	RSC 12119 126 ST	C_223	6-Apr	6-Apr			C_223			
12	198970	RSC 8143 79 AVENUE NW	C_214	4-Apr	4-Apr	C_214					
17	201511	9644 155 st	C_217	4-Apr	5-Apr	C_217	C_217				
19	201530	RSC 7611 111 STREET NW	C_217	6-Apr	7-Apr			C_217	C_217		
21	201610	RSC 8706 88 AVE NW	C_223	7-Apr	8-Apr				C_223	C_223	
25	202057	RSC 9520 150 ST NW	C_217	8-Apr	9-Apr					C_217	C_217
26	202531	RSC 7916 132 AVE NW	C_222	4-Apr	5-Apr	C_222	C_222				
32	203341	RSC 9203 111 AVE	C_214	5-Apr	6-Apr		C_214	C_214			
34	203689	RSC 14712 62 STREET	C_214	7-Apr	8-Apr				C_214	C_214	
35	203988	RSC 8411 175 STREET NW	C_218	7-Apr	8-Apr				C_218	C_218	
37	203686	RSC 9015 156 STREET NW	C_213	4-Apr	5-Apr	C_213	C_213				
41	204210	RSC 12908 135 AVE	C_213	6-Apr	7-Apr			C_213	C_213		
42	204445	RSC 9675 84 AVE NW	C_213	8-Apr	8-Apr					C_213	
44	204877	RSC 9850 84 AVE NW	C_222	6-Apr	6-Apr			C_222			
48	205017	RSC 4234 112 AVE	C_222	7-Apr	8-Apr				C_222	C_222	

Figure 5.5: Gannt chart view for standard projects in sprint_01 Case Study_01

Index	WorkOrder	Description_Location	Deadline	Assigned Crew	Start	Finish	4-Apr	5-Apr	6-Apr	7-Apr	8-Apr
1	202530	SUB 42ST 111AVE	2022-04-28	C_229	4-Apr	5-Apr	C_229	C_229			
2	203581	SUB CB 93 ST 150 AVE	2022-04-29	C_231	4-Apr	4-Apr	C_231				
3	204743	REPLACE 11408 59 AVE	2022-04-29	C_226	4-Apr	5-Apr	C_226	C_226			
4	204385	Emrg DIG 8403 71 AVE	2022-04-08	C_227	4-Apr	5-Apr	C_227	C_227			
5	205428	Partial Replace 14116 94 ST	2022-05-02	C_227	6-Apr	7-Apr			C_227	C_227	
6	202084	CB BAR SUB 104 St - 82 Ave	2022-04-28	C_225	4-Apr	4-Apr	C_225				
7	204402	CI 58 AVE & 103 A ST	2022-04-27	C_226	6-Apr	7-Apr			C_226	C_226	
8	217160	SUB REPAIR 13308 DELWOOD RD	2022-04-30	C_230	4-Apr	5-Apr	C_230	C_230			
9	204634	SPOT REPAIR 9816 156 ST	2022-04-29	C_229	6-Apr	6-Apr			C_229		
10	206134	RSC 16116 110B AVE	2022-04-28	C_229	7-Apr	8-Apr				C_229	C_229
11	206265	RSC 8839 - 161 STREET NW	2022-05-02	C_225	5-Apr	6-Apr		C_225	C_225		
12	206266	RSC 4708 - 144 STREET NW	2022-05-03	C_230	6-Apr	7-Apr			C_230	C_230	
13	206292	RSP 165 GALLAND CRESCENT	2022-05-06	C_231	5-Apr	6-Apr		C_231	C_231		
14	206460	RSC 5307 - 109A AVENUE NW	2022-05-11	C_231	7-Apr	8-Apr				C_231	C_231
15	206548	RSC 3828 - 106 STREET NW	2022-04-27	C_227	8-Apr	8-Apr					C_227
16	206880	RSC 3912 116 ST NW	2022-04-30	C_226	8-Apr	8-Apr					C_226
17	206744	RSC 9220 79 STREET	2022-04-30	C_225	7-Apr	8-Apr				C_225	C_225
18	207606	RSC 8712 163 STREET NW	2022-04-29	C_230	8-Apr	8-Apr					C_230

Figure 5.6: Gannt chart view for prioritized projects in sprint_01 Case Study_01

Case study_02: Another study comprising 85 projects in a scrum backlog was conducted, as the project records depicted in Table 5.4, with crew availability displayed in Table 5.5. It is worth noting that the priority scale, in this case, differs from the previous investigation, as it was conducted to examine the model with a varied priority scale. Additionally, emergency projects with a one-day duration and a response time of 72 hours (3 days) were registered in adherence to the department's policy.

Table 5-4: Scrum backlog _case of 85 projects

Site ID	Work Order	Date Rec.	Duration	Deadline	PIj
3	210225.0	01-03-2022	1	15-03-2022	0.2
5	207823.1	01-03-2022	1	16-03-2022	0.1
6	210790.0	01-03-2022	1	16-03-2022	0.1
4	206683.1	01-03-2022	3	17-03-2022	0.4
3	210808.0	02-03-2022	2	17-03-2022	0.3
7	207843.1	03-03-2022	1	17-03-2022	0.2
3	206876.3	03-03-2022	3	17-03-2022	0.2
7	206317.5	03-03-2022	1	17-03-2022	0.1
4	210215.0	03-03-2022	3	17-03-2022	0.1
3	210682.0	03-03-2022	2	17-03-2022	0.1

Site ID	Work Order	Date Rec.	Duration	Deadline	PIj
4	210076.2	04-03-2022	3	18-03-2022	0.4
6	210754.0	04-03-2022	2	18-03-2022	0.3
4	210844.0	03-03-2022	1	18-03-2022	0.2
8	206701.2	01-03-2022	1	18-03-2022	0.1
6	206905.1	05-03-2022	1	19-03-2022	0.4
9	206848.1	04-03-2022	2	19-03-2022	0.4
9	210203.0	03-03-2022	1	19-03-2022	0.4
8	206741.2	04-03-2022	2	19-03-2022	0.3
10	210224.0	02-03-2022	2	19-03-2022	0.3
7	210196.0	05-03-2022	2	19-03-2022	0.3
4	210628.0	05-03-2022	3	19-03-2022	0.3
1	207577.1	05-03-2022	3	19-03-2022	0.2
2	210412.0	02-03-2022	1	19-03-2022	0.2
5	210880.0	01-03-2022	3	19-03-2022	0.2
9	206226.6	04-03-2022	3	20-03-2022	0.4
7	202594.0	06-03-2022	3	20-03-2022	0.4
3	210358.0	06-03-2022	2	20-03-2022	0.4
6	210646.0	02-03-2022	3	20-03-2022	0.4
5	206801.3	04-03-2022	2	20-03-2022	0.3
2	210214.0	04-03-2022	2	20-03-2022	0.3
9	2062765.3	02-03-2022	3	20-03-2022	0.2
9	206768.5	01-03-2022	1	20-03-2022	0.2
1	219908.0	01-03-2022	1	20-03-2022	0.1
8	210504.0	01-03-2022	3	20-03-2022	0.1
9	210304.0	06-03-2022	1	20-03-2022	0.1
1	210430.0	03-03-2022	1	20-03-2022	0.1
10	208512.3	03-03-2022	2	21-03-2022	0.4
7	206459.2	01-03-2022	3	21-03-2022	0.4
10	210484.0	07-03-2022	2	21-03-2022	0.4
2	206800.9	01-03-2022	3	21-03-2022	0.3
10	206723.2	02-03-2022	2	21-03-2022	0.3
2	219526.0	07-03-2022	3	21-03-2022	0.3
5	210286.0	05-03-2022	1	21-03-2022	0.3
7	210466.0	06-03-2022	2	21-03-2022	0.3
6	210556.0	07-03-2022	2	21-03-2022	0.3
4	206701.8	05-03-2022	2	21-03-2022	0.2
3	210448.0	07-03-2022	2	21-03-2022	0.2

Site ID	Work Order	Date Rec.	Duration	Deadline	PIj
1	206752.5	01-03-2022	2	21-03-2022	0.1
1	210502.0	07-03-2022	1	21-03-2022	0.1
8	210664.0	05-03-2022	3	21-03-2022	0.1
3	210718.0	07-03-2022	3	21-03-2022	0.1
9	210520.0	07-03-2022	1	22-03-2022	0.4
7	210700.0	02-03-2022	3	22-03-2022	0.4
4	210934.0	05-03-2022	3	22-03-2022	0.3
3	208061.1	02-03-2022	3	22-03-2022	0.2
5	210610.0	03-03-2022	2	22-03-2022	0.2
4	210340.0	05-03-2022	2	22-03-2022	0.1
7	207732.1	07-03-2022	2	23-03-2022	0.4
8	210598.0	03-03-2022	1	23-03-2022	0.4
3	206706.8	06-03-2022	2	23-03-2022	0.3
3	216990.0	06-03-2022	3	23-03-2022	0.3
7	206538.7	07-03-2022	1	23-03-2022	0.2
9	210916.0	05-03-2022	2	23-03-2022	0.2
6	206709.3	06-03-2022	3	23-03-2022	0.1
8	206724.1	04-03-2022	1	23-03-2022	0.1
4	210574.0	06-03-2022	1	23-03-2022	0.1
9	210736.0	07-03-2022	3	23-03-2022	0.1
8	210826.0	05-03-2022	2	24-03-2022	0.4
6	210862.0	04-03-2022	2	24-03-2022	0.4
10	208395.0	04-03-2022	1	24-03-2022	0.2
9	210250.0	04-03-2022	2	24-03-2022	0.2
7	210538.0	04-03-2022	1	24-03-2022	0.2
6	205954.1	07-03-2022	3	24-03-2022	0.1
6	210206.0	05-03-2022	2	24-03-2022	0.1
7	210592.0	06-03-2022	3	25-03-2022	0.3
8	210898.0	06-03-2022	3	25-03-2022	0.3
5	210772.0	08-03-2022	1	25-03-2022	0.2
4	210268.0	06-03-2022	3	26-03-2022	0.3
7	208412.1	08-03-2022	2	26-03-2022	0.1
2	210322.0	07-03-2022	3	26-03-2022	0.1
10	210477.0	07-03-2022	1	27-03-2022	0.4
1	210394.0	07-03-2022	3	27-03-2022	0.1
8	206723.8	08-03-2022	1	28-03-2022	0.4
10	210376.0	08-03-2022	2	28-03-2022	0.4

Site ID	Work Order	Date Rec.	Duration	Deadline	PIj
2	210232.0	08-03-2022	3	28-03-2022	0.1

Table 5-5: Crews availabilities recorded in four sprints

Crews	Cr1	Cr2	Cr3	Cr4	Cr5	Cr6	Cr7	Cr8
Availability_Sprint1	5	5	5	5	5	5	5	5
Availability_Sprint2	5	5	5	5	5	5	5	5
Availability_Sprint3	5	5	5	5	5	5	5	4
Availability_Sprint4	5	5	5	5	5	5	4	4

As outlined in Table 5-6, applying the method to the selected case study over four incremental iterations (i.e., four sprints) yielded highly promising results. Notably, the PPI consistently remained at or above one for each sprint, while the CUP and CSI metrics remained at their maximum levels of significance. Furthermore, all projects involved in the case study were successfully completed within their respective deadlines. These findings suggest that the method employed plays a significant role in achieving the desired outcomes and meeting project goals.

Table 5-6: Results of four sprint planning for the case study

Sprint Planning	Sprint1	Sprint2	Sprint3	Sprint4
Scrum Backlog	85	58	52	38
Scheduled	28	17	21	18
Remained in Backlog	57	41	31	20
Emergency Projects	1	0	1	1
Added Projects	0	11	6	9
Updated Scrum	58	52	38	30
PPI	1.43	1	1.26	1.16
CUP	1	1	1	1
CSI	1	1	1	1

Average Duration	2.05	2.35	2.33	2.45
Total Crew Availability	40 d	40 d	39 d	38 d

One potential obstacle in implementing the proposed framework pertains to procuring commercial optimization engine licenses. A heuristic algorithm was developed and coded in VBA to address this issue. This algorithm can generate feasible and reasonable solutions in the event that the optimization engine is unavailable. The subsequent section provides a step-by-step presentation of this algorithm.

5.3 Sprint Planning Algorithm

The developed algorithm receives the project data, including the site location, estimated time duration, remaining buffer time, which is the time available prior to the project's deadline, and project priority. Additionally, it requires updating each crew's availability information for the current sprint. A step-by-step explanation of the algorithm is given as follows:

Step1) calculate the remaining buffer time (*RBF*) for each project in the Scrum backlog as

$$RBF_j = deadline\ job_j - duration\ job_j \qquad (5.3.1)$$

Step 2) calculate the final priority (PIF) as the multiplication of priority index and *RBF* for each project as

$$PIF_j = PI_j * (1 - \frac{RBF_j}{\sum RBF_j}) \qquad (5.3.2)$$

Step 3) Sort the projects based on their final priority PIF in descending order.

Step 4) Initialize the t variable in the time dimension as 1.

Step5) Loop through the projects starting from the top of the list.

Step 6) Loop through crews and assign the project if the crew's availability is greater than or equal to the project duration and the crew's utilization is less than *t*.

Step 7) Record the project assigned to the crew and add the given project's duration to the respective crew utilization.

Step 8) Remove the project from the list and iterate back to Step 5

Step 9) Increment *t* by one and loop back to Step 5

Step 10) Increment *t* by one and loop back to Step 5

Step 11) If $t >$ sprint period (e.g., seven intervals in this study), then print out crew project allocation information, and then, exit.

5.4 Other Benefits

In addition to the significant benefits already demonstrated, the proposed framework for agile planning development offers even more advantages that are worth exploring. One of the most prominent features of this framework is its ability to limit the amount of work in progress (WIP), which has long been recognized as a costly aspect of inventory management in the manufacturing industry. The lean product development community has also acknowledged the significance of WIP, as demonstrated in the works of (Poppendieck and Poppendieck 2003) and (Reinertsen 2009). The proposed framework fully embraces this concept and prioritizes its implementation, leading to better customer service, significant social cost savings, and improved crews' work efficiency.

Another key benefit of the proposed framework is its ability to facilitate continuous improvement. Agile development is not a one-time, rigid process that follows a set formula. Instead, it encourages iterative development and ongoing refinement. One way to support this process is by establishing a dedicated forum for identifying and planning improvement actions, such as a retrospective meeting. During this meeting, the scrum team can discuss what worked well and what did not and then apply the lessons learned to subsequent sprints. This iterative approach allows for ongoing improvements and increased productivity over time.

Finally, the proposed agile framework provides tighter control over the planning and execution process. This control is achieved through daily scrum meetings, during which team members plan their work and update task status. Additionally, work completed is compiled and integrated daily from the first sprint onward, providing up-to-date information about team progress and enabling high levels of control over the entire process. This level of control ensures that the project stays on track and the team can quickly address any issues that arise, leading to improved efficiency and better outcomes.

Chapter 6: Addressing Planning Uncertainties

The project's execution phase may encounter various uncertain factors that could impact the outcome. The following processes are put in place to manage these uncertainties.

- Referring to section 1.6, uncertainties were reviewed and categorized.
- Chapter 2, section 2.8, briefly reviewed the most common and standard methods for addressing uncertainties.

After careful consideration based on the nature of the problem, reviewed literature, type of uncertainties, and discussions with experts in the industry partner company, three methods are recommended for addressing uncertainties in this problem. The following sections elaborate on these methods.

6.1 Buffer time

The first method is to incorporate buffer time into the project deadline, effectively protecting against the negative impacts of disruptions and variability. Buffers are used as protection mechanisms against uncertainty. They provide a cushion or shield against the negative impact of disruptions and variability. The primary function of buffers within a production system is reasonably well understood and, in concept, transfers reasonably well to the construction setting (Sarker et al. 2012). Several recent studies have shown how buffers function in construction settings (Thomas et al. 2004), including smoothing workflow (Horman et al. 2003), increasing labor productivity (Horman and Thomas 2005), and adding reliability(Park and Peña-Mora 2004).

Buffer time is scheduled before slack time and is utilized to proactively and reactively control potential disruptions in a multi-project scheduling system, like resource interruptions or changes in activities (Wang et al. 2019). In the context critical chain scheduling (CCS), three types of buffers have been defined by (Ma et al. 2014).

1. Project buffer: safety factors are typically included in estimates of activity durations to account for possible uncertainties. These safety factors are removed from the activities and aggregated at the end of the critical chain as a project buffer, which aims to prevent project delays.
2. Feeding buffer: in addition to the critical chain, paths that merge with the critical chain are also considered, and feeding buffers are added at the end of these paths. This allows delays on feeding paths to be absorbed without affecting the start time of critical chain activities.
3. Resource buffer: this buffer ensures that resources are available some time before they are needed by a critical chain activity, which again helps to prevent delays in critical chain activities due to resource availability issues. If the buffer source is formulated, the interruptions of one or more resources will not necessarily cause the project schedule to be interrupted. The setting of the resource buffer depends on the historical data. It is necessary to statistically analyze the distribution of available resources and make a relevant buffer resource according to the data.

For the current problem, the only applicable buffer type is the project buffer, the only viable buffer type, as there is no recognition of any critical chain. Additionally, it is highly unlikely that the entire crew will be unavailable without prior knowledge during the planning stage.

There are two well-known methods for calculating the size of buffers: the 50% rule and the Root Square Error Method (RSEM). In the 50% rule, the duration of the chain is calculated using safe estimates, and half of that duration is added as a buffer. This approach is known as the "cut and paste method" (Tukel et al. 2006). This can be considered an implementation of risk pooling, where buffers address uncertainty in the sum of several durations instead of buffering against uncertainty in each activity duration individually. By addressing uncertainty in the sum of multiple durations, this approach provides a more comprehensive solution than buffering against uncertainty in each activity duration individually.

The RSEM, the other hand, requires two estimates: a safe estimate and an average value. The difference between these estimates is assumed to equal two standard deviations of the activity duration. Taking independence between activities, it is straightforward to calculate the standard deviation of the sum of activity times in the chain. Twice this standard deviation is then used as the buffer size. Both methods offer reliable solutions, and project managers can select the most suitable approach for their projects.

Upon consultation with subject matter experts within the industry partner company, the 50% rule is already implemented in the project's deadline settings per the company's contracting policy. During the project duration estimation phase, this is achieved by establishing agreed-upon project deadlines with clients and considering preconstruction requirements, such as permit requirements, road closures, and weather conditions. The factors mentioned are taken into account to ensure a safe estimate, and subsequently, the 50% rule is applied to determine the project deadlines.

6.2 Agile response method

In order to tackle the remaining uncertainties associated with the problem at hand, I suggested a second method which involves implementing a framework based on agility. The core idea behind this approach is to leverage an agile project planning methodology that can help crews adapt to project uncertainty. This is achieved by breaking down the planning process into smaller increments, known as sprints, which makes it more manageable and allows for just-in-time responses to uncertainties if they arise.

The devised agile planning framework can be highly beneficial in enabling crews to respond to unexpected challenges and adjust their approach as needed. It is particularly effective when dealing with project uncertainty as it allows teams to be more flexible and responsive to changing circumstances. Essentially, the framework catches and responds to uncertainties on the fly, ensuring that the project remains on track.

The proposed agile project planning framework encourages a shift from traditional planning to planning around uncertainties and adapting to change. This involves accepting that uncertainties are inherent in any project and developing a plan that can respond to them in real-time. By doing so, teams can be more proactive in their approach rather than being reactive to unexpected events. Overall, the agile planning framework is a powerful tool that can support crews in navigating uncertainty and delivering successful outcomes.

6.3 Expert- Judgment based method

A novel method has been developed for managing uncertainties related to the problem at hand. This method involves transforming expert opinions into measured scales, which can then be used to guide replanning in the event of uncertainties arising. In the context of this research, this method has been applied to the study of productivity in collaboration with the industry partner. The following subsections will provide a detailed description of this creative approach, which has the potential to significantly enhance the accuracy of utilizing expert judgments in dealing with uncertainties in the current problem.

6.3.1. Method explanation on productivity uncertainty

Accurately modeling productivity is crucial to ensuring that construction process models align with actual practice. However, gathering quantitative data can be complicated and expensive, making it challenging to develop productivity models. As a result, industry experts often provide information that is subject to their personal biases. This approach frequently results in oversimplified or insufficient productivity models, hindering decision-making.

To overcome this challenge, this research has developed a groundbreaking framework that reduces the subjectivity associated with labor productivity modeling. This framework identifies the interrelationships between factors that affect productivity, which individual subject experts may have overlooked. A Decision-Making Trial and Evaluation Laboratory (DEMATEL) is employed to identify the dependencies between factors. This information is then integrated with an Analytic Network Process (ANP)-based approach to determine the strength of each relationship.

The proposed method yields higher-quality inputs for productivity modeling-based decision-support systems than traditional input preparation approaches. Moreover, the results can support decision-making or provide productivity data for simulation, empirical, or dynamic models of construction systems. Ultimately, this framework supports the development of more accurate and reliable models, which can help to improve decision-making in the construction industry.

The effectiveness of the framework is demonstrated through an illustrative example. The results indicate that the proposed method can significantly reduce the subjectivity associated with labor productivity modeling, resulting in more accurate and reliable productivity models. This approach can improve decision-making in the construction industry and support the development of more efficient and effective construction systems. Accurately modeling labor productivity is critical to ensuring that construction process models align with practical industry standards. However, obtaining quantitative data for this purpose can be burdensome and expensive. As a result, productivity models are often developed using the insights provided by industry experts. However, the subjective nature of such information can lead to oversimplified or inadequate productivity models. To tackle this challenge, this research introduces a novel framework that reduces the subjectivity associated with labor productivity modeling. By identifying interrelationships between productivity factors that individual subject experts may have overlooked, this framework leverages a Decision-Making Trial and Evaluation Laboratory (DEMATEL) to establish dependencies between factors. This approach is then integrated with an Analytic Network Process (ANP)-based method to determine the strength of each relationship. The results of this method can be used to support decision-making or provide productivity data to simulation, empirical, or dynamic models of construction systems. Overall, the proposed method yields higher-quality inputs for productivity modeling-based decision-support systems than traditional input preparation approaches. The effectiveness of the framework is demonstrated through an illustrative example.

6.3.2. Background Review

Researchers have developed various modeling techniques to analyze or predict construction labor productivity. Existing models can be broadly categorized into expectancy, action-response, statistical and regression models, expert systems, artificial neural networks (ANNs), and fuzzy expert systems (Fayek and Oduba 2005; Lu et al. 2001; Song and AbouRizk 2008; Sonmez and Rowings 1998). While these models can be used to measure construction labor productivity, their ability to quantify the interrelations between the multiple factors in productivity studies remain inadequate (Yi and Chan 2014). Bounded by the number of included factors, the ability of statistical and regression models to measure the combined impact of productivity factors is also limited (Song and AbouRizk 2008). Techniques capable of accounting for the correlations and interactions between productivity factors within the dynamic construction environment, however, have yet to be reported in literature (Gerami Seresht and Fayek 2018; Sterman 2002).

Analytic Network Process (ANP) is a pragmatic tool used to solve complex decision structures. ANP was introduced by Thomas L. Saaty in 1996 as an advanced extension of the well-known Analytic Hierarchy Process (AHP) to overcome hierarchical structure limitations (Saaty 1996). AHP assumes that criteria are independent of each other, and hierarchical relationships among these criteria are unidirectional. As such, AHP is unable to consider the interactions and dependencies between criteria ((Karpak and Topcu 2010; Tjader et al. 2014).

In contrast to AHP, ANP measures multiple relationships between decision elements by replacing a hierarchical structure with a network structure (Saaty 1996), thereby overcoming the linearity assumption of AHP. ANP offers more flexibility for taking complex interactions between various elements into consideration, while retaining all of the positive features of AHP, including simplicity, adaptability, and simultaneous quantitative and qualitative criteria. Since ANP considers each issue as a network of criteria, sub-criteria, it counts for the feedback and interconnections between clusters in a network (Garcia-Melon et al. 2008).

Although ANP can handle complexities by incorporating interdependencies, external dependencies, and feedback between the elements in the hierarchical or non-hierarchical structures (He et al. 2012; Saaty 1996), ANP assumes equal weights for each cluster when generating a weighted supermatrix and it does not identify the interdependencies between factors. This can limit the accuracy of ANP models of practical situations where cluster priorities differ ((Azizi et al. 2014; Eshtehardian et al. 2013). To overcome these issues, the DEMATEL method can be used. The Geneva Research Centre introduced the DEMATEL method to more accurately analyze the various criteria that affect a system by determining the influence and strength between criteria to draw a structural model of the problem (Si et al. 2018). DEMATEL has been found successful at visualizing cause and effect criteria, obtaining broader insight into relationships between measures and clusters, and identifying a project's most important factors. The DEMATEL method has been applied to numerous studies in construction, including the analysis, identification, and prioritization of occupational risks, supplier selection criteria, safety management practices, and social sustainability standards (Pai 2014)

6.3.3. Proposed method

This novel method was devised by integrating DEMATEL and ANP and putting them in place, as shown in a framework. The framework is comprised of three stages, namely factor identification, DEMATEL, and ANP. After factor identification, the DEMATEL stage identifies relationships (i.e., dependencies) between factors. Relationships are then input into the ANP stage, which determines the strength (i.e., weight) of each relationship. Altogether, the proposed method is able to calculate the interrelationships and the influence of various productivity factors on construction labor productivity. The schematic framework, as illustrated in Figure 6.1, is detailed as follows.

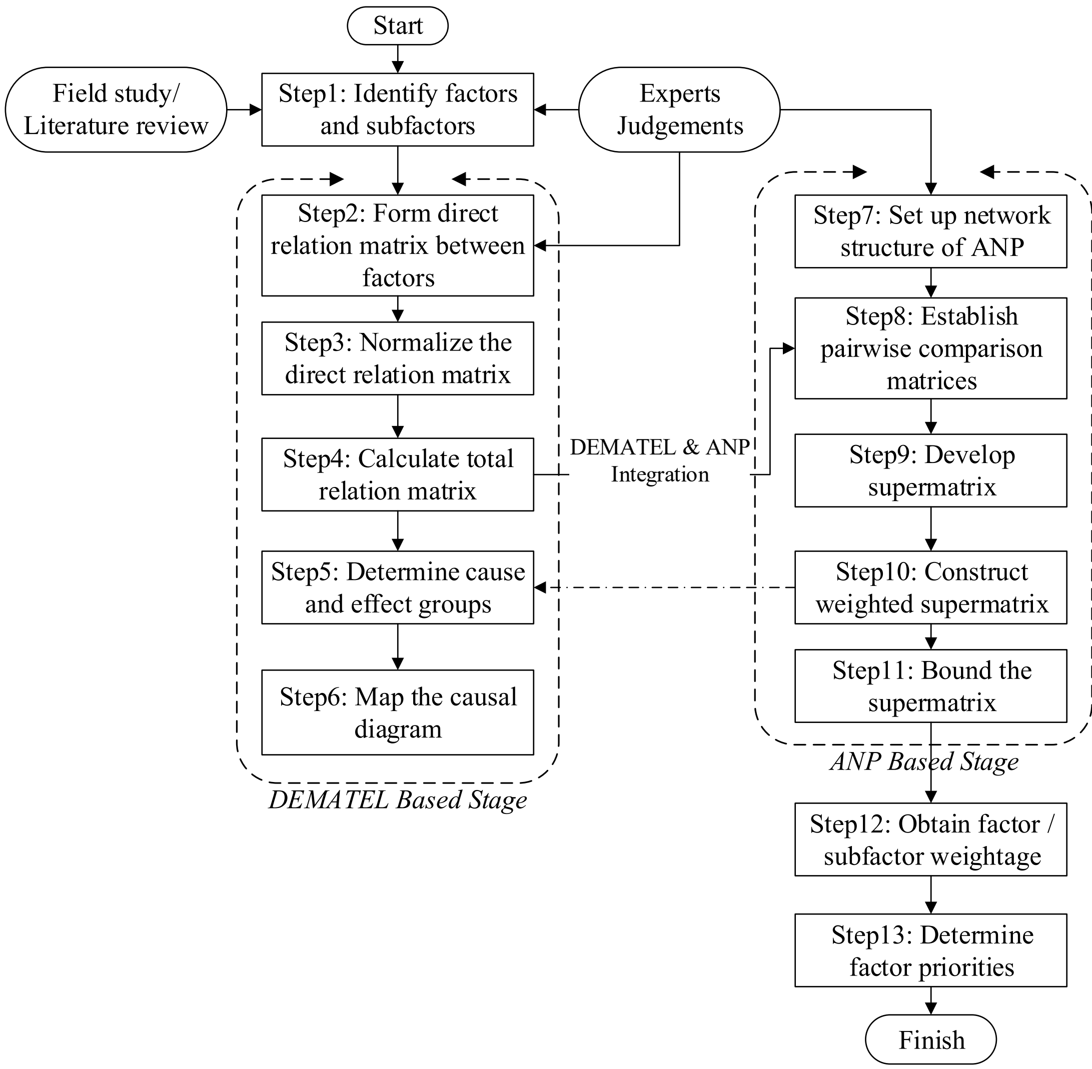


Figure 6.1: Schematic overview of the integrated DEMATEL and ANP-based framework

Factor Identification: Step 1

First, a list of productivity factors is developed following preliminary studies (e.g., field study of project) and a review of relevant literature. Once the preliminary list is created, the list is reviewed by subject matter experts. A repetitious feedback approach is recommended, where the results of the preceding round of feedback are shared with participants in subsequent rounds until a consensus is obtained. Once the experts have agreed on a final list of factors, the factors are then grouped, as detailed in the illustrative example. It is important to note that the process should be repeated for all new projects, as changes to project conditions or characteristics may have a differential impact on construction labor productivity.

DEMATEL Process: Steps 2-6

In the next stage, the DEMATEL technique is applied. First, experts perform multiple pairwise comparisons between each factor within each group. Experts rate the influence of the relationship of each pairwise comparison using a comparison scale. An example scale is detailed in Table 6-1.

Table 6-1: Comparison scale for assessing relationship between factors

None	Weak	Average	Strong	Very Strong
0	1	2	3	4

Then, based on these evaluations, a direct-relation matrix with dimensions of n × n is constructed using Eq. 6.1, where a_{ij} is the degree to which factor i influences factor j.

$$\mathbf{A} = [a_{ij}]_{n \times n} \qquad (6.1)$$

The mean score of the responses is used to derive element a_{ij} and form matrix $\boldsymbol{A}$. Once the direct-relation matrix is established, the matrix is normalized. A commonly used method for normalization is the application of the normalization factor, as proposed by (Tzang et.al, 2007), that is described by Eq. 6.2.

$$\boldsymbol{N} = \text{Min}\left(\frac{1}{\text{Max}_{1\le i\le n}\ \sum_{j=1}^{n}|\text{a}_{ij}|}, \frac{1}{\text{Max}_{1\le j\le n}\sum_{i=1}^{n}|\text{a}_{ij}|}\right) \qquad (6.2)$$

The normalized matrix ($\boldsymbol{N_A}$) is calculated by multiplying matrix $\boldsymbol{A}$ by $\boldsymbol{N}$ (Eq. 6.3).

$$\boldsymbol{N_A} = \boldsymbol{N} \times \boldsymbol{A} \qquad (6.3)$$

Thereafter, the total-influence matrix ($\boldsymbol{T_c}$) is calculated using Eq.6. 4, where $\boldsymbol{I}$ is the identity matrix.

$$\boldsymbol{T_c} = [t_c^{ij}]n \times m = \lim_{S\to\infty}(\boldsymbol{N_A} + \boldsymbol{N_A}^2 + \ldots + \boldsymbol{N_A}^s) = \boldsymbol{N_A}(\boldsymbol{I} - \boldsymbol{N_A})^{-1} \qquad (6.4)$$

Using the results of the total-influence matrix ($\boldsymbol{T_c}$), the factor group (i.e., either cause or effect) and the number of factors that are influenced by each factor is determined. First, the sum of the rows and the sum of the columns for each matrix $\boldsymbol{T}$ is calculated using Eq. 6.5 and Eq. 6.6, respectively.

$$R = \left[\sum_{j=1}^{n} t_c^{ij}\right]_{n\times 1} \qquad (6.5) \qquad\qquad D = \left[\sum_{i=1}^{n} t_c^{ij}\right]_{1\times n} \qquad (6.6)$$

Next, the Relation Value is calculated as per Eq. 6.7.

Relation Value = R - D (6.7)

If the Relation Value is positive, the factor belongs to the cause group, indicating that the factor exerts more influence on the other factors than it receives. Cause group factors express higher preferences. If the Relation Value is negative, the factor belongs to the effect group, indicating that it receives more influence from the other factors than it exerts. Effect group factors express lower preferences.

Also, the Prominence Value that indicates the factor's importance is calculated per Eq. 6.8.

Prominence Value = R + D (6.8)

The Prominence value represents the strength of influences given and received of the factor, whereas the Relation value designates the factor's net effect contributed to the system.

ANP Process: Steps 7-13

Once the presence of relationships has been identified using DEMATEL in Steps 2-6, ANP is used to determine the strengths of the relationships. The ANP stage is initiated by setting the ANP network structure. Then, pairwise comparisons are carried out between factors with interdependencies identified in Steps 2-6. The results are used to create an unweighted supermatrix, $\boldsymbol{S}_{uw}$, which can be obtained by transposing the total influence matrix $\boldsymbol{T_c}^{\propto}$. In Eq. 6.9, the matrix generated by Eq. 6.4 is normalized by each column of its sums to unity. Then, a weighted supermatrix is generated by multiplying the unweighted supermatrix by the corresponding cluster.

$$S_{uw} = (\boldsymbol{T_c}^{\propto})' \tag{6.9}$$

Afterwards, the factor and subfactor weights are obtained by transforming the weighted supermatrix into the limit matrix by raising itself to a sufficiently large power (i.e., $r \to \infty$) until the results are sufficiently stable, using Eq. 6.10,

$$\lim_{r \to \infty} {S_w}^r \tag{6.10}$$

The Relation Values and Prominence Values of the new weighted supermatrix are calculated using Eq. 6.7 and Eq. 6.8, resulting in a Weighted Relation Value and Weighted Prominence Value for each factor, respectively. priorities are then determined based on the weights obtained for each factor.

Framework Outputs

Outputs of the proposed framework include the Weighted Relation Value and Weighted Prominence Value for each of the factors from which causality can be inferred. Causal diagrams that plot a factor's Weighted Relation Value (R-D, y-axis) versus its Prominence Value (D+R, x-axis) assist with visualizing relationships between the factors and provide useful decision-support.

6.3.4. Illustrative Example

To demonstrate the functionality of the proposed framework, the method was applied to an illustrative highway road and bridge construction example. A comprehensive list of 34 factors affecting productivity was compiled following a thorough review of construction literature. The factors were categorized into groups based on recommendations from literature and the authors' previous experience, as detailed in Table 6-2.

Table 6-2: Significant factors influencing labor productivity in illustrative example

Cluster (Category)	Factor (ID)
Labor Competence (Human Factors)	Labor Skill (LC1), Fatigue (LC2), Motivation and Morale (LC3), Work Satisfaction (LC4), Laborer Experience (LC5), Training and Learning (LC6), Job Security (LC7), Teamwork (LC8)
Site (Field) Conditions	Site Layout (FC1), Site Restricted Access (FC2), Site Congestion (FC3), Site Facilities and Accommodations (FC4)
Planning Factors	Project Scheduling (PF1), Crew Size and Composition (PF2), Workflow/Project Sequence (PF3)
Management Competence	Field Supervision (MC1), Trade Coordination (MC2), Effective Communication (MC3), Rate of Labor Turnover (MC4)
Health, Safety and Environment (HSE)	Site Health and Safety (HSE1), Occupational Injury/Accident Rate (HSE2), Hazardous Work Area (HSE3)
Technical Excellence	Incomplete/Deficient Drawings and Specifications (TE1), Construction Methods (TE2), Constructability/Buildability (TE3)

Materials, Tools, Equipment	Equipment Reliability (MTE1), Tools and Materials Availability (MTE2), Proper Tools/Equipment Shortage (MTE3)
Schedule Compression	Scheduled Overtime (SC1), Over-Staffing (SC2), Shift Work (SC3)
Unfavorable Conditions	Adverse Weather Conditions (UC1), Rework (UC2), Frequent Change Orders (UC3)

Each of the 34 factors were compared to other factors within their cluster. Then, clusters were compared to each other, resulting in a total of 94 pairwise comparisons. This approach was adopted to reduce the number of comparisons needed to carry out the analysis (from 561 to 94), thereby improving the practical functionality of the method. While this approach does not directly examine interdependencies between individual factors of different clusters, interdependencies between individual factors will be reflected as an increase in the overall strength of the relationship between clusters. As such, additional or unexpected interdependencies between individual factors are expected to be captured at the cluster level. Therefore, this approach can adequately evaluate the factor's interrelation in the cluster's level. The list prepared for the illustrative example is very comprehensive, and the number of factors used in practice can be reduced to facilitate application. To mimic the practical application of the method, 9 illustrative responses were prepared. The proposed methodology was applied as described in the Proposed Framework section. Because of the large number of factors included, MATLAB software was used to perform the calculations. However, calculations involving a shorter list of factors are manageable using spreadsheet-based software applications. A sample of the weighted supermatrix is shown in Table 6-3. Then, the Weighted Relation Value and Weighted Prominence Value of each factor were determined; the causal diagram is visualized in Figure 6.2: Causal diagram of illustrative example.

Table 6-3: Sample of the weighted supermatrix of illustrative example

Factors	LC1	LC2	LC3	…	UC1	UC2	UC3
LC1	0	-	-	…			
LC2	0.0233	0	-	…			
LC3	0.0233	0.0233	0	…			
…	…	…	…	…			
UC1	0.0253	0.0465	0.0465	…	0		
UC2	0.0237	0.0243	0.0383	…	0.0283	0	
UC3	0.0341	0.0083	0.0143	…	0.0143	0.0239	0

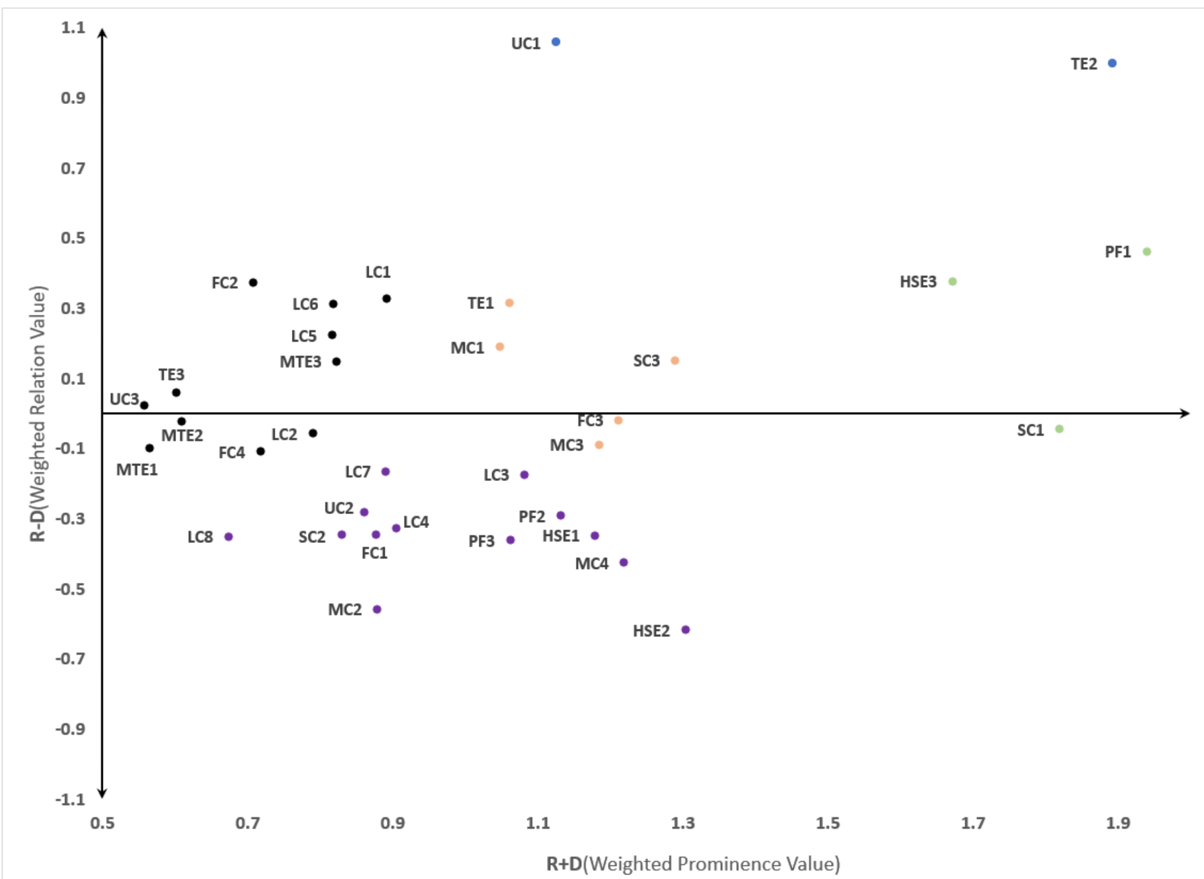


Figure 6.2: Causal diagram of illustrative example

In the illustrative example, Adverse Weather Conditions (UC1) had the most considerable Weighted Relation Value, suggesting that, out of the 34 factors, Adverse Weather Conditions

(UC1) have the most notable effect contribution to the productivity (i.e., affects the most factors). Project Scheduling was found to have the highest Weighted Prominence Value, suggesting that Project Scheduling (PF1) has the most significant influence on productivity. The outputs of the proposed framework were then clustered using the K-means method. Five clusters were identified, as shown in Figure 6.2. The top two clusters encompassed five productivity factors, specifically Adverse Weather Conditions (UC1), Construction Methods (TE2), Project Scheduling (PF1), Hazardous Work Area (HSE3), and Scheduled Overtime (SC1). These results can be (1) input into a system dynamics-based model to enhance root cause analysis or (2) be used as-is to prioritize resources for enhancing factors with the greatest and/or most widespread impact on productivity.

6.3.5. Method Validation

The suitability and accuracy of the proposed method was evaluated using face validation. The illustrative example was presented to nine subject matter experts, including construction managers and engineers. After reviewing the output results, subject matter experts provided their feedback by answering nine evaluation questions (Table 6-4) using a numerical rating scale based on their knowledge and experience. Face validation results are shown in

Table 6-5.

Table 6-4: Evaluation questions

No.	Questions
Q1	How applicable and valuable is the proposed method?
Q2	To what extent does this method consider the relationships between factors affecting productivity?
Q3	To what extent is the method able to provide objective information to support experts' judgement of productivity?
Q4	How well does the proposed method integrate experts' judgements?

Q5	To what extent does this method facilitate construction managers' and project managers' decision-making?
Q6	To what extent does the method assist with the assessment of productivity in construction projects?
Q7	How well is the method able to identify factors that affect productivity of a construction project?
Q8	To what extent are the results of the model consistent with expected performance and productivity implications?
Q9	How transparent and rational are the results of the proposed method?

Table 6-5: Evaluation results

Question	Impact					Mean	Standard Deviation
	Very Low	Low	Average	High	Very High		
Q1	0	1	3	4	1	3.56	0.83
Q2	0	0	2	4	3	4.11	0.74
Q3	0	1	1	4	3	4.00	0.94
Q4	1	1	1	4	2	3.56	1.26
Q5	0	1	2	5	1	3.67	0.82
Q6	0	1	3	5	0	3.44	0.68
Q7	1	0	2	3	3	3.78	1.23
Q8	0	1	3	5	0	3.44	0.68
Q9	0	2	2	3	2	3.56	1.07

The proposed method was evaluated as average or high impact for all questions. The ability of the method to consider relationships between factors affecting productivity and to support experts' decision-making of project productivity was high, verifying the logic of the method and the ability of the approach to generate useful and representative results.

6.3.6. Discussion

Outputs of the framework can be used to improve decision-making in practice in a number of ways. First, results can be used as-is to identify the most significant productivity-influencing factors on a construction project, allowing practitioners to more appropriately allocate resources to factors with the largest potential impact. Second, outputs can be used as inputs for other decision-support systems, such as system dynamics models, capable of modeling the impact of the factors' dynamic behavior on labor productivity. Given that the framework attempts to reduce subjectivity while also deriving weights for relationships, outputs of the proposed method are expected to yield higher quality inputs for productivity modeling-based decision-support systems compared to traditional input preparation approaches. Finally, the approach can be used to conduct scenario analyses (i.e., what if analysis). Practitioners can modify inputs to examine various scenarios that may mitigate or enhance the impact of the high-influence factors to enhance labor productivity.

From an academic perspective, this research sheds light on the path and foundation required to more accurately model construction labor productivity. The highly complex and dynamic nature of construction labor productivity together with the complex inter-related structure of productivity-influencing factors throughout the life cycle of a project requires detailed methods capable of providing sufficient information to develop reliable and representative productivity models. Through the integration of DEMATEL and ANP, this research has contributed to the advancement of this endeavor by reducing subjectivity and improving accuracy of construction productivity modeling by considering the interrelationships and effects between the evaluation dimensions and factors to precisely position and select them. Future opportunities, therefore, include extending the framework through the implementation of agent-based or simulation modeling to further improve output reliability and accuracy.

In addition to its academic and practical benefits, the following limitations of the method should be considered. First, although the method is designed to reduce subjectivity through response aggregation, the accuracy and reliability of the method remain dependent on the knowledge and experience of experts with regards to project context. Second, functionality of the method was demonstrated using an illustrative data set, and the reasonableness of the method and results was confirmed by face validation. However, accuracy of the proposed method should be examined by comparing method-derived results with actual project outcomes.

6.3.7. Conclusions

Managing labor productivity in construction is time-consuming, involving a complex, multi-criteria decision-making process. Identifying essential productivity-influencing factors and their relationships with each other throughout a project's life cycle remains a primarily subjective and unstructured task. However, methods capable of identifying and determining the strength of these relationships in a quantifiable and comprehensive manner have yet to be developed.

The proposed framework attempts to address this research gap by introducing a structured framework for identifying and determining the strength of relationships between productivity-influencing factors. Automating most of the method through the development of an implementable

MATLAB-based tool, the method uses DEMATEL to identify relationships between factors and ANP to determine the strength of each relationship. The method is designed to capture several industrial practitioners' practical know-how as inputs, capitalizing on the aggregation of information from multiple experts (i.e., project team) to ensure all relationships between productivity-influencing factors are identified. Face validation results from 9 experts confirm that the framework can provide "objective information to support experts' judgement of productivity." The result is a flexible method for exploring the relationships between factors and the influential directions affecting labor productivity that can be applied to any construction type.

Chapter 7: Conclusions

This dissertation delved into an intriguing investigation of a pertinent challenge in project management. It concentrated on multiple scattered projects subject to strict deadlines and limited resources with dynamic scope changes, necessitating prudent planning, resource allocation, and scheduling. The research was motivated by a pressing industry need; it merged the application of agile methodologies with streamlined mathematical optimization models to tackle this complex challenging problem.

The research has successfully achieved its objectives through the outlined steps as follows.

1. A comprehensive research methodology was designed based on the concept of the CIFE method developed at the Center for Integrated Facility Engineering at Stanford University. This methodology was followed through iterative investigations of the problem, on-site observations, participation in preconstruction, construction planning, and construction work to identify, document, and characterize the problem as best as possible.
2. A short-term, multiple-project management problem with dynamic constraints on project information, resource availability, and contractual obligations (penalty/cancel charges) was thoroughly and effectively defined following the research methodology in close collaboration with the industry partner.
3. A comprehensive literature review encompassing multiple disciplines was conducted to identify potential solutions to the problem. Following that, it was determined that integrating agile project management techniques with mathematical optimization methodologies would represent a novel and effective approach to tackling the problem.

This recommendation is grounded in the specific problem specifications, insights gleaned from industry professionals, and the literature review findings.

4. A set of innovative models were developed that combined mixed integer linear (MIP) and binary (0-1) elements. The models were designed to take into account the constraints that are inherent to the problem at hand.
5. Performance metrics were devised to evaluate the goodness of the resultant plans, and a heuristic method, a generalized representation of the current industry practice, was developed to verify the model outcomes. The model's results on case studies using the developed Excel-based program were compared with those obtained through the heuristic method.
6. A customized Agile methodology framework was introduced through a step-by-step flowchart and forms tailored to the problem's context. The Agile-based framework was complemented by an Excel-based program implemented in VBA to provide pragmatic solutions.
7. The uncertainties inherent in the multi-project environment of the problem were thoroughly explored and categorized. Common approaches for addressing uncertainties were reviewed. An innovative management approach to address uncertainties was proposed.
8. Finally, an analytical method was proposed to handle underlying issues with the subjectivity of expert opinions and quantify the results in a Multi-Criteria Decision Making (MCDM) application, which was applied to model the crew productivity in this research.

The research is distinguished by its practical significance and potentially transformative impact in tackling the intricate challenges faced by contractors, especially in situations complicated by dynamic uncertainties related to resource allocation. It holds promise in offering substantial optimization advantages, exhibiting its utility in enhancing the effectiveness of project planning and management.

7.1 Research Contributions

This study presents novel academic contributions to the construction engineering and management discipline in the following areas.

1. The effectively defined short-term planning problem in a scattered multi-project management domain with dynamic constraints on project information, resource availability, and contractual obligations (penalty/cancel charges) is a significant contribution as a solid foundation to the research in this field.
2. A novel solution by merging agile project management and mathematical optimization models contributes to the research, emphasizing the application of agile methodologies to optimize planning and scheduling processes, particularly for geographically dispersed projects subject to strict deadlines and limited resources.
3. A well-thought agile-based framework tailored to the context of the problem, governing the planning process at the level of the projects, is another contribution, encouraging self-organized team structure instead of traditional hierarchical methods to facilitate a streamlined and efficient planning and execution process.
4. The sophisticated models tailored to the problem's specific constraints and challenges contribute to the research by transforming many "If-Then" conditions conceived from the problem's combinatorial nature and incorporating commonly applicable project terms and contract conditions in the real world. This feature makes optimization more efficient and

expeditious, catalyzing agile project management. The models are distinct from overly complex optimization models, enhancing their adaptability to the dynamic problem domain while capturing all the necessary constraints and providing the optimal solution in a quick turnaround time for practical-sized problems with complexity.

5. Additionally, the proposed management approach to address uncertainties is a valuable addition to the holistic approach undertaken by the research.
6. Finally, another contribution is the novel analytical method proposed to address underlying issues with the subjectivity of expert opinions and quantify the results in a Multi-Criteria Decision Making (MCDM) application. It adds value to the research, especially when dealing with inadequate data for crew productivity variation.
7. The study laid out the linear models in a prototype Excel-based program that can be matched with less expensive or open-source solver engines. The program minimized or eliminated human errors and sped up the planning process by designing data entry and optimization interfaces. The coded program demonstrated the research's commitment to delivering pragmatic solutions and contributed to its practical implementation in the industry.

The close collaboration with the industry partner underscored the real-world applicability and industry relevance of the developed methods that make the following practical contributions.

1. The agile-based optimized planning and scheduling methodology prototyped in an Excel-based program demonstrates the research's commitment to delivering a cost-effective and pragmatic solution to the industry.

2. The practical research outcomes yield direct cost savings in the industry by planning for more projects, maximizing resource efficiency and work continuity, preventing or minimizing delay penalties, and eliminating cancellation charges.
3. Furthermore, it reduces the application cost of optimization by using cost-effective optimization engines to find solutions in line with the agile project management framework.
4. The practical methods established in this research can be adapted to facilitate the time-sensitive dispatching of finite crew resources to multiple projects across various sectors.

In conclusion, the innovative solutions and insights presented in this dissertation yield substantial benefits for both the industry and academic communities. The research is distinguished for its applicability to real-world scenarios and its potential to bring about transformative change in managing the complex challenges faced by contractors, particularly regarding managing resources in the face of uncertainties that constantly arise. The study holds promise in offering significant optimization advantages, demonstrating its utility in enhancing the effectiveness of project planning and management. Ultimately, this work contributes to a deeper understanding of complex project management challenges and enables organizations to develop more effective project management strategies and methods.

7.2 Research Limitations and Future Work

Potential extensions to this dissertation are presented below.

1. Firstly, the agile-based framework and optimization models can be extended to construction projects with larger timeframes.

2. Secondly, a comprehensive analysis of the proposed planning methodology's impact on project completion, resource utilization efficiency, and cost optimization is highly recommended.
3. Furthermore, analyzing the robustness, flexibility, and scalability of the developed methodologies compared to established benchmarks would yield valuable insights into areas that may require further refinement of the proposed solutions. Statistical evaluations can help identify more realistic improvement opportunities to enhance the proposed methodologies' overall effectiveness.
4. A combination of the above two proposed future research directions would contribute to a more thorough understanding of the performance advantages and unique capabilities of the agile-based optimized planning and scheduling approach. The benchmarking analysis should ideally encompass various performance metrics, such as cost-effectiveness, time management, resource utilization, and the ability to adjust to dynamic project settings.
5. An area that warrants further exploration in this research is the utilization of AI techniques such as certain methods like Reinforcement Learning from Human Feedback (RLHF), as well as new technologies for gathering and analyzing real-time data to enhance the replanning processes within an optimized planning methodology based on Agile principles.
6. Furthermore, additional research opportunities can be pursued based on the present study. One such area is investigating a hybrid Agile-Waterfall methodology to augment other management aspects of construction projects, particularly in handling changes, as Agile project management has yet to prove itself in this regard(Ajam 2018).
7. Finally, a promising field of research involves the identification of potential obstacles to the implementation of developed methodologies, as well as the development of

management strategies to address them. Such elements as the organizational management structure, culture, and client relationships and their impacts necessitate analysis.

REFERENCES

AbouRizk, S. (2010). "Role of Simulation in Construction Engineering and Management." *Journal of Construction Engineering and Management*, 136(10), 1140-1153.

Abourizk, S., and Mohamed, Y. "Optimal construction project planning." *Proc., Proceedings of the Winter Simulation Conference*, IEEE, 1704-1708.

Adeli, H., and Karim, A. (2001). *Construction scheduling, cost optimization and management*, CRC Press.

Ajam, M. A. (2018). *Project Management beyond Waterfall and Agile*, Taylor and Francis Group, LLC CRC Press.

Alliance®, S. (2017). "State of Scrum 2017-2018: scaling and agile transformation."

Arefazar, Y., Nazari, A., Hafezi, M. R., and Maghool, S. A. H. (2019). "Prioritizing agile project management strategies as a change management tool in construction projects." *International Journal of Construction Management*, 22(4), 678-689.

Atef, A., Osman, H., and Moselhi, O. (2012). "Multiobjective genetic algorithm to allocate budgetary resources for condition assessment of water and sewer." *Canadian Journal of Civil Engineering*, 39(9), 978-992.

Atkinson, R., Crawford, L., and Ward, S. (2006). "Fundamental uncertainties in projects and the scope of project management." *International Journal of Project Management*, 24(8), 687-698.

Azizi, A., Malekmohammadi, B., Jafari, H. R., Nasiri, H., and Amini Parsa, V. (2014). "Land suitability assessment for wind power plant site selection using ANP-DEMATEL in a GIS environment: case study of Ardabil province, Iran." *Environmental monitoring and assessment*, 186, 6695-6709.

Bakry, I., Moselhi, O., and Zayed, T. (2016). "Optimized scheduling and buffering of repetitive construction projects under uncertainty." *Engineering, Construction and Architectural Management*, 23(6), 782-800.

Birrell, G. S. (1980). "Construction Planning-Beyond the Critical Path." *Journal of The Construction Division*, 106(3), 389-407.

Birrell, G. S. (1987). "Discussion of ‘Criticism of CPM for project planning analysis." *Journal of Civil Engineering and Management*, 13(2), 343-345.

Błażewicz, J., Ecker, K. H., Pesch, E., Schmidt, G., and Weglarz, J. (2007). *Handbook on scheduling: from theory to applications*, Springer Science & Business Media.

Boer, R. d. (1998). "Resource -Constrained Multi -Project Management -A Hierarchical Decision Support System." University of Twente, Febodruk B.V., Enschede, The Netherlands.

Bräysy, O., and Gendreau, M. (2005). "Vehicle Routing Problem with Time Windows, Part I: Route Construction and Local Search Algorithms." *Transportation Science*, 39(1), 104-118.

Browning, T. R., and Yassine, A. A. (2010). "Resource-constrained multi-project scheduling: Priority rule performance revisited." *International Journal of Production Economics*, 126(2), 212-228.

Brucker, P., Drexl, A., Möhring, R., Neumann, K., and Pesch, E. (1999). "Resource-constrained project scheduling: Notation, classification, models, and methods." *European journal of operational research*, 112(1), 3-41.

Brucker, P., and Knust, S. (2006). "Complex scheduling Springer-Verlag Berlin." *Heidelberg, Germany*.

Chakrabortty, R. K., Rahman, H. F., Haque, K. M. A., Paul, S. K., and Ryan, M. J. (2021). "An event-based reactive scheduling approach for the Resource Constrained Project Scheduling Problem with unreliable resources." *Computers & Industrial Engineering*, 151.

Cheng, J., Fowler, J., Kempf, K., and Mason, S. (2015). "Multi-mode resource-constrained project scheduling problems with non-preemptive activity splitting." *Computers & Operations Research*, 53, 275-287.

Cheng, M.-Y., Prayogo, D., and Tran, D.-H. (2016). "Optimizing Multiple-Resources Leveling in Multiple Projects Using Discrete Symbiotic Organisms Search." *Journal of Computing in Civil Engineering*, 30(3).

Choo, H. J., Tommelein, I. D., Ballard, G., and Zabelle, T. R. (1999). "WorkPlan: Constraint-based database for work package scheduling." *Journal of Construction Engineering and Management*, 125(3).

Cohen, I., Mandelbaum, A., and Shtub, A. (2004). "Multi-project scheduling and control: A process-based comparative study of the critical chain methodology and some alternatives." *Project management journal*, 35(2), 39-50.

Cole, R., and Scotcher, E. (2016). *Brilliant Agile project management: a practical guide to using Agile, Scrum and Kanban*, Pearson UK.

Creswell, J. W., and Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*, Sage publications.

Das, S., and Bhattacharyya, B. K. (2015). "Optimization of municipal solid waste collection and transportation routes." *Waste Manag*, 43, 9-18.

Dasović, B., Galić, M., and Klanšek, U. (2020). "A Survey on Integration of Optimization and Project Management Tools for Sustainable Construction Scheduling." *Sustainability*, 12(8).

Deblaere, F., Demeulemeester, E., and Herroelen, W. (2011). "Proactive policies for the stochastic resource-constrained project scheduling problem." *European Journal of Operational Research*, 214(2), 308-316.

Dhaliwal, G. (2011). "Optimization Models and Algorithms for Workforce Scheduling with Uncertain Demand." Master of Applied Science, Waterloo, Ontario, Canada.

digital.ai (2020). "14th Annual State of Agile Report." www.stateofagile.com.

Eason, R., Rosenberger, R., Kokalis, T., Selinger, E., and Grim, P. (2007). "What kind of science is simulation?" *Journal of Experimental & Theoretical Artificial Intelligence*, 19(1), 19-28.

East, E. W., and Liu, L. Y. (2006). "Multiproject Planning and Resource Controls for Facility Management." *Journal of Construction Engineering and Management*.

Elmasry, M., Zayed, T., and Hawari, A. (2019). "Multi-Objective Optimization Model for Inspection Scheduling of Sewer Pipelines." *Journal of Construction Engineering and Management*, 145(2).

Engwall, M., and Jerbrant, A. (2003). "The resource allocation syndrome: the prime challenge of multi-project management?" *International Journal of Project Management*, 21(6), 385-386.

Eshtehardian, E., Ghodousi, P., and Bejanpour, A. (2013). "Using ANP and AHP for the supplier selection in the construction and civil engineering companies; Case study of Iranian company." *KSCE Journal of Civil Engineering*, 17, 262-270.

Fayek, A. R., and Oduba, A. (2005). "Predicting industrial construction labor productivity using fuzzy expert systems." *Journal of construction engineering and management*, 131(8), 938-941.

Fisher, M. "Formalizing construction knowledge for concurrent performance-based design." *Proc., Smith, I.F.C. (eds) Intelligent Computing in Engineering and Architecture. EG-ICE 2006*, Springer, 186-205.

Fontecha, J. E., Guaje, O. O., Duque, D., Akhavan-Tabatabaei, R., Rodríguez, J. P., and Medaglia, A. L. (2020). "Combined maintenance and routing optimization for large-scale sewage cleaning." *Annals of Operations Research*, 286(1-2), 441-474.

Fowler, M., and Highsmith, J. (2001). "The agile manifesto." *Software development*, 9(8), 28-35.

Franco-Duran, D. M., and Garza, J. M. d. l. (2019). "Review of Resource-Constrained Scheduling Algorithms." *Journal of Construction Engineering and Management*, 145(11).

Fréville, A. (2004). "The multidimensional 0–1 knapsack problem: An overview." *European Journal of Operational Research*, 155(1), 1-21.

Frontline Systems, I. (2023). *Frontline Solvers User Guide Version 2023 Q2*, Frontline Systems

Gálvez, E. D., and Capuz-Rizo, S. F. (2016). "Assessment of global sensitivity analysis methods for project scheduling." *Computers & Industrial Engineering*, 93, 110-120.

Garcia-Melon, M., Ferris-Onate, J., Aznar-Bellver, J., Aragonés-Beltran, P., and Poveda-Bautista, R. (2008). "Farmland appraisal based on the analytic network process." *Journal of Global Optimization*, 42, 143-155.

Gerami Seresht, N., and Fayek, A. R. (2018). "Dynamic modeling of multifactor construction productivity for equipment-intensive activities." *Journal of Construction Engineering and Management*, 144(9), 04018091.

Gomar, J. E., Haas, C. T., and Morton, D. P. (2002). "Assignment and Allocation Optimization of Partially Multiskilled Workforce." *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT*, 128(2), 103-109.

Gómez Sánchez, M., Lalla-Ruiz, E., Fernández Gil, A., Castro, C., and Voß, S. (2023). "Resource-constrained multi-project scheduling problem: A survey." *European Journal of Operational Research*, 309(3), 958-976.

Goncalves, M., and Heda, R. (2010). "Fundamentals of agile project management." New York: American Society of Mechanical Engineers.

Goodpasture, J. C. (2016). *Project Management the Agile Way: Making It Work in the Enterprise*, J. Ross Publishing

Grim, P., Rosenberger, R., Rosenfeld, A., Anderson, B., and Eason, R. E. (2011). "How simulations fail." *Synthese*, 190(12), 2367-2390.

Habibi, F., Barzinpour, F., and Sadjadi, S. J. (2018). "Resource-constrained project scheduling problem: review of past and recent developments." *Journal of Project Management*, 55-88.

Halfawy, M. R., Dridi, L., and Baker, S. (2008). "Integrated Decision Support System for Optimal Renewal planning of swer network." *OURNAL OF COMPUTING IN CIVIL ENGINEERING* 22(6), 360-372.

Harrison, F., and Lock, D. (2004). *Advanced Project Management_ A Structured Approach*, Gower Publishing Company, England And USA.

Hartmann, S., and Briskorn, D. (2022). "An updated survey of variants and extensions of the resource-constrained project scheduling problem." *European Journal of Operational Research*, 297(1), 1-14.

Hassannayebi, E., Sheikholeslami, A., and Ilati, G. (2014). "A Simulation-Based Optimization Approach for Integrated Port Resource Allocation Problem." *PROMET - Traffic&Transportation*, 26(3), 243-255.

Hazır, Ö., and Ulusoy, G. (2020). "A classification and review of approaches and methods for modeling uncertainty in projects." *International Journal of Production Economics*, 223, 107522.

He, Q.-h., Luo, L., Wang, J., Li, Y.-k., and Zhao, L. "Using analytic network process to analyze influencing factors of project complexity." *Proc., 2012 International Conference on Management Science & Engineering 19th Annual Conference Proceedings*, IEEE, 1781-1786.

He, W., Li, W., and Wang, W. (2021). "Developing a Resource Allocation Approach for Resource-Constrained Construction Operation under Multi-Objective Operation." *Sustainability*, 13(13).

Hegazy, T. (2006). "Computerized System for Efficient Delivery of Infrastructure Maintenance Repair Programs." *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT*.

Hegazy, T., Elhakeem, A., and Elbeltagi, E. (2004). "Distributed Scheduling Model for Infrastructure Networks." *OURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT*, 130(2), 160-167.

Hegazy, T., and Kassab, M. (2003). "Resource optimization using combined simulation and genetic algorithms." *Journal of construction engineering and management*, 129(6), 698-705.

Herroelen, W., Demeulemeester, E., and De Reyck, B. (1999). "A classification scheme for project scheduling." *Project scheduling: Recent models, algorithms and applications*, 1-26.

Herroelen, W., and Leus, R. (2005). "Project scheduling under uncertainty: Survey and research potentials." *European journal of operational research*, 165(2), 289-306.

Herroelen, W., and Leus, R. (2007). "Robust and reactive project scheduling: a review and classification of procedures." *International Journal of Production Research*, 42(8), 1599-1620.

Hillier, F. S., and Lieberman, G. J. (2001). *Introduction to operations research*, McGraw hill Companies, Inc.

Horman, M. J., Messner, J. I., Riley, D. R., and Pulaski, M. H. "Using buffers to manage production: A case study of the Pentagon renovation project." *Proc., 11th Annual Conference of the Internation Group for Lean Construction (IGLC-11), Blacksburg, Virginia*.

Horman, M. J., and Thomas, H. R. (2005). "Role of inventory buffers in construction labor performance." *Journal of Construction Engineering and Management*, 131(7), 834-843.

Issa, S. B., and Tu, Y. (2020). "A survey in the resource-constrained project and multi-project scheduling problems." *Journal of Project Management*, 117-138.

Jin, C. (2017). "Agile in Construction projects." Master of Science (MS), Harrisburg University of Science and Technology, Project Management (PMGT).

Jörg Kalcsics, S. N. (2008). *Selected Papers of the Annual International Conference ofthe GermanOperationsResearchSociety(GOR)_Operations Research Proceedings 2007*, Springer-Verlag Berlin Heidelberg.

Karpak, B., and Topcu, I. (2010). "Small medium manufacturing enterprises in Turkey: An analytic network process framework for prioritizing factors affecting success." *International Journal of Production Economics*, 125(1), 60-70.

Kastor, A., and Sirakoulis, K. (2009). "The effectiveness of resource levelling tools for Resource Constraint Project Scheduling Problem." *International Journal of Project Management*, 27(5), 493-500.

Kelley, J. E., and Walker, M. R. "Critical-path planning and scheduling." *Proc., Eastern joint IRE-AIEE-ACM computer conference*, 160-173.

Kim, J., Kang, C., and Hwang, I. (2012). "A practical approach to project scheduling: considering the potential quality loss cost in the time–cost tradeoff problem." *International Journal of Project Management*, 30(2), 264-272.

Kim, K. (2009). "Delay analysis in resource-constrained schedules." *Canadian Journal of Civil Engineering*, 36(2), 295-303.

Kim, K., and de la Garza, J. M. (2005). "Critical path method with multiple calendars." *Journal of Construction Engineering and Management*, 131(3), 330-342.

Kim, K., Yun, Y., Yoon, J., Gen, M., and Yamazaki, G. (2005). "Hybrid genetic algorithm with adaptive abilities for resource-constrained multiple project scheduling." *Computers in Industry*, 56(2), 143-160.

Kong, F., and Dou, D. (2021). "Resource-Constrained Project Scheduling Problem under Multiple Time Constraints." *Journal of Construction Engineering and Management*, 147(2).

Kuhpfahl, J. (2016). *Job Shop Scheduling with Consideration of Due Dates_ Potentials of Local Search Based Solution Techniques*, Springer Gabler, Springer Fachmedien Wiesbade.

Kung, D., Alex, D. P., Al-Hussein, M., and Fernando, S. (2008). "Application of lean thinking to improve the productivity of water and sewer service installations." *Canadian Journal of Civil Engineering*, 35(4), 418-430.

Laporte, G. (1992). "The Vehicle Routing Problem:An Overview of Exact and Approximate." *European Journal of Operational Research*, 59, 345-358.

Laslo, Z., and Goldberg, A. I. (2008). "Resource allocation under uncertainty in a multi-project matrix environment: Is organizational conflict inevitable?" *International Journal of Project Management*, 26(8), 773-788.

Layton, M. C., Ostermiller, S. J., and Kynaston, D. J. (2020). *Agile Project Management For Dummies*, John Wiley & Sons.

Lester, A. (2006). *Project management, planning and control: managing engineering, construction and manufacturing projects to PMI, APM and BSI standards*, Elsevier.

Li, H., Xiong, L., Liu, Y., and Li, H. (2017). "An effective genetic algorithm for the resource levelling problem with generalised precedence relations." *International Journal of Production Research*, 56(5), 2054-2075.

Liu, J., and Lu, M. (2019). "Robust dual-level optimization framework for resource-constrained multiproject scheduling for a prefabrication facility in construction." *Journal of Computing in Civil Engineering*, 33(2), 04018067.

Liu, S.-S., and Wang, C.-J. (2012). "Optimizing linear project scheduling with multi-skilled crews." *Automation in Construction*, 24, 16-23.

Liu, Y., and Mohamed, Y. (2012). "Modelling industrial construction operations using a multi-agent resource allocation framework." *Engineering, Construction and Architectural Management*, 19(4), 406-427.

Logue, K., and McDaid, K. (2008). "Handling Uncertainty in Agile Requirement Prioritization and Scheduling Using Statistical Simulation." *Agile 2008 Conference*, 73-82.

Lova, A., Maroto, C., and Tormos, P. (2000). "A multicriteria heuristic method to improve resource allocation in multiproject scheduling." *European journal of operational research*, 127(2), 408-424.

Lu, M. (2006). "Discussion of Critical path method with multiple calendars by Kyunghwan Kim and Jesús M. de la Garza." *Journal of Construction Engineering and Management*, 132(5), 540-541.

Lu, M., AbouRizk, S., and Hermann, U. (2001). "Sensitivity analysis of neural networks in spool fabrication productivity studies." *Journal of Computing in Civil Engineering*, 15(4), 299-308.

Lu, M., Anson, M., S.L.Tang, and Ying, Y. C. (2003). "HKCONSIM_ A Practical Simulation Solution to Planning Concrete Plant Operations in Hong Kong." *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT*, 129:5(547).

Lu, M., Lam, H.-C., and Dai, F. (2008). "Resource-constrained critical path analysis based on discrete event simulation and particle swarm optimization." *Automation in Construction*, 17(6), 670-681.

Lu, M., and Li, H. (2003). "Resource-Activity Critical-Path Method for Construction Planning." *Journal of Construction Engineering and Management*, 129(4), 412-420.

Lu, M., and Wong, L.-C. (2007). "Comparison of two simulation methodologies in modeling construction systems: Manufacturing-oriented PROMODEL vs. construction-oriented SDESA." *Automation in Construction*, 16(1), 86-95.

Lu, M., Wu, D.-p., and Zhang, J.-p. (2006). "A Particle Swarm Optimization-Based Approach to Tackling Simulation Optimization of Stochastic, Large-Scale and Complex Systems." Springer, Verlag Berlin Heidelberg, 528-537.

Ma, G., Gu, L., and Li, N. (2015). "Scenario-based proactive robust optimization for critical-chain project scheduling." *Journal of Construction Engineering and Management*, 141(10), 04015030.

Ma, G., Wang, A., Li, N., Gu, L., and Ai, Q. (2014). "Improved Critical Chain Project Management Framework for Scheduling Construction Projects." *Journal of Construction Engineering and Management*, 140(12).

Mahdavian, A., and Shojaei, A. (2020). "Hybrid Genetic Algorithm and Constraint-Based Simulation Framework for Building Construction Project Planning and Control." *Journal of Construction Engineering and Management*, 146(12).

Mavromatidis, G., Orehounig, K., and Carmeliet, J. (2018). "Uncertainty and global sensitivity analysis for the optimal design of distributed energy systems." *Applied Energy*, 214, 219-238.

Meredith, J. R., Jr., S. J. M., and Shafer, S. M. (2017). *Project Management_ A Managerial Approach*, Wiley.

Nijland, F., Gkiotsalitis, K., and van Berkum, E. C. (2021). "Improving railway maintenance schedules by considering hindrance and capacity constraints." *Transportation Research Part C: Emerging Technologies*, 126.

Osman, H., Ammar, M., and El-Said, M. (2017). "Optimal Scheduling of Water Network Repair Crews Considering Multiple Objectives." *Journal of Civil Engineering and Management*, 23(1), 28-36.

Oyetunji, E. (2009). "Some common performance measures in scheduling problems." *Research Journal of Applied Sciences, Engineering and Technology*, 1(2), 6-9.

Pai, F.-Y. (2014). "Analyzing consumers' decisions to select micro-invasive aesthetic service providers using a hybrid method." *Applied Mathematics & Information Sciences*, 8(6), 3071.

Papadimitriou, C. H., and Steiglitz, K. (1998). *Combinatorial optimization: algorithms and complexity*, Courier Corporation.

Park, M., and Peña-Mora, F. (2004). "Reliability Buffering for Construction Projects." *Journal of Construction Engineering and Management*, 130(5), 626-637.

Payne, J. H. (1995). "Management of multiple simultaneous projects: a state-of-the-art review." *International journal of project management*, 13(3), 163-168.

Pellerin, R., and Perrier, N. (2018). "A review of methods, techniques and tools for project planning and control." *International Journal of Production Research*, 57(7), 2160-2178.

Pich, M. T., Loch, C. H., and Meyer, A. D. (2002). "On Uncertainty, Ambiguity, and Complexity in Project Management." *Management Science*, 48(8), 1008-1023.

Pinedo, M. L. (2009). *Planning and scheduling in manufacturing and services* Springer, Verlag New York.

PMI (2021). "Project management body of knowledge (pmbok® guide)."

Poppendieck, M., and Poppendieck, T. (2003). *Lean software development: an agile toolkit*, Addison-Wesley.

Priemus, H., Bosch-Rekveldt, M., and Giezen, M. (2013). "Dealing with the complexity, uncertainties and risk of megaprojects: redundancy, resilience and adaptivity." *International Handbook on Mega-Projects*.

Pritsker, A., Watters, L., and Wolfe, P. (1969). "A paper on Management Science." *Multiproject Scheduling with Limited Resources: A Zero-One Programming Approach*, 16, 93-108.

Reinertsen, D. G. (2009). "The principles of product development flow: second generation lean product development." *(No Title)*.

Royce, W. W. "Managing the development of large software systems: concepts and techniques." *Proc., Proceedings of the 9th international conference on Software Engineering*, 328-338.

RSMeans (2023). "RSMeans." Gordian.

Rubin, K. S. (2012). *Essential Scrum: A practical guide to the most popular Agile process*, Addison-Wesley.

S.Hiller, F., and J.Leberman, G. (1999). *Introduction To Operations Research*, Stanford University.

Saaty, T. L. (1996). *Decision making with dependence and feedback: The analytic network process*, RWS publications Pittsburgh.

Sahinidis, N. V. (2004). "Optimization under uncertainty: state-of-the-art and opportunities." *Computers & Chemical Engineering*, 28(6-7), 971-983.

Salvendy, G. (2001). *Handbook of Industrial Engineering - Technology and Operations Management*, Wiley, New York.

Sarker, B. R., Egbelu, P. J., Liao, T. W., and Yu, J. (2012). "Planning and design models for construction industry: A critical survey." *Automation in Construction*, 22, 123-134.

Schrader, S., Riggs, W. M., and Smith, R. P. (1993). "Choice over uncertainty and ambiguity in technical problem solving." *Journal of Engineering and Technology Management*, 10(1-2), 73-99.

Schultmann, F., and Sunke, N. (1999). "Resource Allocation In Construction Projects_introduction for paper_charts." *CME 25 Conference Construction Management and Economics*.

Schwaber, K., and Sutherland, J. (2022). "The Scrum Guide, The Definitive Guide to Scrum: The Rules of the Game, November 2020."

Shrnhur, A. J., Levy, O., and Dvir, D. (1997). "Mapping the dimensions of project success." *Project management journal*, 28(2), 5-13.

Si, S.-L., You, X.-Y., Liu, H.-C., and Zhang, P. (2018). "DEMATEL technique: A systematic review of the state-of-the-art literature on methodologies and applications." *Mathematical Problems in Engineering*, 2018, 1-33.

Simon, H. A. (1969). "The science of the artificial cambridge." *MA. MIT*.

Siraj, N. B., and Fayek, A. R. (2019). "Risk identification and common risks in construction: Literature review and content analysis." *Journal of construction engineering and management*, 145(9), 03119004.

Siu, M.-F. F., Lu, M., and AbouRizk, S. (2015). "Methodology for Crew-Job Allocation Optimization in Project and Workface Scheduling." *ASCE Computing in Civil Engineering*

Sohi, A. J., Hertogh, M., Bosch-Rekveldt, M., and Blom, R. "Does Lean and Agile Project Management Help Coping with Project Complexity?" *Proc., Procedia - Social and Behavioral Sciences*, 252-259.

Solvers, F. (2023). "Frontline Solvers Reference Guide." Frontline Solvers Inc.

Song, L., and AbouRizk, S. M. (2008). "Measuring and Modeling Labor Productivity Using Historical Data." *Journal Of Construction And Engineering Management*, 134(10).

Song, L., and AbouRizk, S. M. (2008). "Measuring and modeling labor productivity using historical data." *Journal of construction engineering and management*, 134(10), 786-794.

Sonmez, R., and Rowings, J. E. (1998). "Construction labor productivity modeling with neural networks." *Journal of construction engineering and management*, 124(6), 498-504.

Sonmez, R., and Uysal, F. (2015). "Backward-Forward Hybrid Genetic Algorithm for Resource-Constrained Multiproject Scheduling Problem." *Journal of Computing in Civil Engineering*, 29(5).

Sterman, J. (2002). "System Dynamics: systems thinking and modeling for a complex world."

Stevenson, M., Hendry, L. C., and Kingsman †, B. G. (2005). "A review of production planning and control: the applicability of key concepts to the make-to-order industry." *International Journal of Production Research*, 43(5), 869-898.

Takeuchi, H., and Nonaka, I. (1986). "The new new product development game." *Harvard business review*, 64(1), 137-146.

Tekin, E., and Sabuncuoglu, I. (2004). "Simulation optimization: A comprehensive review on theory and applications." *IIE Transactions*, 36(11), 1067-1081.

Thomas, H. R., Horman, M. J., and de Souza, U. E. L. (2004). "Symbiotic Crew Relationships and Labor Flow." *Journal of Construction Engineering and Management*, 130(6), 908-917.

Thunnissen, D. P. (2005). "Propagating and Mitigating Uncertainty in the Design of Complex Multidisciplinary Systems." Doctor of Philosophy, California Institute of Technology.

Tjader, Y., May, J. H., Shang, J., Vargas, L. G., and Gao, N. (2014). "Firm-level outsourcing decision making: A balanced scorecard-based analytic network process model." *International Journal of Production Economics*, 147, 614-623.

Tukel, O. I., Rom, W. O., and Eksioglu, S. D. (2006). "An investigation of buffer sizing techniques in critical chain scheduling." *European Journal of Operational Research*, 172(2), 401-416.

Ulusoy, G., and Hazır, Ö. (2021). *An Introduction to Project Modeling and Planning*, Springer.

Van Eynde, R., and Vanhoucke, M. (2020). "Resource-constrained multi-project scheduling: benchmark datasets and decoupled scheduling." *Journal of Scheduling*, 23(3), 301-325.

Wang, W., Ge, X., Li, L., and Su, J. (2019). "Proactive and Reactive Multi-Project Scheduling in Uncertain Environment." *IEEE Access*, 7, 88986-88997.

Wiest, J. D. (1964). "Some properties of schedules for large projects with limited resources." *Operations research*, 12(3), 395-418.

Willis, R. J. (1985). "Critical path analysis and resource constrained project scheduling-Theory and practice." *Europeaa Journal of Operational Research*, 21, 149-155.

Wu, J., Lee, T., Tsai, C., Chang, T., and Tsai, S. "A fuzzy rule-based system for crew management of distribution systems in large-scale multiple outages." *Proc., 2004 International Conference on Power System Technology, 2004. PowerCon 2004.*, IEEE, 1084-1089.

Wysocki, R. K. (2019). *Effective Project Management: Traditional, Agile, Extreme, Hybrid*, John Wiley & Sons, Inc.

Yi, W., and Chan, A. P. (2014). "Critical review of labor productivity research in construction journals." *Journal of management in engineering*, 30(2), 214-225.

Zhong, Y., Chen, Z., Zhou, Z., and Hu, H. (2018). "Uncertainty Analysis and Resource Allocation in Construction Project Management." *Engineering Management Journal*, 30(4), 293-305.

Zhou, J., Love, P. E. D., Wang, X., Teo, K. L., and Irani, Z. (2017). "A review of methods and algorithms for optimizing construction scheduling." *Journal of the Operational Research Society*, 64(8), 1091-1105.

Zhu, G., Bard, J. F., and Yu, G. (2017). "Disruption management for resource-constrained project scheduling." *Journal of the Operational Research Society*, 56(4), 365-381.

APPENDIX A: PROJECTS DATA FOR CASE STUDIES

Standard Projects in Scrum Backlog (duration is in days)					
Index	Work Order	Description Location	Duration	Arrival Date	Deadline
1	204063	RSC 13540 126 St. NW	2	2022-03-17	2022-04-21
2	189545	RSC 14328 - 106 Ave. NW	2	2022-03-19	2022-04-23
3	206239	RSC 9237 - 86 St. NW	2	2022-03-19	2022-04-23
4	209566	SUB 12816 93 St. NW	3	2022-03-18	2022-04-22
5	199264	RSP 15216 98 Ave.	2	2022-03-20	2022-04-24
6	197817	RSC 7401A 151 St. NW	2	2022-03-17	2022-04-21
7	199383	RSC 9761 90 Ave. NW	3	2022-03-18	2022-04-22
8	199227	RSC 14011 120A St. NW	2	2022-03-18	2022-04-22
9	199366	RSC 11448 97 St. NW	2	2022-03-20	2022-04-24
10	199434	RSC 11444 97 St. NW	1	2022-03-19	2022-04-23
11	199006	RSC 12119 126 St. NW	1	2022-03-20	2022-04-24
12	198970	RSC 8143 79 Ave. NW	1	2022-03-18	2022-04-22
13	198380	RSC 9031 - 152 St. NW	2	2022-03-19	2022-04-23
14	199472	RSC 15800 - 93 Ave. NW	2	2022-03-18	2022-04-22
15	201406	RSC 7016 106 St. NW	2	2022-03-17	2022-04-21
16	201252	RSC 14016 91A Ave. NW	2	2022-03-18	2022-04-22
17	201511	9644 155 St. NW	2	2022-03-17	2022-04-21
18	201531	RSP 6327 105A St. NW	2	2022-03-18	2022-04-22
19	201530	RSC 7611 111 St. NW	2	2022-03-17	2022-04-21
20	201411	RSC 4010 112 Ave. NW	2	2022-03-18	2022-04-22
21	201610	RSC 8706 88 Ave. NW	2	2022-03-17	2022-04-21
22	201695	RSC 9319 91 St. NW	2	2022-03-20	2022-04-24
23	202033	RSC 15912 110B Ave. NW	2	2022-03-20	2022-04-24
24	202308	9807 88 Ave. NW	2	2022-03-19	2022-04-23
25	202057	RSC 9520 150 ST NW	2	2022-03-17	2022-04-21
26	202531	RSC 7916 132 Ave. NW	2	2022-03-17	2022-04-21
27	202585	RSC 7727 157 St. NW	2	2022-03-20	2022-04-24
28	191367	RSC 8829 92 St. NW	2	2022-03-18	2022-04-22
29	203213	RSC 16534 105A Ave. NW	3	2022-03-18	2022-04-22

Index	Work Order	Description Location	Duration	Arrival Date	Deadline
30	203283	RSC 8515 106A St. NW	1	2022-03-20	2022-04-24
31	203281	RSC 7503 155 St. NW	3	2022-03-17	2022-04-21
32	203341	RSC 9203 111 Ave. NW	2	2022-03-17	2022-04-21
33	203296	RSC 3020 116 St. NW	2	2022-03-18	2022-04-22
34	203689	RSC 14712 62 St. NW	2	2022-03-17	2022-04-21
35	203988	RSC 8411 175 St. NW	2	2022-03-17	2022-04-21
36	203688	RSC 8311 171 St. NW	2	2022-03-19	2022-04-23
37	203686	RSC 9015 156 St. NW	2	2022-03-17	2022-04-21
38	204061	RSC 15404 103 Ave. NW	2	2022-03-17	2022-04-21
39	204135	RSC 13416 127 St. NW	2	2022-03-19	2022-04-23
40	204096	RSC 6004 149 Ave. NW	2	2022-03-20	2022-04-24
41	204210	RSC 12908 135 Ave. NW	2	2022-03-17	2022-04-21
42	204445	RSC 9675 84 Ave. NW	1	2022-03-19	2022-04-23
43	204854	12211 134B Ave. NW	2	2022-03-19	2022-04-23
44	204877	RSC 9850 84 Ave. NW	1	2022-03-18	2022-04-22
45	205039	RSC 14631 SUMMIT DRIVE	2	2022-03-19	2022-04-23
46	205086	RSC 10719 135 St. NW	2	2022-03-18	2022-04-22
47	205001	RSC 9323 169 St. NW	2	2022-03-17	2022-04-21
48	205017	RSC 4234 112 Ave. NW	2	2022-03-17	2022-04-21
49	205574	RSC 14107 47 Ave. NW	3	2022-03-19	2022-04-23
50	205713	RSC 9667 75 Ave. NW	2	2022-03-20	2022-04-24
51	205714	RSC 9667 76 Ave. NW	2	2022-03-19	2022-04-23
52	205720	RSP 9736 73 Ave. NW	2	2022-03-20	2022-04-24

The following table depicts the prioritized projects records for the case study_01 section 5-2.

Prioritized Projects in Scrum Backlog (duration is in days)						
Id	Work Order	Description Location	Dur.	PI	Arrival Date	Deadline
1	201697	SUB 9927-51Ave. NW	1	886	2022-03-20	2022-04-30
2	202530	SUB 42ST 111Ave. NW	2	1028	2022-03-18	2022-04-28
3	203581	SUB CB 93 ST 150 Ave. NW	1	1015	2022-03-19	2022-04-29

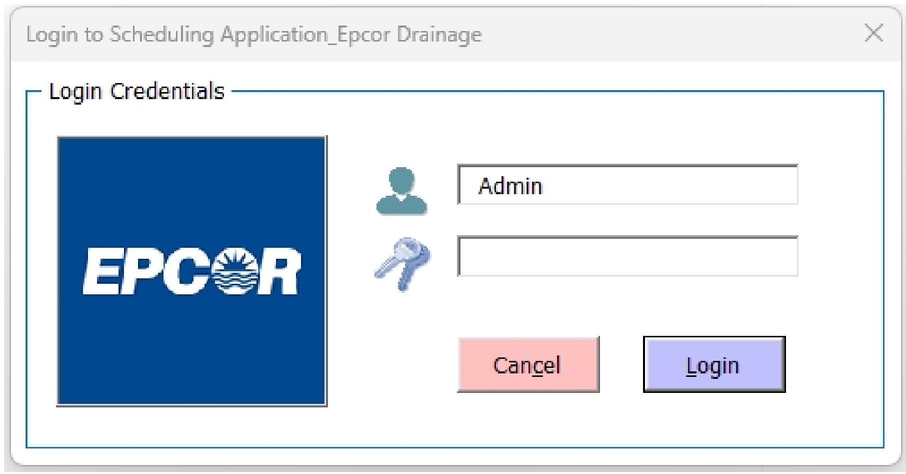
Id	Work Order	Description Location	Dur.	PI	Arrival Date	Deadline
5	203830	SUB 175 ST 87 Ave. NW	2	992	2022-03-18	2022-04-28
6	204371	SUB 109 St 99Ave. NW	3	962	2022-03-19	2022-04-29
7	204533	Replace 13712 56 St. NW	2	1020	2022-03-17	2022-04-27
8	202614	Replace MH 9720 45 Ave. NW	3	946	2022-03-17	2022-04-27
9	204796	SUB RINGS 8504 69 St. NW	2	959	2022-03-18	2022-04-28
10	204580	SUB MH 107 Ave. 149 St. NW	3	982	2022-03-22	2022-05-02
11	204743	Replace 11408 59 Ave. NW	2	1031	2022-03-19	2022-04-29
12	204359	Major Repair 3412 71St. NW	3	1071	2022-03-22	2022-05-02
13	205428	Partial Replace 14116 94 St	1	1155	2022-03-22	2022-05-02
14	205790	Replace MH 17928 92A St	1	1023	2022-03-18	2022-04-28
15	206925	156a Ave and 88 St	3	1056	2022-03-21	2022-05-01
16	209566	SUB 12816 93 St. NW	2	1003	2022-03-21	2022-05-01
17	210613	SUB Rpl. MH 10054 158 St.	1	943	2022-03-19	2022-04-29
18	201334	CB barrel 131 Ave - 125 St.	1	901	2022-03-21	2022-05-01
19	202084	CB BAR SUB 104 St - 82 Ave.	1	1106	2022-03-18	2022-04-28
20	203549	CBL/sub 10523 107 St.	2	994	2022-03-21	2022-05-01
21	204219	CB 12906 124 ST	1	968	2022-03-19	2022-04-29
22	204402	CI 58 Ave. & 103 A ST	2	1051	2022-03-17	2022-04-27
23	205078	SUB Repair Pipe 11601 96 ST	3	998	2022-03-22	2022-05-02
24	210815	RSC 13612 103 Ave	1	1009	2022-03-18	2022-04-28
25	216389	MH Barrell Rplc.13315 68 ST	1	946	2022-03-22	2022-05-02
26	217160	SUB Repair 13308 Delwood RD	1	1058	2022-03-20	2022-04-30
27	203014	SPOT REPAIR 11512 128 ST	2	940	2022-03-19	2022-04-29
28	204634	SPOT REPAIR 9816 156 ST	1	969	2022-03-19	2022-04-29
29	205444	SPOT Repair 114 Ave. 128 ST	3	931	2022-03-21	2022-05-01
30	201854	CUL 18621 122 Ave. NW	2	974	2022-03-17	2022-04-27
31	205767	134ave & 50st	3	987	2022-03-20	2022-04-30
32	205854	RSC 15942 110B Ave.	1	983	2022-03-17	2022-04-27
33	205768	RSC 9641 151 St.	3	962	2022-03-20	2022-04-30
34	205887	RSP STORM SRV 1215 70 Ave.	2	948	2022-03-21	2022-05-01
35	206134	RSC 16116 110B Ave.	1	1063	2022-03-18	2022-04-28
36	206225	RSC 7404 - 108 St. NW	1	1004	2022-03-19	2022-04-29
37	206236	RSC 7708 - 98A Ave. NW	1	962	2022-03-20	2022-04-30

Id	Work Order	Description Location	Dur.	PI	Arrival Date	Deadline
39	206265	RSC 8839 - 161 St. NW	2	1025	2022-03-22	2022-05-02
40	206266	RSC 4708 - 144 St. NW	1	1028	2022-03-23	2022-05-03
41	206271	RSC 9833 - 89 Ave. NW	2	983	2022-03-24	2022-05-04
42	206274	RSC 9736 - 150 St. NW	1	1010	2022-03-25	2022-05-05
43	206292	RSP 165 Galland Crescent	1	1086	2022-03-26	2022-05-06
44	206183	RSC 8125 112 St. NW	1	1010	2022-03-27	2022-05-07
45	206308	7611 119 Ave.	2	1013	2022-03-28	2022-05-08
46	205749	RSC 7715 158 ST	2	886	2022-03-29	2022-05-09
47	206454	RSC 9517 - 110 Ave. NW	2	998	2022-03-30	2022-05-10
48	206460	RSC 5307 - 109A Ave. NW	1	1094	2022-03-31	2022-05-11
49	206545	RSC 7611 - 152 St. NW	2	958	2022-03-17	2022-04-27
50	206548	RSC 3828 - 106 St. NW	1	1032	2022-03-17	2022-04-27
51	206865	RSC 7618 83 Ave. NW	1	926	2022-03-21	2022-05-01
52	206566	RSC 11037 85 Ave. NW	3	1062	2022-03-22	2022-05-02
53	206880	RSC 3912 116 ST NW	1	1001	2022-03-20	2022-04-30
54	206570	RSC 7926 106 St. NW	2	969	2022-03-22	2022-05-02
55	207291	RSC 3644 116 Ave.	3	940	2022-03-19	2022-04-29
56	206744	RSC 9220 79 St.	2	1046	2022-03-20	2022-04-30
57	207120	RSC 11115 62 Ave.	2	1003	2022-03-17	2022-04-27
58	207580	RSC 6611 123 St.	3	1027	2022-03-19	2022-04-29
59	207606	RSC 8712 163 St. NW	1	995	2022-03-19	2022-04-29
60	207744	RSC 13911 86 Ave.	2	979	2022-03-21	2022-05-01
61	208400	RSC Storm11345 126 St Cancell	2	800	2022-03-17	2022-04-27

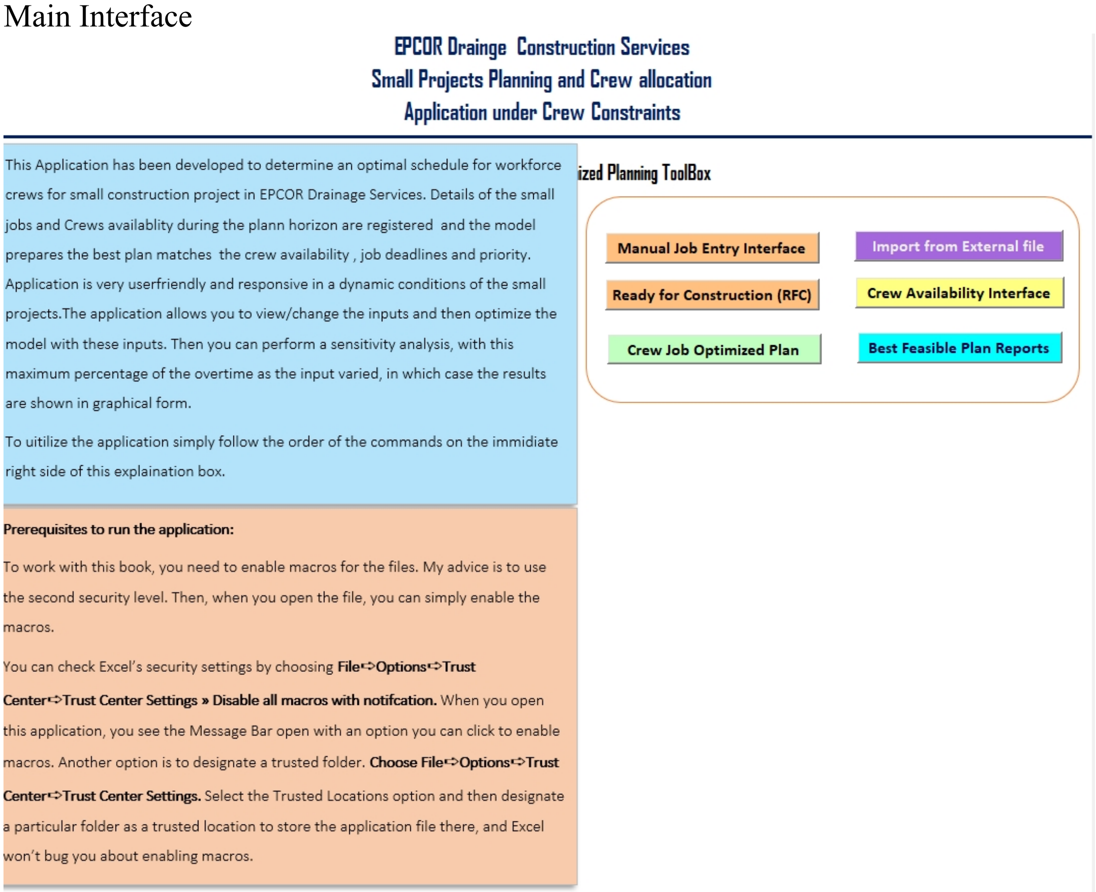
APPENDIX B. PROTYPED SYTEM_CODES AND FORMS

This appendix attaches some of the forms and code developed for the prototyped system

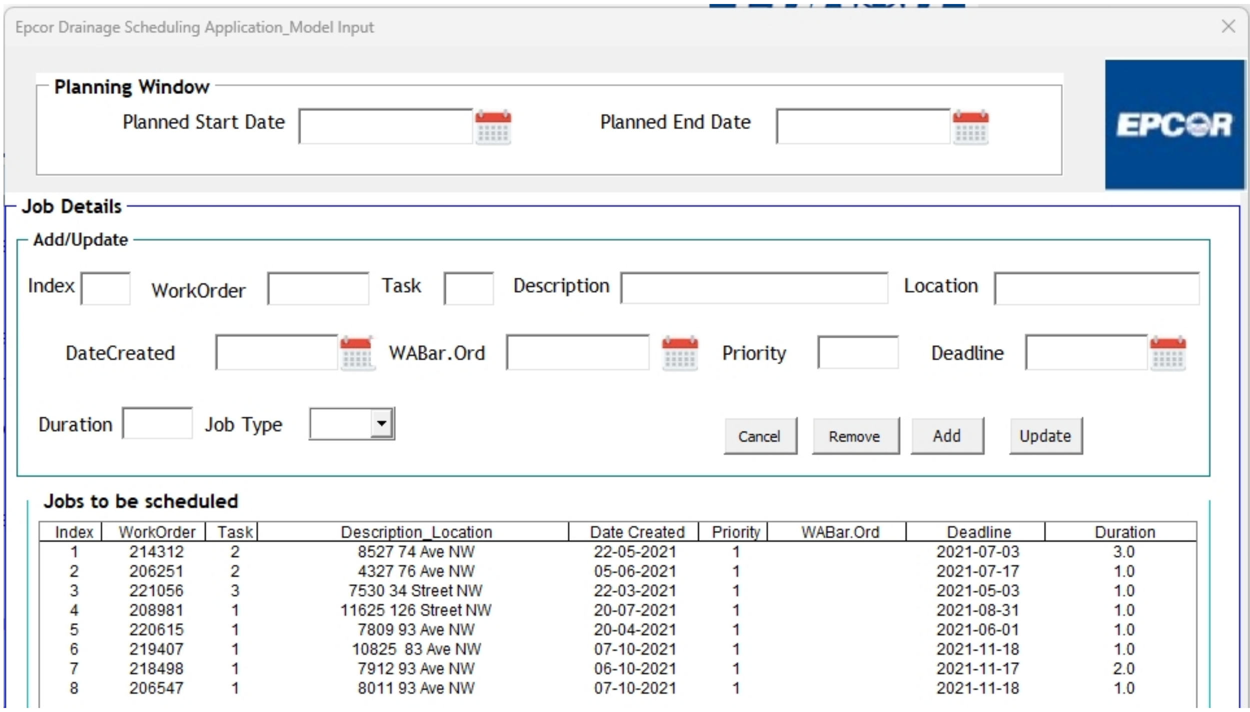
1. Login into:



2. Main Interface

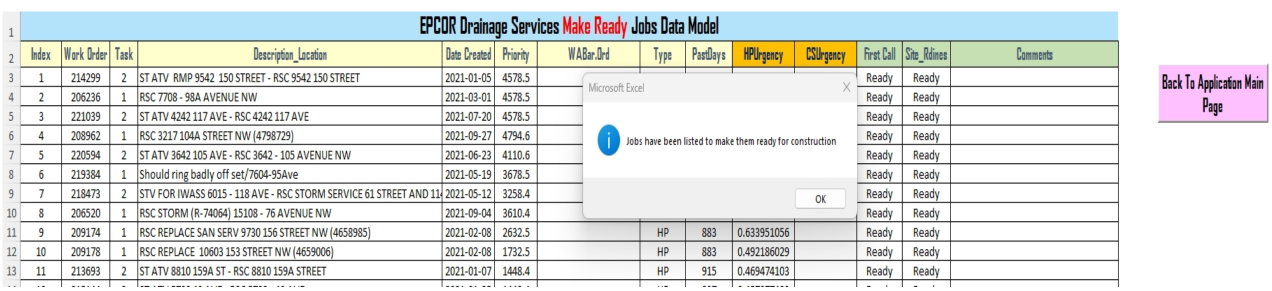


3. Manual Project Data Entry

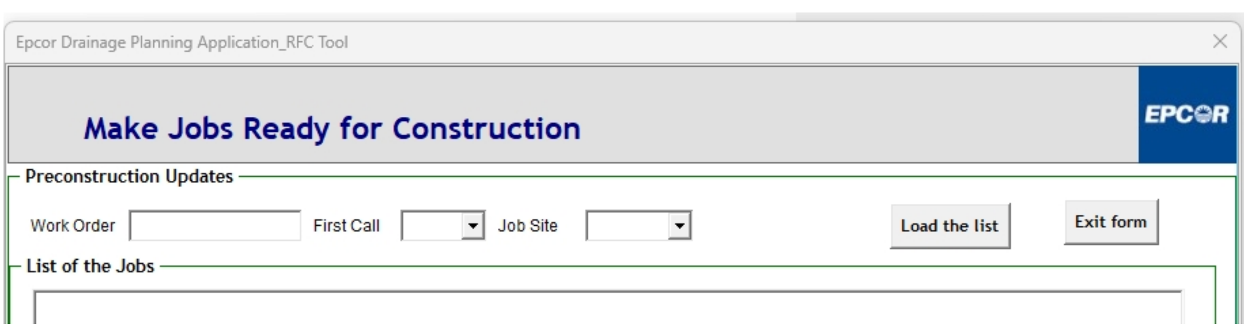


Index	WorkOrder	Task	Description_Location	Date Created	Priority	WABar.Ord	Deadline	Duration
1	214312	2	8527 74 Ave NW	22-05-2021	1		2021-07-03	3.0
2	206251	2	4327 76 Ave NW	05-06-2021	1		2021-07-17	1.0
3	221056	3	7530 34 Street NW	22-03-2021	1		2021-05-03	1.0
4	208981	1	11625 126 Street NW	20-07-2021	1		2021-08-31	1.0
5	220615	1	7809 93 Ave NW	20-04-2021	1		2021-06-01	1.0
6	219407	1	10825 83 Ave NW	07-10-2021	1		2021-11-18	1.0
7	218498	1	7912 93 Ave NW	06-10-2021	1		2021-11-17	2.0
8	206547	1	8011 93 Ave NW	07-10-2021	1		2021-11-18	1.0

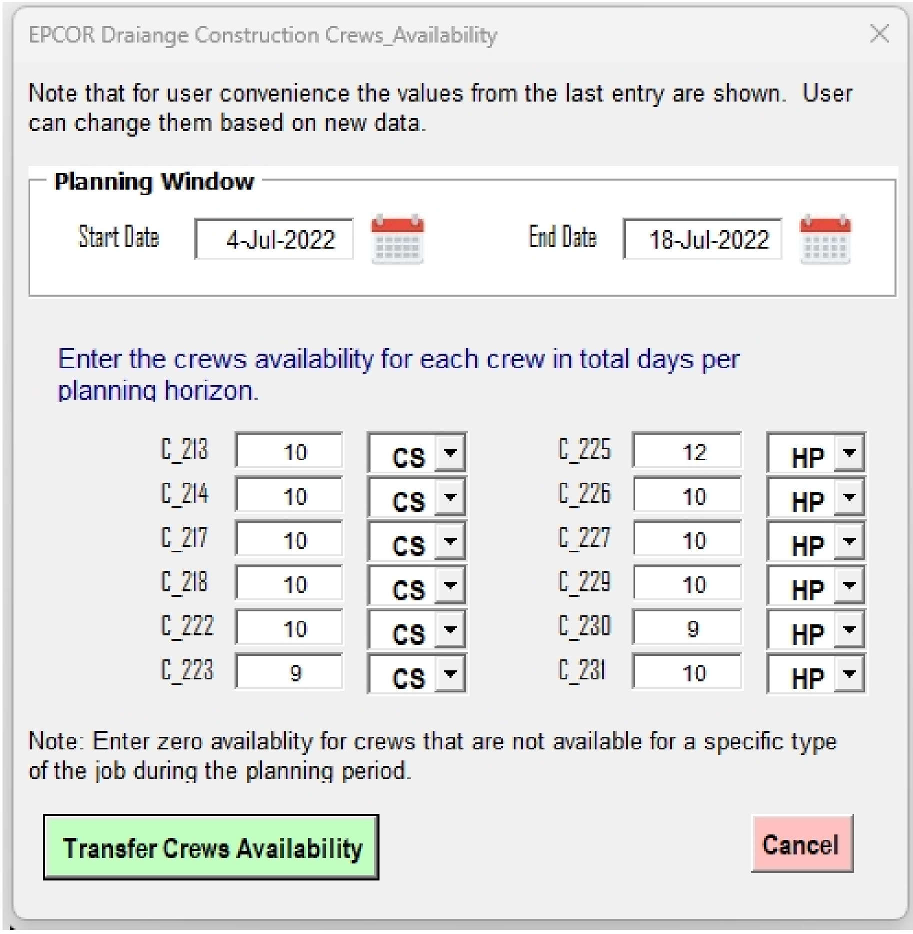
4. Make Ready for Construction Form

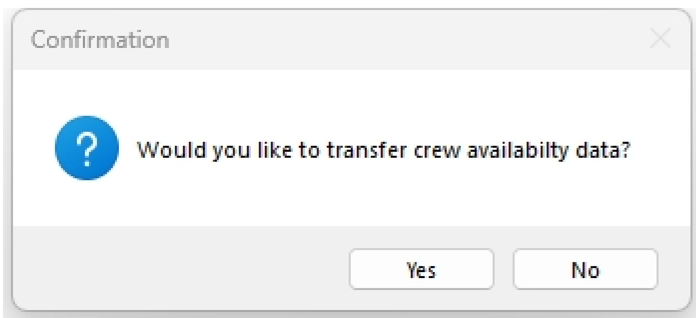


Index	Work Order	Task	Description_Location	Date Created	Priority	WABar.Ord	Type	PastDays	HPUrgency	CSUrgency	First Call	Site_Rdines	Comments
1	214299	2	ST ATV RMP 9542 150 STREET - RSC 9542 150 STREET	2021-01-05	4578.5						Ready	Ready	
2	206236	1	RSC 7708 - 98A AVENUE NW	2021-03-01	4578.5						Ready	Ready	
3	221039	2	ST ATV 4242 117 AVE - RSC 4242 117 AVE	2021-07-20	4578.5						Ready	Ready	
4	208962	1	RSC 3217 104A STREET NW (4798729)	2021-09-27	4794.6						Ready	Ready	
5	220594	2	ST ATV 3642 105 AVE - RSC 3642 - 105 AVENUE NW	2021-06-23	4110.6						Ready	Ready	
6	219384	1	Should ring badly off set/7604-95Ave	2021-05-19	3678.5						Ready	Ready	
7	218473	2	STV FOR IWASS 6015 - 118 AVE - RSC STORM SERVICE 61 STREET AND 11	2021-05-12	3258.4						Ready	Ready	
8	206520	1	RSC STORM (R-74064) 15108 - 76 AVENUE NW	2021-09-04	3610.4						Ready	Ready	
9	209174	1	RSC REPLACE SAN SERV 9730 156 STREET NW (4658985)	2021-02-08	2632.5		HP	883	0.633951056		Ready	Ready	
10	209178	1	RSC REPLACE 10603 153 STREET NW (4659006)	2021-02-08	1732.5		HP	883	0.492186029		Ready	Ready	
11	213693	2	ST ATV 8810 159A ST - RSC 8810 159A STREET	2021-01-07	1448.4		HP	915	0.469474103		Ready	Ready	

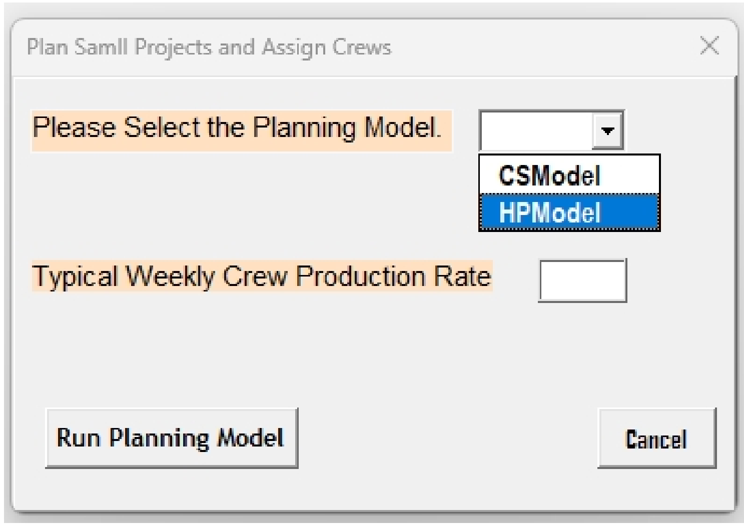


5. Crew Availability Interface and transferring confirmation





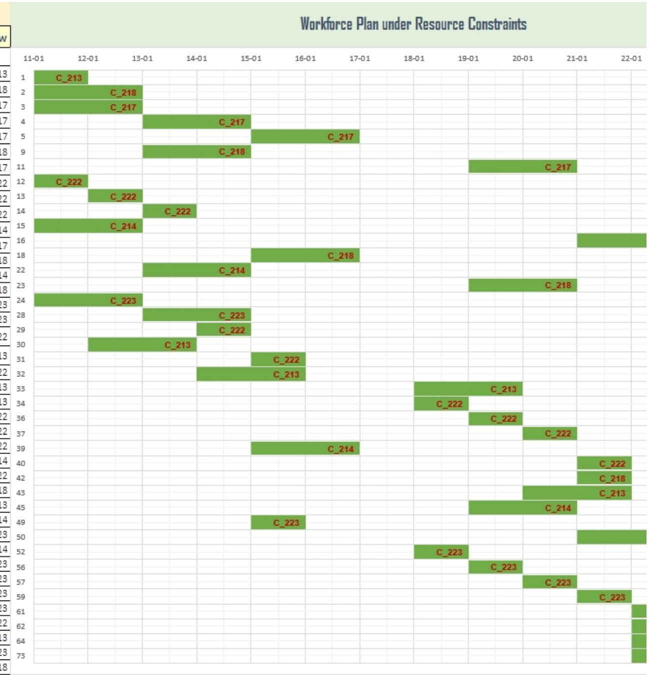
6. Selecting the model to run



7. Calendar Interface

8. One of the runs

Planning_Period: 11-01-2021 To 25-01-2021											
Index	WorkOrder	Task	Description_Location	Date Created	Priority	WABar.Ord	Deadline	Duration	StartDate	FinishDate	Crew
1	214312	2	8527 74 Ave NW	22-05-2021	1		03-07-2021	1	11-01-2021	12-01-2021	C_213
2	206251	2	4327 76 Ave NW	05-06-2021	1		17-07-2021	2	11-01-2021	13-01-2021	C_218
3	221056	3	7530 34 Street NW	22-03-2021	1		03-05-2021	2	11-01-2021	13-01-2021	C_217
4	208981	1	11625 126 Street NW	20-07-2021	1		31-08-2021	2	13-01-2021	15-01-2021	C_217
5	220615	1	7809 93 Ave NW	20-04-2021	1		01-06-2021	2	15-01-2021	19-01-2021	C_217
9	214764	1	REPLACE CBL 9108 75 STREET	13-01-2021	1		24-02-2021	2	13-01-2021	15-01-2021	C_218
11	214826	1	REPLACE CBL 77 STREET AND 94 AVE	14-01-2021	1		25-02-2021	2	19-01-2021	21-01-2021	C_217
12	215052	2	ST ATV 5308 141 ST - RSC 5308 - 141 STREET NW	21-01-2021	1		04-03-2021	1	11-01-2021	12-01-2021	C_222
13	215274	2	STV CBL 81 ST 82 AVE - REPLACE CBL 81 ST 82 AVE	28-01-2021	1		11-03-2021	1	12-01-2021	13-01-2021	C_222
14	215475	1	CB BARREL REPLACEMENT 12104-128AVE	05-02-2021	1		19-03-2021	1	13-01-2021	14-01-2021	C_222
15	216389	1	MH BARREL REPLACEMENT 13315 68 ST	07-03-2021	1		18-04-2021	2	11-01-2021	13-01-2021	C_214
16	216990	3	SUB *ER* 2112 40 ST - SUB REPAIR 2112 40 ST	22-03-2021	1		03-05-2021	2	21-01-2021	25-01-2021	C_217
18	219032	3	SUB *ER* 82 AVE 85 ST - REPLACE CB LEAD 82 AVE 85 S	10-05-2021	1	10-05-2010	21-06-2021	2	15-01-2021	19-01-2021	C_218
22	219382	1	Big crack in barrel/Hooke Rd & Victoria Trail	19-05-2021	1		30-06-2021	2	13-01-2021	15-01-2021	C_214
23	219526	2	(8528 82 AVE- MH243182-CB243182-CBL3840) - REPAIR	22-05-2021	1		03-07-2021	2	19-01-2021	21-01-2021	C_218
24	219799	3	SUB *ER* 16725 STONY PLAIN RD - SUB REBUILD CBMH	01-06-2021	1	01-06-2021	13-07-2021	2	11-01-2021	13-01-2021	C_223
28	220599	2	ROF 11708 135B ST SUBSIDENCE - SUB REPLACE CB 117	23-06-2021	1	23-06-2021	04-08-2021	2	13-01-2021	15-01-2021	C_223
29	220634	3	SUB *ER* 304 WARWICK CRES - SUB REPAIR CB LEAD 30	24-06-2021	1	24-06-2021	05-08-2021	1	14-01-2021	15-01-2021	C_222
30	220633	2	NWC OF 119 AVE 128 ST SUBSIDENCE - SUB REPAIR CB	24-06-2021	1		05-08-2021	2	12-01-2021	14-01-2021	C_213
31	205711	2	SUB STEEL PLATE ALLEY 14716 88 AVE - SUB REPLACE (	26-06-2021	1		07-08-2021	1	15-01-2021	18-01-2021	C_222
32	217331	3	SUB *ER* 9908 77 AVE - SUB SPOT REPAIR 9908 77 AVI	30-06-2021	1	30-03-2021	11-08-2021	2	14-01-2021	18-01-2021	C_213
33	217335	2	SUB Whitemud 53ave Facility replacement - SUB Rep	30-06-2021	1	31-03-2021	11-08-2021	2	18-01-2021	20-01-2021	C_213
34	217254	3	SUB *ER* 2620 135 AVE - SUB Replace Barrel 2620 135	30-06-2021	1		11-08-2021	1	18-01-2021	19-01-2021	C_222
36	220886	3	SUB *ER* 10502 84 ST - SUB REPLACE CB 10502 84 ST	02-07-2021	1	02-07-2021	13-08-2021	1	19-01-2021	20-01-2021	C_222
37	221059	1	10511 - 69 Avenue	09-07-2021	1		20-08-2021	1	20-01-2021	21-01-2021	C_222
39	216327	3	SUB *ER* 139 AVE 51 ST - SUB REPLACE CB 139 AVE 51	14-07-2021	1	04-03-2021	25-08-2021	2	15-01-2021	19-01-2021	C_214
40	218480	3	SUB *ER* 7604 DELWOOD RD - SUB Replace rings, lead	14-07-2021	1	27-04-2021	25-08-2021	1	21-01-2021	22-01-2021	C_222
42	217981	3	SUB - CB #7 (357 LEE RIDGE RD) - SUB Replace MH Ba	17-07-2021	1	19-04-2021	28-08-2021	1	21-01-2021	22-01-2021	C_218
43	221460	1	11332 - 79 Avenue	20-07-2021	1		31-08-2021	2	20-01-2021	22-01-2021	C_213
45	221462	1	21805 - 91A Avenue	20-07-2021	1		31-08-2021	2	19-01-2021	21-01-2021	C_214
49	221466	1	9522 - 90 Street	20-07-2021	1		31-08-2021	1	15-01-2021	18-01-2021	C_223
50	221465	1	14333 - 47 Avenue	20-07-2021	1		31-08-2021	2	21-01-2021	25-01-2021	C_214
52	216771	2	SUB/BROKEN BARREL 17820 93 ST - SUB Replace Barrel/	21-07-2021	1	16-03-2021	01-09-2021	1	18-01-2021	19-01-2021	C_223
56	221559	1	9839 - 67 Avenue	22-07-2021	1		02-09-2021	1	19-01-2021	20-01-2021	C_223
57	208022	1	REPLACE CBL 98 AVE 180 ST	15-08-2021	1		26-09-2021	1	20-01-2021	21-01-2021	C_223
59	210205	1	CULVERT REPLACEMENT 13500 156ST	06-10-2021	1		17-11-2021	1	21-01-2021	22-01-2021	C_223
61	210206	1	CULVERT REPLACEMENT 13500 156ST	06-10-2021	1		17-11-2021	1	22-01-2021	25-01-2021	C_222
62	210196	1	CULVERT REPLACEMENT 131AVE 159ST	06-10-2021	1		17-11-2021	1	22-01-2021	25-01-2021	C_213
64	210225	1	CULVERT REPLACEMENT 131AVE 159ST	07-10-2021	1		18-11-2021	1	22-01-2021	25-01-2021	C_223
73	208395	2	MTV 10345 104 ST - SPOT REPAIR 10345 104 ST	29-10-2021	1		10-12-2021	1	22-01-2021	25-01-2021	C_218



Case of planning HP projects

Epcor Drainage Construction_HP Jobs Plan			
CrewID	Availability	Capacity	Assigned Jobs
C_213	0	0	0
C_214	0	0	0
C_217	0	0	0
C_218	0	0	0
C_222	0	0	0
C_223	0	0	0
C_225	10	6	6
C_226	10	6	6
C_227	10	6	6
C_229	10	6	6
C_230	10	6	6
C_231	10	6	6

HP Jobs Planned.Count	36
HP Jobs.Count	103

Crew Allocation Map Plan

Main Application

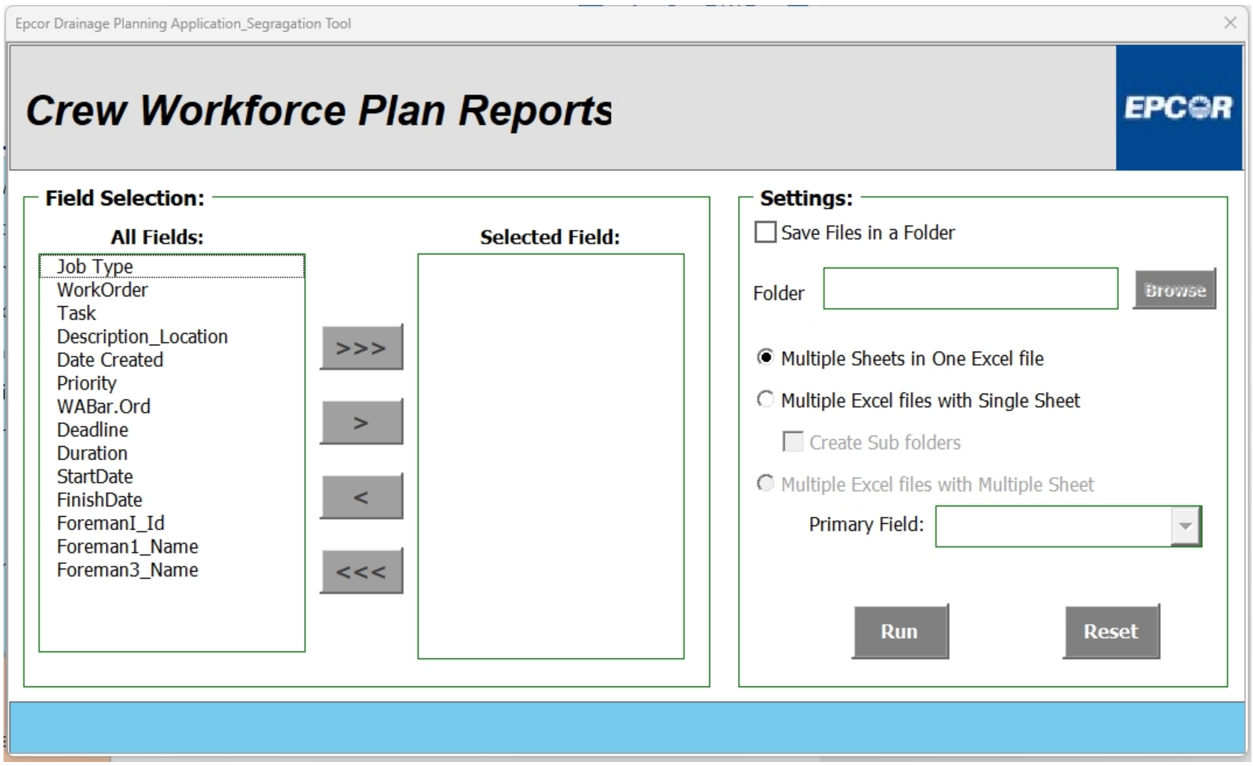
Planning_Period: 11-01-2021 To 25-01-2021								
Index	WorkOrder	Task	Description_Location	Date Created	Priority	WABar.Ord	PastDays	Crew
1	214299	2	ST ATV RMP 9542 150 STREET - RSC 9542 150 STREET	05-01-2021	4578.5		917	C_229
2	206236	1	RSC 7708 - 98A AVENUE NW	01-03-2021	4578.5		862	C_229
3	221039	2	ST ATV 4242 117 AVE - RSC 4242 117 AVE	20-07-2021	4578.5		721	C_229
4	208962	1	RSC 3217 104A STREET NW (4798729)	27-09-2021	4794.6		652	C_229
5	220594	2	ST ATV 3642 105 AVE - RSC 3642 - 105 AVENUE NW					C_227
6	219384	1	Should ring badly off set/7604-95Ave					C_227
7	218473	2	STV FOR IWASS 6015 - 118 AVE - RSC STORM SERVICE 61 STREET AND 11					C_229
8	206520	1	RSC STORM (R-74064) 15108 - 76 AVENUE NW					C_227
9	209174	1	RSC REPLACE SAN SERV 9730 156 STREET NW (4658985)					C_227
10	209178	1	RSC REPLACE 10603 153 STREET NW (4659006)					C_227
11	213693	2	ST ATV 8810 159A ST - RSC 8810 159A STREET					C_226
12	215144	2	ST ATV 5708 40 AVE - RSC 5708 - 40 AVE					C_230
13	215277	2	ST STV 10744 68 AVE - RSC 10744 - 68 AVENUE NW	28-01-2021	1448.4		894	C_230
14	215317	2	ST ATV 10311 163 ST - RSC 10311 - 163 STREET NW	29-01-2021	1448.4		893	C_230
15	206521	1	RSC 10924 - 38 AVENUE NW	04-04-2021	1732.5		828	C_230
16	216131	2	ST ATV 9123 141 ST - RSC 9123 - 141 STREET NW	26-02-2021	1448.4		865	C_226
17	214760	2	ST ATV 11542 123 ST - RSC 11542 123 STREET	13-01-2021	1232.4		909	C_230
18	215348	3	ST ATV 10924 130 ST - RSC 10924 130 STREET	15-03-2021	1448.4		848	C_231
19	216597	3	ST ATV 8204 145 ST - RSC 8204 145 STREET	16-03-2021	1448.4		847	C_231
20	195803	3	STV ATV 11411 79 AVENUE NW - RSC 11411 79 AVENUE	30-01-2021	1232.4		892	C_230
21	206268	1	RSC 10727 - 76 AVENUE NW	21-01-2021	1048.5		901	C_227
22	209168	1	PARTIAL REPLACE SAN SRV 10727 133 STREET NW (4652432)	25-01-2021	1048.5		897	C_231
27	199472	2	ST ATV 15800 93 AVENUE NW $ - RSC 15800 - 93 AVE	18-02-2021	1048.5		873	C_231
28	197641	2	ST ATV 10974 116 STREET NW - RSC 10974 116 STREET NW	08-01-2021	832.5		914	C_231
30	196744	1	RSC 11524 - 72 AVENUE NW	02-03-2021	1048.5		861	C_226
39	206466	1	RSC 15022 - 86 AVENUE NW	22-01-2021	548.4		900	C_229
40	212972	3	ST ATV 11457 78 AVE - RSC 11457 78 AVE	23-01-2021	548.4		899	C_226
43	214758	2	ST ATV 11735 122 ST - RSC 11735 - 122 STREET NW	13-01-2021	458.3		909	C_226
48	206454	1	RSC 9517 - 110 AVENUE NW	25-01-2021	480.4		897	C_226
53	197715	2	ST ATV 13348 109A AVENUE NW - RSC 13348 109A AVE NW	09-01-2021	390.3		913	C_231
57	213779	2	ST ATV 7760 110 ST - RSC 7760 110 STREET	07-01-2021	332.4		915	C_225
58	213923	2	ST ATV 3135 74 ST - RSC 3135 74 STREET	08-01-2021	332.4		914	C_225
59	214560	2	ST ATV 18208 80A AVE - RSC 18208 - 80A AVENUE NW	10-01-2021	332.4		912	C_225
65	206266	1	RSC 4708 - 144 STREET NW	15-01-2021	332.4		907	C_225
73	214058	2	ST ATV 16805 95 AVENUE NW - RSC 16805 95 AVE NW	08-01-2021	264.4		914	C_225
88	206465	1	RSC 10736 - 65 AVENUE NW	02-01-2021	174.3		920	C_225

Microsoft Excel

The model took 21.23 Seconds to run.

OK

9. Plan Reports Interface: selecting and reporting as batch or single sheets



VBA Code

Main Module

```
Option Explicit
Sub Main()
' Turn off calculations, events etc.
   Dim settings As New clsExcelSettings
   settings.TurnOff
   Prarr() = wsGM.Range(wsGM.Cells(Str, di), wsGM.Cells(Str, NPli).End(xlDown)).Value
   'find number of projects, number of crews, number of intervals
   Np = UBound(Prarr, 1): Nc = 3: Nt = 7
  Call  rgNames
   DefineModel_1
   Call PrepData
   DefineModel_2
      ''''''''''''''''''''''''''''''''''''''''''''
prob.Solver.SolverType= Solver_Type_Maximize
      ActiveSheet.Names.Add "solver_eng", 0, False
```

Excel Settings Module

```
Option Explicit
Private calculation As XlCalculation
Private displayStatus As Boolean
Private enableEvents As Boolean
Private screenUpdating As Boolean
' Procedure : TurnOffFunctionality
' Purpose   : Backup Current settings
' https://excelmacromastery.com/
Public Sub Backup()
   calculation = Application.calculation
   displayStatus = Application.DisplayStatusBar
   enableEvents = Application.enableEvents
   screenUpdating = Application.screenUpdating
End Sub
' Procedure : TurnOffFunctionality
' Purpose   : Backup Current settings
' https://excelmacromastery.com/
Public Sub Restore()
```

```
    On Error GoTo 0
'    ' and solve...
    prob.Solver.Optimize Solve_Type_Solve
Loop While Range("P15").Value > 5
' Turn off calculations, events etc.
  settings.Restore
End Sub
--------------------------------------------
```

```
  Application.calculation = calculation
  Application.DisplayStatusBar = 
displayStatus
  Application.enableEvents = enableEvents
  Application.screenUpdating = 
screenUpdating
End Sub
' Purpose   : Turn off automatic calculations, events and screen updating
' https://excelmacromastery.com/
Public Sub TurnOff()
 Call Backup

  Application.calculation = 
xlCalculationManual
  Application.DisplayStatusBar = False
  Application.enableEvents = False
  Application.screenUpdating = False
End Sub
' Purpose : turn on automatic calculations, events and screen updating
Public Sub TurnOn()
```

```
    Application.calculation                    =
xlCalculationAutomatic
    Application.DisplayStatusBar = True
    Application.enableEvents = True
    Application.screenUpdating = True
End Sub
Sub DefineModel_1()

'create a new problem

Set prob = Nothing
 prob.Init wsGM
   prob.Variables.Clear
prob.Functions.Clear
prob.Model.Params("OperatingMode").Value
= 0

'add objective to the model
        Dim objective As New RSP.Function
        objective.Init Range("BB2")
        objective.FunctionType                    =
Function_Type_Objective
```

```
prob.Functions.Add objective

'defines and adds variables
Dim var1 As New RSP.Variable
var1.Init Range("Yij").Address
var1.VariableType =
Variable_Type_Decision
var1.IntegerType.Array =
Integer_Type_Binary
prob.Variables.Add var1

Dim var2 As New RSP.Variable
var2.Init Range("Xi1t").Address
var2.VariableType =
Variable_Type_Decision
var2.IntegerType.Array =
Integer_Type_Binary
prob.Variables.Add var2

Dim var3 As New RSP.Variable
var3.Init Range("Xi2t").Address
```

```
    var3.VariableType                =
Variable_Type_Decision
    var3.IntegerType.Array           =
Integer_Type_Binary
    prob.Variables.Add var3

    Dim var4 As New RSP.Variable
    var4.Init Range("Xi3t").Address
    var4.VariableType                =
Variable_Type_Decision
    var4.IntegerType.Array           =
Integer_Type_Binary
    prob.Variables.Add var4

    Dim var5 As New RSP.Variable
    var5.Init Range("Zikj").Address
    var5.VariableType                =
Variable_Type_Decision
    var5.IntegerType.Array           =
Integer_Type_Binary
    prob.Variables.Add var5
```

```
        Dim var6 As New RSP.Variable
        var6.Init Range("St").Address
        var6.VariableType                        =
Variable_Type_Decision
        var6.IntegerType.Array                   =
Integer_Type_Integer
        var6.NonNegative
        prob.Variables.Add var6

        Dim var7 As New RSP.Variable
        var7.Init Range("Ti").Address
        var7.VariableType                        =
Variable_Type_Decision
        var7.IntegerType.Array                   =
Integer_Type_Integer
        prob.Variables.Add var7

        Dim var8 As New RSP.Variable
        var8.Init Range("Vi").Address
        var8.VariableType                        =
Variable_Type_Decision
```

```
    var8.IntegerType.Array                    =
Integer_Type_Binary
    prob.Variables.Add var8

End Sub

Sub DefineModel_2()

'       Add constraints
    Dim fcn1 As New RSP.Function
    fcn1.Init Range("Util.1").Address
    fcn1.FunctionType                         =
Function_Type_Constraint
    fcn1.Relation                  Cons_Rel_EQ,
Range("Cap.1").Address
    prob.Functions.Add fcn1

    Dim fcn2 As New RSP.Function
    fcn2.Init Range("Util.2").Address
    fcn2.FunctionType                         =
Function_Type_Constraint
```

```
    fcn2.Relation                    Cons_Rel_EQ,
Range("Cap.2").Address
    prob.Functions.Add fcn2

    Dim fcn3 As New RSP.Function
    fcn3.Init Range("Util.3").Address
    fcn3.FunctionType                                =
Function_Type_Constraint
    fcn3.Relation                    Cons_Rel_EQ,
Range("Cap.3").Address
    prob.Functions.Add fcn3

    Dim fcn4 As New RSP.Function
    fcn4.Init Range("LHS.7").Address
    fcn4.FunctionType                                =
Function_Type_Constraint
    fcn4.Relation Cons_Rel_LE, 1
    prob.Functions.Add fcn4

    Dim fcn5 As New RSP.Function
    fcn5.Init Range("LHS.8.1").Address
```

```
    fcn5.FunctionType                   =
Function_Type_Constraint
    fcn5.Relation               Cons_Rel_EQ,
Range("RHS.8.1").Address
    prob.Functions.Add fcn5

    Dim fcn6 As New RSP.Function
    fcn6.Init Range("LHS.8.2").Address
    fcn6.FunctionType                   =
Function_Type_Constraint
    fcn6.Relation               Cons_Rel_EQ,
Range("RHS.8.2").Address
    prob.Functions.Add fcn6

    Dim fcn7 As New RSP.Function
    fcn7.Init Range("LHS.8.3").Address
    fcn7.FunctionType                   =
Function_Type_Constraint
    fcn7.Relation               Cons_Rel_EQ,
Range("RHS.8.3").Address
    prob.Functions.Add fcn7
```

```
Dim fcn8 As New RSP.Function
fcn8.Init Range("LHS_112").Address
fcn8.FunctionType =
Function_Type_Constraint
fcn8.Relation Cons_Rel_LE,
Range("RHS_11").Address
prob.Functions.Add fcn8

Dim fcn9 As New RSP.Function
fcn9.Init Range("LHS_112").Address
fcn9.FunctionType =
Function_Type_Constraint
fcn9.Relation Cons_Rel_GE,
Range("RHS_12").Address
prob.Functions.Add fcn9

Dim fcn10 As New RSP.Function
fcn10.Init Range("LHS_13").Address
fcn10.FunctionType =
Function_Type_Constraint
fcn10.Relation Cons_Rel_GE, 3
prob.Functions.Add fcn10
```

```
    Dim fcn11 As New RSP.Function
    fcn11.Init Range("LHS_145").Address
    fcn11.FunctionType                    =
Function_Type_Constraint
    fcn11.Relation              Cons_Rel_LE,
Range("RHS_14").Address
    prob.Functions.Add fcn11


    Dim fcn12 As New RSP.Function
    fcn12.Init Range("LHS_145").Address
    fcn12.FunctionType                    =
Function_Type_Constraint
    fcn12.Relation              Cons_Rel_LE,
Range("RHS_15").Address
    prob.Functions.Add fcn12
End Sub




Const msg_title = "EPCOR Darinage Construction Calendar"
```

```
Option Explicit

 Private Sub CmbMonth_Change()

If Me.CmbMonth.Value <> "" And Me.CmbYear.Value <> "" Then

    Call Show_Dates

    Me.lblSelectedMonth = Me.CmbMonth & "-" & Me.CmbYear

End If

End Sub

Private Sub CmbYear_Change()

    If Me.CmbMonth.Value <> "" And Me.CmbYear.Value <> "" Then

        Call Show_Dates

        Me.lblSelectedMonth = Me.CmbMonth & "-" & Me.CmbYear

    End If

End Sub

Sub ButtonClick(btn As MSForms.CommandButton)

    With btn

        If .Caption <> "" Then

            Me.TextBox1.Value = .Caption & "-" & Left(Me.CmbMonth.Value, 3) & "-" &
Me.CmbYear.Value
```

```
      If Me.TextBox2.Value = "1" Then   ''' Add date to selected range on worksheet
        If Selection Is Nothing Then
          MsgBox "No selection found", vbCritical, msg_title
          Exit Sub
        End If
        '''' Check Protection
        If ActiveSheet.ProtectContents = True Then
          MsgBox "Worksheet is Protected", vbCritical, msg_title
          Exit Sub
        End If
        Selection.Value = Me.TextBox1.Value
      End If
      Unload Me
    End If
  End With
```

```
End Sub

Private Sub CommandButton1_Click()

    Call ButtonClick(Me.CommandButton1)

End Sub

Private Sub CommandButton2_Click()

    Call ButtonClick(Me.CommandButton2)

End Sub

Private Sub CommandButton3_Click()

    Call ButtonClick(Me.CommandButton3)

End Sub

Private Sub CommandButton4_Click()

    Call ButtonClick(Me.CommandButton4)

End Sub

Private Sub CommandButton5_Click()

    Call ButtonClick(Me.CommandButton5)

End Sub

Private Sub CommandButton6_Click()
```

```
    Call ButtonClick(Me.CommandButton6)
End Sub
Private Sub CommandButton7_Click()
    Call ButtonClick(Me.CommandButton7)
End Sub
Private Sub CommandButton8_Click()
    Call ButtonClick(Me.CommandButton8)
End Sub
Private Sub CommandButton9_Click()
    Call ButtonClick(Me.CommandButton9)
End Sub
Private Sub CommandButton10_Click()
    Call ButtonClick(Me.CommandButton10)
End Sub
Private Sub CommandButton11_Click()
    Call ButtonClick(Me.CommandButton11)
End Sub
```

```
Private Sub CommandButton12_Click()

   Call ButtonClick(Me.CommandButton12)

End Sub

Private Sub CommandButton13_Click()

   Call ButtonClick(Me.CommandButton13)

End Sub

Private Sub CommandButton14_Click()

   Call ButtonClick(Me.CommandButton14)

End Sub

Private Sub CommandButton15_Click()

   Call ButtonClick(Me.CommandButton15)

End Sub

Private Sub CommandButton16_Click()

   Call ButtonClick(Me.CommandButton16)

End Sub

Private Sub CommandButton17_Click()

   Call ButtonClick(Me.CommandButton17)
```

```
End Sub

Private Sub CommandButton18_Click()

   Call ButtonClick(Me.CommandButton18)

End Sub

Private Sub CommandButton19_Click()

   Call ButtonClick(Me.CommandButton19)

End Sub

Private Sub CommandButton20_Click()

   Call ButtonClick(Me.CommandButton20)

End Sub

Private Sub CommandButton21_Click()

   Call ButtonClick(Me.CommandButton21)

End Sub

Private Sub CommandButton22_Click()

   Call ButtonClick(Me.CommandButton22)

End Sub

Private Sub CommandButton23_Click()
```

```
    Call ButtonClick(Me.CommandButton23)
End Sub
Private Sub CommandButton24_Click()
    Call ButtonClick(Me.CommandButton24)
End Sub
Private Sub CommandButton25_Click()
    Call ButtonClick(Me.CommandButton25)
End Sub
Private Sub CommandButton26_Click()
    Call ButtonClick(Me.CommandButton26)
End Sub
Private Sub CommandButton27_Click()
    Call ButtonClick(Me.CommandButton27)
End Sub
Private Sub CommandButton28_Click()
    Call ButtonClick(Me.CommandButton28)
End Sub
```

```
Private Sub CommandButton29_Click()

    Call ButtonClick(Me.CommandButton29)

End Sub

Private Sub CommandButton30_Click()

    Call ButtonClick(Me.CommandButton30)

End Sub

Private Sub CommandButton31_Click()

    Call ButtonClick(Me.CommandButton31)

End Sub

Private Sub CommandButton32_Click()

    Call ButtonClick(Me.CommandButton32)

End Sub

Private Sub CommandButton33_Click()

    Call ButtonClick(Me.CommandButton33)

End Sub

Private Sub CommandButton34_Click()

    Call ButtonClick(Me.CommandButton34)
```

```
End Sub

Private Sub CommandButton35_Click()

    Call ButtonClick(Me.CommandButton35)

End Sub

Private Sub CommandButton36_Click()

    Call ButtonClick(Me.CommandButton36)

End Sub

Private Sub CommandButton37_Click()

    Call ButtonClick(Me.CommandButton37)

End Sub

Private Sub CommandButton38_Click()

    Call ButtonClick(Me.CommandButton38)

End Sub

Private Sub CommandButton39_Click()

    Call ButtonClick(Me.CommandButton39)

End Sub

Private Sub CommandButton40_Click()
```

```
    Call ButtonClick(Me.CommandButton40)
End Sub
Private Sub CommandButton41_Click()
    Call ButtonClick(Me.CommandButton41)
End Sub
Private Sub CommandButton42_Click()
    Call ButtonClick(Me.CommandButton42)
End Sub


Private Sub img_Next_Click()
    On Error Resume Next
    If Me.CmbMonth.ListIndex = 11 Then
        Me.CmbMonth.ListIndex = 0
        Me.CmbYear.Value = Me.CmbYear.Value + 1
    Else
        Me.CmbMonth.ListIndex = Me.CmbMonth.ListIndex + 1
    End If
```

```
End Sub


Private Sub img_previous_Click()
    On Error Resume Next
    If Me.CmbMonth.ListIndex = 0 Then
        Me.CmbMonth.ListIndex = 11
        Me.CmbYear.Value = Me.CmbYear.Value - 1
    Else
        Me.CmbMonth.ListIndex = Me.CmbMonth.ListIndex - 1
    End If
End Sub


Private Sub UserForm_Activate()


Dim i As Integer
Dim Year_Start, Year_End As Integer
```

```
'================= Add Months to List ==============

With Me.CmbMonth

    .Clear

    For i = 1 To 12

        .AddItem VBA.Format(VBA.DateSerial(2018, i, 1), "MMMM")

    Next i



    .Value = VBA.Format(VBA.Date, "MMMM")

End With



'================ Add Years ========================



  Year_Start = VBA.Year(VBA.Date) - 80

  Year_End = VBA.Year(VBA.Date) + 50



With Me.CmbYear

    .Clear
```

```
    For i = Year_Start To Year_End
        .AddItem i
    Next i
    .Value = VBA.Format(VBA.Date, "YYYY")
End With
Call Show_Dates
If Me.TextBox1.Value <> "" Then
    Call Show_Selected_Date(CDate(Me.TextBox1.Value))
End If
If Me.TextBox2.Value = "1" Then
    Call Show_Selected_Date(VBA.Date)
End If
End Sub


Private Sub Show_Dates()
    Dim first_Date As Date
    first_Date = VBA.DateValue("1-" & Me.CmbMonth.Value & "-" & Me.CmbYear.Value)
```

```
    Dim last_day As Integer
    last_day = VBA.day(VBA.DateSerial(VBA.Year(first_Date), VBA.Month(first_Date) + 1, 1) -
1)
     Dim i As Integer
    Dim btn As CommandButton


    '============ Clear All button
    For i = 1 To 42
        Set btn = Me.Controls("CommandButton" & i)
        btn.Caption = ""
    Next i
    '====================
    For i = 1 To 7   'Set first date of month
        Set btn = Me.Controls("CommandButton" & i)


        If VBA.Weekday(first_Date) = i Then
            btn.Caption = "1"
        Else
```

```
        btn.Caption = ""
      End If
    Next i
    Dim btn1 As CommandButton
    Dim btn2 As CommandButton
    For i = 1 To 41
      Set btn1 = Me.Controls("CommandButton" & i)
      Set btn2 = Me.Controls("CommandButton" & i + 1)
      If btn1.Caption <> "" Then
        If last_day > btn1.Caption Then
          btn2.Caption = btn1.Caption + 1
        End If
      End If
    Next i
Call Reset_Colors
End Sub
```

```
Private Sub Reset_Colors()


Dim i As Integer

Dim btn As CommandButton

Me.img_Star.Visible = False

For i = 1 To 42

    Set btn = Me.Controls("CommandButton" & i)


    With btn

        .BackColor = VBA.RGB(255, 215, 0)  'set background colors

        .Enabled = True  'Enable All


        If .Caption = "" Then  'Disbale for blanks

            .Enabled = False

            .BackColor = VBA.RGB(200, 200, 200)

        End If
```

```
    End With

Next i

End Sub

 Function SelectedDate(Optional Target_Control As Object) As String
    Dim str As String
    If (TypeName(Target_Control)) = "TextBox" Or TypeName(Target_Control) = "Range" Then
str = Target_Control.Value
    If (TypeName(Target_Control)) = "CommandButton" Or TypeName(Target_Control) =
"Label" Then str = Target_Control.Caption
    If IsDate(str) Then
        Me.TextBox1.Value = VBA.Format(CDate(str), "D-MMM-YYYY")
        Else
        Me.TextBox1.Value = VBA.Format(Date, "D-MMM-YYYY")
    End If
    Me.Show
```

```
    If (TypeName(Target_Control)) = "TextBox" Or TypeName(Target_Control) = "Range" Then
        Target_Control.Value = Me.TextBox1.Value
    ElseIf (TypeName(Target_Control)) = "CommandButton" Or TypeName(Target_Control) =
"Label" Then
        Target_Control.Caption = Me.TextBox1.Value
    Else
        SelectedDate = Me.TextBox1.Value
    End If


End Function


Sub Show_Selected_Date(dt As Date)
    Dim i As Integer
    Dim btn As MSForms.CommandButton
    On Error Resume Next
    Me.CmbMonth.Value = VBA.Format(dt, "MMMM")
    Me.CmbYear.Value = VBA.Format(dt, "YYYY")
    For i = 1 To 42
```

```
        Set btn = Me.Controls("CommandButton" & i)

        If btn.Caption = CStr(VBA.day(dt)) Then

            Me.img_Star.Left = btn.Left + 3

            Me.img_Star.Top = btn.Top + 3

            Me.img_Star.Visible = True

            btn.BackColor = vbWhite

        End If

    Next i

End Sub


Sub RunSolver()

    ' The Solver settings are already in place, so this sub just runs Solver.

    Application.ScreenUpdating = False

    Dim WS As Worksheet

    Set WS = ThisWorkbook.ActiveSheet

    Range("Variables").ClearContents

    SolverReset
```

```
    SolverOk SetCell:=WS.Range("Objective_Function"), MaxMinVal:=1, _
    ByChange:=WS.Range("Variables"), Engine:=2
    SolverAdd CellRef:=WS.Range("Scheduled"), Relation:=1, _
    FormulaText:="Demand"
    SolverAdd CellRef:=WS.Range("Utilization"), Relation:=1, _
    FormulaText:="Availability"
    SolverAdd CellRef:=WS.Range("Variables"), Relation:=5
    SolverSolve userfinish:=True
    Call CondFormatting
    Application.ScreenUpdating = True
End Sub


Sub CreateCSReport()
    Application.ScreenUpdating = False
    ' This sub transfers the optimal results from the Model sheet to the Report sheet.
    Dim i As Integer, k As Long, nProjects As Long, m As Long, Mycell As Range, L As Long,
irow As Integer, cj As Long
    nProjects = Application.WorksheetFunction.Count(wsCSModel.Range("B:B"))
```

```
    cj = Application.WorksheetFunction.CountA(wsReport.Range("H:H")) + 3

    ' Unhide the Report sheet and activate it.

With wsReport

    .Visible = True

    .Activate

    ' Clear out old assignments from a previous run (the part below F4).

    .Range("G4:R" & cj).ClearContents

    .Range("G4:R" & cj).ClearFormats

    .Range("D22:D23").ClearContents

    .Range("B5:E16").ClearContents

End With

With wsCSModel

    Call .Range("CrewID").Copy(wsReport.Range("B5:B16"))

    Call .Range("Availability").Copy(wsReport.Range("C5:C16"))

    Call .Range("Utilization").Copy(wsReport.Range("D5:D16"))

End With

With wsReport
```

```
 .Range("P5").Value = .Range("AI1").Value

For Each Mycell In .Range("C5:C16")

   If Mycell.Value = "0" Then

      Mycell.Offset(0, 2).Value2 = "NA"

   Else

      Mycell.Offset(0, 2).FormulaR1C1 = "=C[-1]/C[-2]"

   End If

Next

.Range("E5:E16").NumberFormat = "0%"

.Range("K:K, M:N, P:Q").NumberFormat = "dd-mm-yyyy"

End With

'Call RgNames

   ' Transfer the positive assignments from the Model sheet to the Report sheet.

With wsReport.Range("F5")

   For i = 1 To nProjects

      If wsCSModel.Range("Scheduled").Cells(i) = 1 Then

         .Offset(k, 1).Value2 = wsCSModel.Range("Idex").Cells(i).Value2 'ProjectId
```

```
irow = wsCSModel.Range("Idex").Cells(i).Row

wsCSModel.Range("B" & irow & ":I" & irow).Copy

.Offset(k, 2).PasteSpecial xlPasteValues

.Offset(k, 12).Value2 = WorksheetFunction.Index(wsCSModel.Range("O2:Z2"), _

                          WorksheetFunction.Match(1, wsCSModel.Range("O" & i + 2
& ":Z" & i + 2), 0)) 'AssignedCrew

If k >= 1 Then

    m = k - 1

    Set Mycell = Range("R" & m + 5 & ":R5").Find(What:=.Offset(k, 12).Value2,
LookIn:=xlValues, LookAt:=xlWhole, _

                          SearchOrder:=xlByColumns, SearchDirection:=xlPrevious)

    If Not Mycell Is Nothing Then

        .Offset(k, 10).Value2 = WorksheetFunction.Index(Range("Q:Q"), Mycell.Row)

    Else

        .Offset(k, 10).Value2 = .Offset(0, 10).Value2

    End If

End If

.Offset(k, 11).FormulaR1C1 = "=WORKDAY(RC[-1],RC[-2])" 'FinishDate
```

```
        k = k + 1
        End If
    Next i
End With
cj = Application.WorksheetFunction.Count(wsReport.Range("G:G")) + 4
With Range("G5:R" & cj)
    .Borders(xlEdgeTop).LineStyle = xlContinuous
    .Borders(xlEdgeBottom).LineStyle = xlContinuous
    .Borders(xlEdgeLeft).LineStyle = xlContinuous
    .Borders(xlEdgeRight).LineStyle = xlContinuous
    .Borders(xlInsideHorizontal).LineStyle = xlContinuous
    .Borders(xlInsideVertical).LineStyle = xlContinuous
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
End With
With wsReport
    .Range("J5:J" & cj).HorizontalAlignment = xlLeft
```

```
    .Columns("J").ColumnWidth = 45
    With .Range("G5:R" & cj).Font
        .Name = "Calibri Light"
        .Size = 11
    End With
    '.Range("G:R").Columns.AutoFit
End With
Call ChartCreator
With ActiveWindow
    .DisplayGridlines = False
    .DisplayHeadings = False
    .Zoom = 100
End With
 Range(wsReport.Columns("AJ:AJ"),
wsReport.Columns("AJ:AJ").End(xlToRight)).EntireColumn.Hidden = True
 wsReport.Range("D22").Value2 = wsCSModel.Range("AI4")
 wsReport.Range("D23").Value2=
Val(Application.WorksheetFunction.Count(wsCSModel.Range("A:A")) - 2)
```

```
Application.DisplayFormulaBar = False
Application.ScreenUpdating = True
End Sub


Sub GoToApplication()
  Application.ScreenUpdating = False
   Dim sh As Worksheet
   For Each sh In ThisWorkbook.Sheets
       If sh.CodeName = "wsApplication" Then
           sh.Visible = xlSheetVisible
       Else
          sh.Visible = xlSheetHidden
       End If
   Next
    Range(wsApplication.Columns("N:N"),
wsApplication.Columns("N:N").End(xlToRight)).EntireColumn.Hidden = True
    Range(wsApplication.Rows("45:45"),
wsApplication.Rows("45:45").End(xlDown)).EntireRow.Hidden = True
```

```
Range("E2").FormulaR1C1 = "EPCOR Drainge  Construction Services"

With Range("E2").Font

    .Name = "Agency FB"

    .Size = 17

    .Color = -10477568

 End With

 Range("E2:J2").Merge

Range("E3").FormulaR1C1 = "Small Projects Planning and Crew allocation"

With Range("E3").Font

    .Name = "Agency FB"

    .Size = 17

    .Color = -10477568

 End With

 Range("E3:J3").Merge

Range("E4").FormulaR1C1 = "Application under Crew Constraints"

With Range("E4").Font

    .Name = "Agency FB"
```

```
    .Size = 17

    .Color = -10477568

End With

Range("E4:J4").Merge

Range("G9").FormulaR1C1 = "Optimized Planning ToolBox"

With Range("G9").Font

    .Name = "Agency FB"

    .Size = 16

End With

Range("G9:L9").Select

With Selection

    .HorizontalAlignment = xlCenterAcrossSelection

    .VerticalAlignment = xlCenter

End With

Range("A7:M7").Select

With Selection.Borders(xlEdgeBottom)

    .LineStyle = xlContinuous
```

```
        .Color = -10477568
        .TintAndShade = 0
        .Weight = xlThick
    End With
    Rows("7:7").Select
    Selection.RowHeight = 6.75
    Range("G100").Select
    ActiveWindow.DisplayGridlines = False
    ActiveWindow.DisplayHeadings = False
    Application.DisplayFormulaBar = False
    Application.DisplayStatusBar = True
    Application.DisplayFullScreen = True
    Application.ScreenUpdating = True
End Sub


Sub DeleteCharts()
    Dim co As ChartObject
```

```
    For Each co In wsReport.ChartObjects
        co.Delete
    Next
End Sub
Sub ChartCreator()
    Application.ScreenUpdating = False
Dim LsR As Long, ChtObj As ChartObject, ChtRng As Range, ChtArea As Range, Dlables As
Range
    wsReport.Activate
    LsR = Application.WorksheetFunction.Count(wsReport.Range("G:G")) + 4
    Call DeleteCharts
    With wsReport
         .Range("S2").FormulaR1C1 = "Workforce Plan under Resource Constraints"
        .Range("S2:AI3").Merge
        .Range("S2:AI3").Font.Size = 18
        .Range("S2:AI3").Font.Name = "Agency FB"
        .Range("S2:AI3").Font.FontStyle = "Bold"
        .Range("S2:AI3").HorizontalAlignment = xlCenter
```

```
    .Range("S2:AI3").VerticalAlignment = xlCenter
End With
Call RgNames
Set ChtRng = wsReport.Range("G5:R" & LsR)
Set ChtArea = wsReport.Range("S4:AI" & LsR)
Set Dlables = wsReport.Range("AssignedCrew")
wsReport.Shapes.AddChart2.Select
Set ChtObj = ActiveChart.Parent
With ChtObj
    .Top = ChtArea.Top
    .Left = ChtArea.Left
    .Height = ChtArea.Height
    .Width = ChtArea.Width
End With
With ActiveChart
    .ChartType = xlBarStacked
    .SetSourceData Source:=ChtRng
```

```
.HasTitle = False
.SeriesCollection.NewSeries
.FullSeriesCollection(1).Name = "StartDate"
.FullSeriesCollection(1).Values = wsReport.Range("StartDate")
.FullSeriesCollection(1).XValues = wsReport.Range("Index")
.SeriesCollection.NewSeries
.FullSeriesCollection(2).Name = "Duratn"
.FullSeriesCollection(2).Values = wsReport.Range("Duratn")
.FullSeriesCollection(2).XValues = wsReport.Range("Index")
.Axes(xlCategory).Select
.Axes(xlCategory).ReversePlotOrder = True
.Axes(xlValue).Select
.Axes(xlValue).MinimumScale = Application.WorksheetFunction.Min(Range("StartDate"))
.Axes(xlValue).MaximumScale = 
Application.WorksheetFunction.Max(Range("FinishDate"))
.Axes(xlValue).MajorUnit = 1
.Axes(xlValue).MinorUnit = 0.5
.Axes(xlValue).TickLabels.NumberFormat = "dd-mm"
```

```
.FullSeriesCollection(1).Select

Selection.Format.Fill.Visible = msoFalse

.FullSeriesCollection(2).Select

Selection.Format.Line.Visible = msoFalse

With Selection.Format.Fill

    .Visible = msoTrue

    .ForeColor.ObjectThemeColor = msoThemeColorAccent6

    .Solid

End With

.SetElement (msoElementPrimaryValueGridLinesNone)

.SetElement (msoElementPrimaryValueGridLinesMajor)

.SetElement (msoElementPrimaryValueGridLinesNone)

.SetElement (msoElementPrimaryValueGridLinesMajor)

.SetElement (msoElementPrimaryCategoryGridLinesMajor)

.SetElement (msoElementPrimaryValueGridLinesMinorMajor)

.SetElement (msoElementPrimaryCategoryGridLinesMinorMajor)

.ChartGroups(1).GapWidth = 10
```

```
.ChartArea.Select
With .FullSeriesCollection(2)
    .ApplyDataLabels
    With .DataLabels
        .Format.TextFrame2.TextRange.InsertChartField _
        msoChartFieldRange, Dlables.Address(External:=True), 0
        .ShowCategoryName = False
        .ShowRange = True
        .ShowSeriesName = False
        .ShowValue = False
        .Position = xlLabelPositionInsideEnd
        .Format.TextFrame2.TextRange.Font.Name = "+mj-lt"
        .Format.TextFrame2.TextRange.Font.Bold = msoTrue
    End With
    .HasLeaderLines = False
    ActiveChart.FullSeriesCollection(2).DataLabels.Select
    With Selection.Format.TextFrame2.TextRange.Font
```

```
            .NameComplexScript = "Arial"
            .NameFarEast = "Arial"
            .Name = "Arial"
        End With
        With Selection.Format.TextFrame2.TextRange.Font.Fill
            .Visible = msoTrue
            .ForeColor.RGB = RGB(192, 0, 0)
            .Transparency = 0
            .Solid
        End With
    End With
End With
wsReport.Range("B2").Select
ActiveWindow.DisplayGridlines = False
ActiveWindow.DisplayHeadings = False
Application.DisplayFormulaBar = False
Application.DisplayStatusBar = True
```

```
    Application.DisplayFullScreen = True

End Sub



Function SayIt(txt)

     Application.Speech.Speak txt, True

End Function

Sub Get_Data_From_File()

    Dim FileToOpen As Variant

    Dim wbCopy As Workbook

    Dim wsCopy As Worksheet

    Dim LD As Long, DLr As Long ' last record of data stored in wsData

   Application.ScreenUpdating = False

    FileToOpen = Application.GetOpenFilename(Title:="Browse for your File & Import Range",
FileFilter:="Excel Files (*.xls*),*xls*")

'TryAgain:

    If FileToOpen = False Then

        MsgBox "No file was selected", vbInformation 'vbRetryCancel

        'If vbRetry Then GoTo TryAgain
```

```
    Exit Sub

Else

    Set wbCopy = Application.Workbooks.Open(FileToOpen)

    Set wsCopy = wbCopy.Worksheets(1)

    LD = wsCopy.Cells(wsCopy.Rows.Count, "D").End(xlUp).Row

    DLr = Application.WorksheetFunction.CountA(wsData.Range("A:A"))

    wsCopy.Range("D2:N" & LD).Copy wsData.Range("A" & DLr + 1)

    Application.CutCopyMode = False

    wbCopy.Close False

End If

'wsData.Range("A:K" & DLr).RemoveDuplicates Columns:=1, Header:=xlYes

DLr = wsData.Cells(wsData.Rows.Count, "B").End(xlUp).Row

With wsData

    .UsedRange.EntireColumn.AutoFit

    .UsedRange.EntireRow.AutoFit

    .UsedRange.HorizontalAlignment = xlCenter

    .UsedRange.VerticalAlignment = xlCenter
```

```
        .Range("C2:C" & DLr).HorizontalAlignment = xlLeft
        .Columns("C:C").ColumnWidth = 60
        With Range("H2:H" & DLr)
            .NumberFormat = "0.0"
            .Value = .Value
        End With
    End With
    MsgBox "Data has been transfered successfuly", vbInformation
    Application.ScreenUpdating = True
End Sub


Sub CreateHPModel()
    Application.ScreenUpdating = False
     Dim cell As Range, HPLr As Integer, LHP As Long, i As String, j As Integer, ir As Integer
    wsHPModel.Activate
   HPLr = Application.WorksheetFunction.CountA(wsHPModel.Range("B:B")) + 1
    LHP = Application.WorksheetFunction.CountA(wsMRData.Range("F:F")) + 1
```

```
    For j = 1 To LHP - 2
        If wsMRData.Range("CFCC").Cells(j) = "Ready" And wsMRData.Range("CSite").Cells(j) = "Ready" Then
            ir = wsMRData.Range("CFCC").Cells(j).Row
            HPLr = HPLr + 1
            Call wsMRData.Range("B" & ir & ":" & "G" & ir).Copy(wsHPModel.Range("B" & HPLr))
        End If
    Next j
    Application.CutCopyMode = False
     wsHPModel.Range("A2:AB" & HPLr).RemoveDuplicates Columns:=Array(2), Header:=xlYes
    Call RgNames
    HPLr = Application.WorksheetFunction.Count(wsHPModel.Range("B:B")) + 2
With wsHPModel
    .Range("A3").Value2 = "1"
    .Range("A4").FormulaR1C1 = "=R[-1]C+1"
    .Range("A4").Copy Destination:=Range("A4:A" & HPLr)
    .Range("PastDays").FormulaR1C1 = "=TODAY()-RC[-3]"
```

```
.Range("NorPasDys").FormulaR1C1 = "= (RC[-1]-Min(PastDays))/(Max(PastDays)-
Min(PastDays))" '

.Range("AF6").FormulaR1C1 = "=ROUNDUP(RC[-2]*(R14C35/5),1)"

.Range("AF6").Copy Destination:=Range("Availability")

.Range("BarCaFtr").FormulaR1C1 = _

        "=IFS(ISBLANK(RC[-5])=TRUE,""0"", TODAY()-RC[-5]>60, ""0.25"")"

.Range("NorPrior").FormulaR1C1 = "=(RC[-7]-Min(Priority))/(Max(Priority)-Min(Priority))"

.Range("Demand").FormulaR1C1 = "1"

.Range("Scheduled").FormulaR1C1 = "=SUM(RC[-12]:RC[-1])"

.Range("Work_Factor").FormulaR1C1 = "=RC[-1]*SUM(RC[-19]+RC[-16]+RC[-15])"

.Range("Objective_Function").FormulaR1C1 = "=SUM(Work_Factor)"

.Range("AI4").FormulaR1C1 = "=Sum(Scheduled)"

.Range("AE6").FormulaR1C1 = "=SUM(C_213)"

.Range("AE7").FormulaR1C1 = "=SUM(C_214)"

.Range("AE8").FormulaR1C1 = "=SUM(C_217)"

.Range("AE9").FormulaR1C1 = "=SUM(C_218)"

.Range("AE10").FormulaR1C1 = "=SUM(C_222)"

.Range("AE11").FormulaR1C1 = "=SUM(C_223)"
```

```
  .Range("AE12").FormulaR1C1 = "=SUM(C_225)"
  .Range("AE13").FormulaR1C1 = "=SUM(C_226)"
  .Range("AE14").FormulaR1C1 = "=SUM(C_227)"
  .Range("AE15").FormulaR1C1 = "=SUM(C_229)"
  .Range("AE16").FormulaR1C1 = "=SUM(C_230)"
  .Range("AE17").FormulaR1C1 = "=SUM(C_231)"
  With .Range("A3:AB" & HPLr)
      .Borders(xlEdgeTop).LineStyle = xlContinuous
      .Borders(xlEdgeBottom).LineStyle = xlContinuous
      .Borders(xlEdgeLeft).LineStyle = xlContinuous
      .Borders(xlEdgeRight).LineStyle = xlContinuous
      .Borders(xlInsideHorizontal).LineStyle = xlContinuous
      .Borders(xlInsideVertical).LineStyle = xlContinuous
      .HorizontalAlignment = xlCenter
      .VerticalAlignment = xlCenter
End With
End With
```

```
    Range("Description_Location").HorizontalAlignment = xlLeft

    Range(wsHPModel.Columns("AJ:AJ"),
wsHPModel.Columns("AJ:AJ").End(xlToRight)).EntireColumn.Hidden = True

   Range("I:N").Columns.Hidden = True

   Application.ScreenUpdating = True

End Sub

Sub CreateCSModel()

    Application.ScreenUpdating = False

    ' This sub transfers the Customer Service projects from Data and prepares the Model sheet to
the run the optimization engine.

    Dim LHP As Integer, cell As Range, LCS As Integer, LData As Integer, i As Integer, ir As
Integer

     wsCSModel.Activate

   LHP = Application.WorksheetFunction.CountA(wsMRData.Range("F:F")) + 2

   LCS = Application.WorksheetFunction.CountA(wsCSModel.Range("B:B")) + 1

   LData = Application.WorksheetFunction.CountA(wsMRData.Range("A:A"))

       '  Clear out old assignments from the previous run.

    For i = LHP To LData
```

```
        If wsMRData.Range("CFCC").Cells(i) = "Ready" And wsMRData.Range("CSite").Cells(i) =
"Ready" Then
            ir = wsMRData.Range("CFCC").Cells(i).Row
            LCS = LCS + 1
            Call wsMRData.Range("B" & ir & ":" & "G" & ir).Copy(wsCSModel.Range("B" & LCS))
        End If
    Next i
    Application.CutCopyMode = False
    wsCSModel.Range("A3:G" & LCS).RemoveDuplicates Columns:=Array(2), Header:=xlYes
    LCS = Application.WorksheetFunction.Count(wsCSModel.Range("B:B")) + 2
Call RgNames
With wsCSModel
    .Range("A3").Value2 = "1"
    .Range("A4").FormulaR1C1 = "=R[-1]C+1"
    .Range("A4").Copy Destination:=Range("A4:A" & LCS)
    .Range("Deadline").FormulaR1C1 = "=RC[-3]+42"
    .Range("Dur").FormulaR1C1 = "=RANDBETWEEN(1,3)"
    .Range("Dur").NumberFormat = "0.0"
```

```
.Range("Dur").Value = .Range("Dur").Value

.Range("Dur").Copy Destination:=.Range("Dur")

Application.CutCopyMode = False

.Range("Priority").FormulaR1C1 = "1"

.Range("Float").FormulaR1C1 = "=RC[-2]-RC[-1]-TODAY()"

.Range("ShFloat").FormulaR1C1 = "= Abs(Float)"

.Range("K3").FormulaR1C1 = "=(RC[25]-Min(ShFloat))/(Max(ShFloat)-Min(ShFloat))"

.Range("K3:K" & LCS).FillDown

.Range("NorPrior").FormulaR1C1 = _

   "=IF(RC[-7]=1,""1"",(RC[-7]-MIN(Priority))/(MAX(Priority)-MIN(Priority)))"

.Range("Demand").FormulaR1C1 = "1"

Range("Scheduled").FormulaR1C1 = "=SUM(RC[-12]:RC[-1])"

Range("Work_Factor").FormulaR1C1 = "=RC[-1]*SUM(RC[-17]+RC[-16]+RC[-15])"

Range("Objective_Function").FormulaR1C1 = "=SUM(Work_Factor)"

.Range("AI4").FormulaR1C1 = "=Sum(Scheduled)"

.Range("AE6").FormulaR1C1 = "=SUMPRODUCT((C_213),(Dur))"

.Range("AE7").FormulaR1C1 = "=SUMPRODUCT((C_214),(Dur))"
```

```
.Range("AE8").FormulaR1C1 = "=SUMPRODUCT((C_217),(Dur))"

.Range("AE9").FormulaR1C1 = "=SUMPRODUCT((C_218),(Dur))"

.Range("AE10").FormulaR1C1 = "=SUMPRODUCT((C_222),(Dur))"

.Range("AE11").FormulaR1C1 = "=SUMPRODUCT((C_223),(Dur))"

.Range("AE12").FormulaR1C1 = "=SUMPRODUCT((C_225),(Dur))"

.Range("AE13").FormulaR1C1 = "=SUMPRODUCT((C_226),(Dur))"

.Range("AE14").FormulaR1C1 = "=SUMPRODUCT((C_227),(Dur))"

.Range("AE15").FormulaR1C1 = "=SUMPRODUCT((C_229),(Dur))"

.Range("AE16").FormulaR1C1 = "=SUMPRODUCT((C_230),(Dur))"

.Range("AE17").FormulaR1C1 = "=SUMPRODUCT((C_231),(Dur))"

With .Range("A3:AB" & LCS)

    .Borders(xlEdgeTop).LineStyle = xlContinuous

    .Borders(xlEdgeBottom).LineStyle = xlContinuous

    .Borders(xlEdgeLeft).LineStyle = xlContinuous

    .Borders(xlEdgeRight).LineStyle = xlContinuous

    .Borders(xlInsideHorizontal).LineStyle = xlContinuous

    .Borders(xlInsideVertical).LineStyle = xlContinuous
```

```
        .HorizontalAlignment = xlCenter

        .VerticalAlignment = xlCenter

    End With

    .Range("Description_Location").HorizontalAlignment = xlLeft

    .Range(wsCSModel.Columns("AJ:AJ"),
wsCSModel.Columns("AJ:AJ").End(xlToRight)).EntireColumn.Hidden = True

    .Range("AF:AF").ColumnWidth = "0.50"

    .Range("J:N , AB:AB").Columns.Hidden = True

    .Activate

 End With

   Application.ScreenUpdating = True

End Sub

Sub RgNames()

Dim lr As Integer, WS As Worksheet, LHP As Long, LsR As Long

Set WS = ThisWorkbook.ActiveSheet

lr = Application.WorksheetFunction.CountA(WS.Range("B:B")) + 1

LHP = Application.WorksheetFunction.CountA(wsMRData.Range("F:F")) + 1

 LsR = Application.WorksheetFunction.Count(wsReport.Range("G:G")) + 4
```

```
If WS.CodeName = "wsCSModel" Or WS.CodeName = "wsHPModel" Then
With WS
    .Range("A3:A" & lr).Name = "Idex"
    .Range("B3:B" & lr).Name = "WorkOrder"
     .Range("C3:C" & lr).Name = "Task"
    .Range("D3:D" & lr).Name = "Description_Location"
    .Range("E3:E" & lr).Name = "DateCreated"
    .Range("DateCreated").NumberFormat = "dd-mm-yyyy"
    .Range("F3:F" & lr).Name = "Priority"
     .Range("F3:F" & lr).NumberFormat = "General"
    .Range("G3:G" & lr).Name = "WABarOrd"
    .Range("WABarOrd").NumberFormat = "dd-mm-yyyy"
    .Range("L3:L" & lr).Name = "BarCaFtr"
    .Range("BarCaFtr").NumberFormat = "0.00"
    .Range("M3:M" & lr).Name = "NorPrior"
    .Range("NorPrior").NumberFormat = "0.00000"
    .Range("N3:N" & lr).Name = "Demand"
```

```
.Range("O3:Z" & lr).Name = "Variables"

.Range("O3:O" & lr).Name = "C_213"

.Range("P3:P" & lr).Name = "C_214"

.Range("Q3:Q" & lr).Name = "C_217"

.Range("R3:R" & lr).Name = "C_218"

.Range("S3:S" & lr).Name = "C_222"

.Range("T3:T" & lr).Name = "C_223"

.Range("U3:U" & lr).Name = "C_225"

.Range("V3:V" & lr).Name = "C_226"

.Range("W3:W" & lr).Name = "C_227"

.Range("X3:X" & lr).Name = "C_229"

.Range("Y3:Y" & lr).Name = "C_230"

.Range("Z3:Z" & lr).Name = "C_231"

.Range("AA3:AA" & lr).Name = "Scheduled"

.Range("AB3:AB" & lr).Name = "Work_Factor"

 .Range("AI2").Name = "Objective_Function"

.Range("AC6:AC17").Name = "CrewID"
```

```
 .Range("AE6:AE17").Name = "Utilization"
End With
End If
 If WS.CodeName = "wsCSModel" Then
    Range("AD6:AD17").Name = "Availability"
    Range("H3:H" & lr).Name = "Deadline"
    Range("I3:I" & lr).Name = "Dur"
    Range("J3:J" & lr).Name = "Float"
    Range("AJ3:AJ" & lr).Name = "ShFloat"
    Range("K3:K" & lr).Name = "NorFloat"
    Range("NorFloat").NumberFormat = "0.00000"
    Range("A3:I" & lr).Name = "CSProjects"
 ElseIf WS.CodeName = "wsHPModel" Then
    Range("AF6:AF17").Name = "Availability"
    Range("H3:H" & lr).Name = "PastDays"
    Range("I3:I" & lr).Name = "NorPasDys"
    Range("NorPasDys").NumberFormat = "0.00000"
```

```
        Range("A3:G" & lr).Name = "HPProjects"
    ElseIf WS.CodeName = "wsMRData" Then
        Range("A3:A" & lr).Name = "Id"
        Range("I3:I" & lr).Name = "PDD"
        Range("J3:J" & lr).Name = "NrPDD"
        Range("F3:F" & LHP).Name = "Pr"
        Range("K3:K" & LHP).Name = "NrPr"
        Range("L3:L" & LHP).Name = "HPUrIdx"
        Range("H3:H" & lr).Name = "Typ"
        Range("M" & LHP + 1 & ":M" & lr).Name = "CSUrIdx"
        Range("N3:N" & lr).Name = "CFCC"
        Range("O3:O" & lr).Name = "CSite"
    ElseIf WS.CodeName = "wsReport" Then
        Range("G5:G" & LsR).Name = "Index"
        Range("P5:P" & LsR).Name = "StartDate"
        Range("O5:O" & LsR).Name = "Duratn"
        Range("R5:R" & LsR).Name = "AssignedCrew"
```

```
        Range("Q5:Q" & LsR).Name = "FinishDate"
    End If
End Sub

Sub CreateHPReport()
Application.ScreenUpdating = False
    ' This sub transfers the optimal results from the Model sheet to the Report sheet.
    Dim i As Integer, k As Long, nProjects As Long, m As Long, Mycell As Range, L As Long,
irow As Integer, cj As Long
    nProjects = Application.WorksheetFunction.Count(wsHPModel.Range("B:B"))
    cj = Application.WorksheetFunction.CountA(wsHPReport.Range("H:H")) + 3
    ' Unhide the Report sheet and activate it.
With wsHPReport
        .Visible = True
        .Activate
        ' Clear out old assignments from a previous run (the part below F4).
        .Range("G4:P" & cj).ClearContents
        .Range("G4:P" & cj).ClearFormats
        .Range("B4:E15").ClearContents
```

```
    wsHPModel.Range("CrewID").Copy
    .Range("B4:B15").PasteSpecial xlPasteAll
    wsHPModel.Range("AD6:AD17").Copy
    .Range("C4:C15").PasteSpecial xlPasteValues
    wsHPModel.Range("Availability").Copy
    .Range("D4:D15").PasteSpecial xlPasteValues
    wsHPModel.Range("Utilization").Copy
    .Range("E4:E15").PasteSpecial xlPasteValues
    .Range("K:K, M:M").NumberFormat = "dd-mm-yyyy"
    .Range("N:N").NumberFormat = "General"
  End With
'k = 0
' Transfer the positive assignments from the Model sheet to the Report sheet.
With wsHPReport.Range("F5")
    For i = 1 To nProjects
        If wsHPModel.Range("Scheduled").Cells(i) = 1 Then
            irow = wsHPModel.Range("Idex").Cells(i).Row
```

```
            wsHPModel.Range("A" & irow & ":H" & irow).Copy            .Offset(k, 1).PasteSpecial
xlPasteValues .Offset(k, 9).Value2 = WorksheetFunction.Index(wsHPModel.Range("O2:Z2"), _
WorksheetFunction.Match(1, wsHPModel.Range("O" & i + 2 & ":Z" & i + 2), 0)) 'AssignedCrew
          k = k + 1
        End If
      Next i
    End With
    cj = Application.WorksheetFunction.Count(wsHPReport.Range("G:G")) + 4
    With Range("G5:O" & cj)
      .Borders(xlEdgeTop).LineStyle = xlContinuous
      .Borders(xlEdgeBottom).LineStyle = xlContinuous
      .Borders(xlEdgeLeft).LineStyle = xlContinuous
      .Borders(xlEdgeRight).LineStyle = xlContinuous
      .Borders(xlInsideHorizontal).LineStyle = xlContinuous
      .Borders(xlInsideVertical).LineStyle = xlContinuous
      .HorizontalAlignment = xlCenter
      .VerticalAlignment = xlCenter
    End With
```

```
With wsHPReport
    .Range("J5:J" & cj).HorizontalAlignment = xlLeft
    .Columns("J").ColumnWidth = 60
    .Range("M5:M" & cj).NumberFormat = "General"
    With .Range("G5:O" & cj).Font
        .Name = "Calibri Light"
        .Size = 11
    End With
End With
With ActiveWindow
    .DisplayGridlines = False
    .DisplayHeadings = False
    .Zoom = 92
End With
 Range(wsHPReport.Columns("Q:Q"),
wsHPReport.Columns("Q:Q").End(xlToRight)).EntireColumn.Hidden = True
 wsHPReport.Range("D23").Value2 = wsHPModel.Range("AI4")
```

```
wsHPReport.Range("D24").Value2=
Val(Application.WorksheetFunction.Count(wsHPModel.Range("A:A")))
    Application.DisplayFormulaBar = False
    Application.ScreenUpdating = True
End Sub
Sub CondFormatting()
    Range("Variables").Select
    Selection.FormatConditions.Delete
    Selection.NumberFormat = ";;;"
    Selection.FormatConditions.Add Type:=xlCellValue, Operator:=xlEqual, _
        Formula1:="=1"
    With Selection.FormatConditions(1).Interior
        .PatternColorIndex = xlAutomatic
        .Color = 12611584
        .TintAndShade = 0
    End With
    Selection.FormatConditions(1).StopIfTrue = False
    Range("Scheduled").Select
```

```
    Selection.FormatConditions.Delete

    Selection.NumberFormat = ";;;"

    Selection.FormatConditions.Add Type:=xlCellValue, Operator:=xlEqual, _

        Formula1:="=1"

    Selection.FormatConditions(Selection.FormatConditions.Count).SetFirstPriority

    With Selection.FormatConditions(1).Interior

        .PatternColorIndex = xlAutomatic

        .ThemeColor = xlThemeColorAccent6

        .TintAndShade = 0.799981688894314

        .PatternTintAndShade = 0

    End With

    Selection.FormatConditions(1).StopIfTrue = False

End Sub

Sub MRJbs()

    Application.ScreenUpdating = False

     Dim cell As Range, LHP As Integer, WorkRange As Range, DLr As Long, MRLr As Long  '
last record of data stored in wsMRData

   wsMRData.Activate
```

```
MRLr = Application.WorksheetFunction.CountA(wsMRData.Range("B:B")) + 1

DLr = Application.WorksheetFunction.CountA(wsData.Range("A:A"))

 With wsData

     Call .Range("A2:C" & DLr).Copy(wsMRData.Range("B" & MRLr + 1))

     Call .Range("E2:E" & DLr).Copy(wsMRData.Range("E" & MRLr + 1))

     Call .Range("H2:H" & DLr).Copy(wsMRData.Range("F" & MRLr + 1))

     Call .Range("K2:K" & DLr).Copy(wsMRData.Range("G" & MRLr + 1))

 End With

  Application.CutCopyMode = False

 wsMRData.Cells.RemoveDuplicates Columns:=2, Header:=xlYes

 MRLr = Application.WorksheetFunction.CountA(wsMRData.Range("B:B")) + 1

 LHP = Application.WorksheetFunction.CountA(wsMRData.Range("F:F")) + 1

Call RgNames

With wsMRData

 For Each cell In Range("Typ")

      If IsEmpty(cell) = True And cell.Offset(0, -2).Value > 0 Then

         cell.Value = "HP"
```

```
        ElseIf IsEmpty(cell) = True And IsEmpty(cell.Offset(0, -2)) = True Then
            cell.Value = "CS"
        End If
    Next
    .Range("PDD").FormulaR1C1 = "=TODAY()-RC[-4]"
    .Range("NrPDD").FormulaR1C1 = "= (RC[-1]-Min(PDD))/(Max(PDD)-Min(PDD))"
    .Range("NrPr").FormulaR1C1 = "=(RC[-5]-Min(Pr))/(Max(Pr)-Min(Pr))"
    .Range("HPUrIdx").FormulaR1C1 = "=(RC[-1]*0.75)+(RC[-2]*0.25)"
    For Each cell In Range("CSUrIdx")
        If cell.Offset(0, -5).Value2 = "CS" Then
                cell.Value2 = cell.Offset(0, -3).Value2
        Else
                cell.Value2 = ""
        End If
    Next
End With
With wsMRData.Sort
```

```
    .SortFields.Clear
    .SortFields.Add Key:=Range("L2:L" & MRLr), Order:=xlDescending
    .SortFields.Add Key:=Range("M2:M" & MRLr), Order:=xlDescending
     .SetRange Range("A2:P" & MRLr)
    .Header = xlYes
    .Apply
End With
 With wsMRData
    Application.Union(Range(("A3:E") & MRLr), Range(("N3:O" & MRLr))).Name = "MRD"
    .Range("A3").Value2 = "1"
    .Range("A4").FormulaR1C1 = "=R[-1]C+1"
    .Range("A4").Copy Destination:=Range("A4:A" & MRLr)
    .Range("J:K").Columns.Hidden = True
    With Range("N3:N" & MRLr).Validation
    .Delete
    .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
    xlBetween, Formula1:="Ordered,Ready"
```

```
End With
With .Range("O3:O" & MRLr).Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
        xlBetween, Formula1:="Ready,on_hold"
End With
With .Range("A3:P" & MRLr)
    .Borders(xlEdgeTop).LineStyle = xlContinuous
    .Borders(xlEdgeBottom).LineStyle = xlContinuous
    .Borders(xlEdgeLeft).LineStyle = xlContinuous
    .Borders(xlEdgeRight).LineStyle = xlContinuous
    .Borders(xlInsideHorizontal).LineStyle = xlContinuous
    .Borders(xlInsideVertical).LineStyle = xlContinuous
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
End With
.Range("D3:D" & MRLr).HorizontalAlignment = xlLeft
```

```
   .Range("A" & MRLr + 1).EntireRow.Delete
End With
Application.ScreenUpdating = True
End Sub
Sub DeleteDuplicates()
    Application.ScreenUpdating = False
  Dim LastColumn As Integer
 LastColumn = Cells.Find(What:="*", After:=Range("A1"), SearchOrder:=xlByColumns,
SearchDirection:=xlPrevious).Column + 1
 With Range("A1:A" & Cells(Rows.Count, 1).End(xlUp).Row)
Use AdvanceFilter to filter unique values
        .AdvancedFilter Action:=xlFilterInPlace, Unique:=True
        .SpecialCells(xlCellTypeVisible).Offset(0, LastColumn - 1).Value = 1
        On Error Resume Next
          ActiveSheet.ShowAllData
          ' Delete the blank rows
  Columns(LastColumn).SpecialCells(xlCellTypeBlanks).EntireRow.Delete
     Err.Clear
```

```
    End With
  Columns(LastColumn).Clear
       With wsData
           .Activate
           .UsedRange.RemoveDuplicates Columns:=1, Header:=xlYes
       End With
 Application.ScreenUpdating = True
End Sub
Sub OpenfrmSolver()
frmSolver.Show
End Sub
Sub OpencrewForm()
crewForm.Show
End Sub
Sub ReportTransfer()
Dim lr As Integer, CLr As Integer, HLr As Integer, cell As Range
 wsSegData.Activate
```

```
lr = Application.WorksheetFunction.CountA(wsSegData.Range("B:B"))

CLr = Application.WorksheetFunction.CountA(wsReport.Range("H:H")) + 3

HLr = Application.WorksheetFunction.CountA(wsHPReport.Range("H:H")) + 3

If lr > 1 Then

    wsSegData.Range("A2:O" & lr).ClearContents

    wsSegData.Range("A2:O" & lr).ClearFormats

End If

Call wsReport.Range("H5:R" & CLr).Copy(wsSegData.Range("B2"))

lr = Application.WorksheetFunction.CountA(wsSegData.Range("B:B"))

Call wsHPReport.Range("H5:M" & HLr).Copy(wsSegData.Range("B" & lr + 1))

Call wsHPReport.Range("O5:O" & HLr).Copy(wsSegData.Range("L" & lr + 1))

Application.CutCopyMode = False

lr = Application.WorksheetFunction.CountA(wsSegData.Range("B:B"))

With wsSegData

    For Each cell In Range("A2:A" & lr)

        If cell.Offset(0, 5).Value2 = 1 Then

            cell.Value2 = "CS"
```

```
    Else
        cell.Value2 = "HP"
    End If
Next
With Range("A1:N" & lr)
    .Borders(xlEdgeTop).LineStyle = xlContinuous
    .Borders(xlEdgeBottom).LineStyle = xlContinuous
    .Borders(xlEdgeLeft).LineStyle = xlContinuous
    .Borders(xlEdgeRight).LineStyle = xlContinuous
    .Borders(xlInsideHorizontal).LineStyle = xlContinuous
    .Borders(xlInsideVertical).LineStyle = xlContinuous
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
End With
Range("L2:L" & lr).Name = "F1Id"
For Each cell In Range("F1Id")
    Select Case cell.Value2
```

```
Case Is = "C_213"

cell.Offset(0, 1).Value2 = "Steve L'Hirondelle"

cell.Offset(0, 2).Value2 = "Tony Kalakalo"

Case Is = "C_214"

cell.Offset(0, 1).Value2 = "Travis Kotyk"

cell.Offset(0, 2).Value2 = "Terry O'Neill"



Case Is = "C_217"

cell.Offset(0, 1).Value2 = "Terry O'Neill"

cell.Offset(0, 2).Value2 = "Terry O'Neill"

Case Is = "C_218"

cell.Offset(0, 1).Value2 = "Rod Peacocke"

cell.Offset(0, 2).Value2 = "Terry O'Neill"

Case Is = "C_222"

cell.Offset(0, 1).Value2 = "Greg Annawi"

cell.Offset(0, 2).Value2 = "Tony Kalakalo"

Case Is = "C_223"
```

```
cell.Offset(0, 1).Value2 = "Mark Nutbrown"

cell.Offset(0, 2).Value2 = "Brian Conn"

Case Is = "C_225"

cell.Offset(0, 1).Value2 = "Rushan Amarawickrama"

cell.Offset(0, 2).Value2 = "Tony Kalakalo"

Case Is = "C_226"

cell.Offset(0, 1).Value2 = "Nathan Reiter"

cell.Offset(0, 2).Value2 = "Dewey Boychuck"

Case Is = "C_227"

cell.Offset(0, 1).Value2 = "Travis Stahn"

cell.Offset(0, 2).Value2 = "Dewey Boychuck"

Case Is = "C_229"

cell.Offset(0, 1).Value2 = "Brandon Pagacz"

cell.Offset(0, 2).Value2 = "Brian Conn"

Case Is = "C_230"

cell.Offset(0, 1).Value2 = "Jeffrey Melmoth"

cell.Offset(0, 2).Value2 = "Brian Conn"
```

```
        Case Is = "C_231"

        cell.Offset(0, 1).Value2 = "Steph Richard"

        cell.Offset(0, 2).Value2 = "Dewey Boychuck"

      End Select

   Next

End With

End Sub
```

Crew Form Code

```
Private Sub btnCancel_Click()

   Me.Hide

End Sub

Private Sub btnTransfer_Click()

   Dim m As Variant, ctl As Control

   '''''''''' Validation

   For Each ctl In Me.Controls

      If TypeName(ctl) = "TextBox" Then
```

```
    If ctl.Text = "" Then
        MsgBox "Enter a value in each box.", _
            vbInformation, "Improper entry"
        ctl.SetFocus
        Exit Sub
    ElseIf InStr(2, ctl.Name, "Avl") > 0 And ctl.Text < 0 Then
        MsgBox "Enter a nonnegative integer in each day box.", _
            vbInformation, "Improper entry"
        ctl.SetFocus
        Exit Sub
    End If
ElseIf TypeName(ctl) = "ComboBox" Then
    If ctl.ListIndex = -1 Then
        MsgBox "Please select the assigned project type", vbCritical, "Void entry"
        Exit Sub
        ctl.SetFocus
    End If
```

```
        End If
    Next
    ''''''''''''''''''''''''''''''

    wsReport.Range("G2").Value = ("Planning_Period: " & Format(Me.txtStartDate.Value, "dd-mm-yyyy") & "  To  " & _
    Format(Me.txtEndDate.Value, "dd-mm-yyyy"))
    wsHPReport.Range("G2").Value = ("Planning_Period: " & Format(Me.txtStartDate.Value, "dd-mm-yyyy") & "  To  " & _
    Format(Me.txtEndDate.Value, "dd-mm-yyyy"))
     wsReport.Range("AI1").Value = Me.txtStartDate.Value
        ' The entry is valid, so put it in the appropriate cell in the Required
        ' range. Note that a textbox always returns a string.
            For Each ctl In Me.Controls
                If InStr(6, ctl.Name, "A") > 0 Then
                    m = Right(ctl.Name, 2)
                    If Controls("ComboBox" & m).Value = "CS" Then
                        wsCSModel.Range("AD6:AD17").Cells(m).Value = Val(ctl.Text)
                        wsHPModel.Range("AD6:AD17").Cells(m).Value = "0"
```

```
                Else
                    wsHPModel.Range("AD6:AD17").Cells(m).Value = Val(ctl.Text)
                    wsCSModel.Range("AD6:AD17").Cells(m).Value = "0"
                End If
            End If
        Next ctl
    Dim j As VbMsgBoxResult
    j = MsgBox("Would you like to transfer crew availabilty data?", vbYesNo + vbQuestion,
"Confirmation")
    If j = vbNo Then Exit Sub
    Me.Hide
End Sub


Private Sub Image1_Click()
  Call Calendar.SelectedDate(Me.txtStartDate)
End Sub


Private Sub Image2_Click()
```

```
    Call Calendar.SelectedDate(Me.txtEndDate)
End Sub


Private Sub txtEndDate_Change()
    If Me.txtEndDate.Value = "" Then Me.txtEndDate.Value = Format(DateAdd("d", 14,
Me.txtStartDate.Value), "dd-mm-yyyy")


End Sub
Private Sub UserForm_Initialize()
    With crewForm
        .Font.Name = "Arial"
        .ComboBox01.List = Array("CS", "HP")
        .ComboBox02.List = Array("CS", "HP")
        .ComboBox03.List = Array("CS", "HP")
        .ComboBox04.List = Array("CS", "HP")
        .ComboBox05.List = Array("CS", "HP")
        .ComboBox06.List = Array("CS", "HP")
        .ComboBox07.List = Array("CS", "HP")
```

```
        .ComboBox08.List = Array("CS", "HP")

        .ComboBox09.List = Array("CS", "HP")

        .ComboBox10.List = Array("CS", "HP")

        .ComboBox11.List = Array("CS", "HP")

        .ComboBox12.List = Array("CS", "HP")

    End With

End Sub
```