

Comprehensive Repetitive Scheduling for Linear and Scattered Infrastructure Projects

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Applied Science

in

Civil Engineering

Waterloo, Ontario, Canada, 2022

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The majority of civil infrastructure projects involve activities that are repeated across a number of units (e.g., linear highway sections; or scattered multi-bridge repairs). While repetition represents a potential for benefiting from the economy of scale, reality is far different and infrastructure projects continue to exhibit large cost overruns, delays, and disputes. With existing solutions for scheduling repetitive projects unable to adequately cater to infrastructure projects, more efficient tools are needed to support efficient planning and resource management for such projects. To address this need, this research introduces a comprehensive scheduling framework able to address the unique challenges and decision-support requirements for linear and scattered projects. The framework presented improves on the existing integrated critical path method & line-of-balance repetitive scheduling formulation to better achieve synchronized completion of a project's activities, which reduces both time and cost. The proposed framework also incorporates procedures to resolve resource constraints at both the individual-resource and the crew levels as well. To address the lack of efficient repetitive-scheduling solutions, a new easy-to-use interactive scheduling tool has been developed to combine the benefits of CPM/LOB calculations with the introduced schedule improvements, along with new clearer visualizations of all schedule details (i.e., activities, units, crews etc.). The scheduling improvements proposed in this research and the developed scheduling tool prototype were validated on case studies and proved to greatly facilitate the efficient planning and delivery for repetitive infrastructure projects, which represent an increasing portion of construction business and are most challenging to execute.

Acknowledgements

I would like to take this opportunity to first and foremost thank Almighty Allah for granting me the strength and guidance through all the work completed towards this research and throughout my course duration. An accomplishment such as this is not done alone and there are several people I am indebted to for their contribution in this research and thesis write up.

I would like to express my sincerest respect and gratitude to my supervisor Professor Tarek Hegazi for allowing me access to not just his extensive knowledge in the construction industry but his many work and life advice and guidance, all of which was essential to my drive and ability to power through this research and generally push and challenge myself. The skill and potential you saw in me was further developed and nourished through this special opportunity and guidance you provided me, and I will always be humbly appreciative.

I would like to extend very special thanks to my review committee members, Prof. Liping Fu, and Dr. Nadine Ibrahim, for their valuable time offered to share their insightful comments and guidance to help me refine and produce high-quality work through this research.

A special thanks to my dear colleagues and family for their ever-continued support, friendship, and motivation over the course of my study at the University and my family for their love and prayers which continue to help me push forward through the easy and hard times.

Finally, I would like to thank the most wonderful, inspiring, and motivating support system in my life, my husband. His unselfish, selfless, and never-ending support mentally, spiritually, and financially all through my master's study has been ineffable and irreplaceable. I can't imagine having done this without your support. May Allah bless you all.

Dedication

I dedicate this thesis to my big family who continue to love and support me in my endeavors: My parents, parents-in-law, brothers and sisters, my husband, and my beloved Zara.

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Nomenclature

CPM - Critical Path Method

VPM - Vertical Production Method

BIM/GIS - Building Information Modelling / Geographic Information Systems

LOB - Line-Of-Balance

MRCSP - Multimode Resource Constrained Scheduling Problem

LSM - Linear Scheduling Method

LBMS - Location-Based Management and Scheduling

HLOB - Heuristic Line-of-Balance

ALoB - Advanced Line-of-Balance

FCFS - First-Come-First-Served

CRS - Constrained Resource Scheduling

FSM - Fixed Start Method

eFCFS - Enhanced First-Come-First-Served

Chapter 1

Introduction

1.1 General

The construction industry contributes significantly to the national Gross Domestic Product and the global economy, and in October 2021, the industry alone accounted for almost 7.5% of the Canadian economy (Dang-Trinh et al., 2022; IBISWorld, 2021; Statistics Canada, 2022). Public investment in the industry is continually on the rise with billions of dollars being spent and forecasted for not only constructing new infrastructure but also rehabilitating existing assets (Kamarah, 2018; Siemiatycki, 2015). Despite the size of the industry, the construction sector is characterized by excessive schedule delays, cost overruns, and large disputes. Major or large-scale projects are rarely completed on time or on budget; and about a quarter to half of all routine construction and maintenance projects (i.e., simpler, or smaller projects) finish over time and over budget (Flyvbjerg, 2011; Siemiatycki, 2015). Different studies in the transportation sector found that about half of all road projects completed over the years 1992 – 1995 and in 2006 experienced cost overruns (Bordat et al., 2004; Ellis et al., 2007; Odeck, 2004). Similarly in another study, Berechman and Wu (2006) found that of 163 routine highway, bridge and tunnel projects on Vancouver Island completed between 1993 to 2003, 80% had cost overruns. Other studies have also found that in 2017, 63% of projects in the UK suffered delays, with 58% experiencing cost overruns (Wellington Project Management, 2017) and that 31 - 55% of highway projects experienced an average of 44% delays (Anastasopoulos et al., 2012).

One of the key challenges in construction projects, particularly related to the civil infrastructure, is that they are repetitive in nature. Examples include linear projects such as highways and pipelines, in addition to scattered projects such as multi-bridge rehabilitations (Bhoyar & Parbat, 2014; Dang-Trinh et al., 2022) (Radziszewska-Zielina & Bartlomiej, 2018; Bhoyar & Parbat, 2014; Dang-Trinh et

al., 2022). While managing a project in a single location is challenging, repetitive projects involve multiple levels of complexities due to the multiple locations involved (linear road sections or scattered school repairs) and the need to coordinate the resources among the various tasks in all the locations (work units). Many factors, however, prevent construction projects from being optimally planned to benefit from the economy of scale associated with repetitive projects. Unlike assembly lines where the asset being built moves from one workstation to the other along a conveyor belt, in repetitive projects the workstations (crews) move from one asset to the other (e.g., schools) or from one section to the other (e.g., sections of a highway). This represents a great planning challenge that requires optimal allocation of the work crews among the units in a manner that maintains work continuity and allows the crews to develop a useful learning momentum that saves time and cost (Altuwaim & El-Rayes, 2018). This challenge is further exacerbated under resource limits and strict deadlines. Additionally, repetitive projects can involve both identical units (e.g., same-size floors) and non-identical units (e.g., varying floor sizes), and this makes it extremely difficult to determine the appropriate number of crews and their efficient allocations while considering variable activity durations across units, project deadlines and resource constraints (Tomar & Bansal, 2019).

The scheduling techniques proposed in existing literature to address the challenges of linear and scattered repetitive construction projects can be grouped into three categories: (1) Widely used Gantt charts and Critical Path Method (CPM) based tools for general-purpose scheduling; (2) A large body of formal repetitive scheduling techniques such as linear planning methods, Line of Balance method, and vertical production method (VPM), which suit different types of repetitive projects; and (3) Optimization modelling with complex mathematical formulations and specialized solvers such as constraint programming tools or metaheuristics. Despite the extensive research efforts in categories 2 and 3, the extent of repetitive scheduling in actual practical implementation across the industry has

been limited (Lucko et al., 2014). Gantt charts and CPM tools (category 1) are still the main tools used for repetitive projects, despite their acknowledged shortcomings for primarily not being able to consider project deadlines and resource limits (Duffy et al., 2012). At the commercial level, only few repetitive scheduling software systems exist (e.g., TILOS for linear projects, VICO for high-rise, and TurboChart for viewing repetitive-project data) and yet they are still only used sporadically in the industry. While they include interesting features such as BIM/GIS integration, built-in project templates, and import/export integration to CPM-based software, they use proprietary algorithms with little decision support or manipulation for meeting deadlines, determining crew formations and types, or handling resource constraints (Hegazy et al., 2021). In a survey among 25 professionals and researchers, Boton et al. (2013) reported that, when compared to the use of bar charts, repetitive project planning techniques was known by only 32% of respondents and used by an even smaller 4% of respondents. This clearly provides insight into the continued reality of many linearly repetitive transportation projects experiencing copious delays and cost overruns, as mentioned earlier.

Several factors greatly contribute to the successful planning and execution of construction projects. Of these factors, accurate and realistic project scheduling and effective resource management are two of the top functions that must be performed efficiently (Dang-Trinh et al., 2022; Kamarah, 2018; Alarcón et al., 2004). However, as the size of projects with repetitive tasks grows larger and the demand for faster and more cost-effective delivery increases, so does the complexity of managing modern repetitive projects (Micheloud, 2018). Therefore, more efficient methods for reliable repetitive scheduling, schedule enhancements and resource planning are in great demand (Kamarah, 2018). Based on the above discussion, there is a large need to establish a flexible yet comprehensive framework with an adaptable methodology to facilitate the efficient delivery of both linear and scattered repetitive projects to meet their deadline and resource constraints.

1.2 Research Motivation

This research aims to introduce a new unified scheduling formulation with flexible schedule improvement options, integrated resource planning, and a simplified implementation tool for linear and scattered infrastructure projects. The research has been motivated by the following:

1. Need for a combined scheduling features for repetitive infrastructure projects,
2. Need to meet both deadlines and resource limits in repetitive projects,
3. Need for a simplified scheduling tool with better visualization.

1.2.1 Need for Combined Scheduling Features for Repetitive Infrastructure Projects

Repetitive infrastructure projects (linear and scattered) require construction crews to repeat the same activity in a number of units, ideally with each crew scheduled to work continuously from one unit to another without interruption and project activities completed synchronously. All repetitive project types share the same tough project constraints such as respecting precedence relationships, maintaining crew-work continuity, handling limited resources, meeting deadlines, etc. Yet, each type has its unique requirements. Linear repetitive projects such as roads, require large flexibility in assigning crews to units. For example, crews can execute a road project starting from first unit (station) and moving towards the last one or use two sets of crews from both ends to save execution time. Scattered projects, on the other hand, require more flexibility to take into account the different geographical locations of various units (e.g., schools), the time and cost to move crews among units, and the ability to change the order of execution among units to save time and cost (Mostafa, 2021; Hegazy & Kamarah, 2008). A generic repetitive scheduling system, therefore, needs to integrate these features and allow them to be applied according to the type of project being scheduled. While a large body of research exists on repetitive scheduling, current efforts target only one type of repetitive

project at a time and not the others, thus, an integrated approach that is adaptable to both linear and scattered projects is greatly needed.

1.2.2 Need To Meet Both Deadlines and Resource Limits in Repetitive Projects

Many practical situations can cause violations to project constraints. In repetitive projects, many situations such as non-identical units, limited crews, and/or individual resource shortages can hamper the synchronization among project activities and result in large variations in the activity delivery rates, leading to schedule time gaps, resource overallocations, and project delays. Lengthy schedules in-turn force project managers to crash the schedule using more expensive construction methods to meet deadlines.

Combining flexible repetitive scheduling features with different crew assignment methods and various procedures for activity rate synchronization, resource allocation, and cost optimization into one single tool is lacking in current literature. To address this research gap, one of the popular repetitive scheduling techniques, the Line-Of-Balance (LOB) method, has been enhanced in this research to incorporate flexible scheduling option & resource allocation, and to create reports that are clear and easy to understand legible. Because the original LOB method does not resolve the shortage in individual resources (Tomar & Bansal, 2019), this research seeks to improve upon existing heuristic and metaheuristic resource allocation methods (Hegazy & Wassef, 2001; Hyari & El-Rayes, 2006; Garcia-Nieves et al., 2018; Herayi & Moridi, 2019). Because of the many possible combinations of scheduling options to handle deadline and resource limits, a heuristic optimization procedure that arrives at near-optimum decisions, thus, becomes a necessity to support efficient delivery of repetitive infrastructure projects (Sonmez & Gürel, 2016; Wuliang & Chengen, 2009).

1.2.3 Need for a Simplified Scheduling Tool with Better Visualization

To increase the acceptability and benefit of repetitive scheduling in practice, there is also a need for a simple-to-use tool that provides the improved scheduling framework as described above. Such a tool can be used without a steep learning curve and offers the flexibility to generate multiple schedules and what-if scenarios quickly. Repetitive schedules involve large amounts of information about project activities, units, crews, durations, crew work sequences, start and finish times, etc., hence researchers (e.g., Vorster et al. (1991), Kamarah (2018)) have promoted the importance of enhanced visuals to increase schedule legibility. Such a tool therefore will introduce enhanced visualizations to facilitate better communication and avoid the drawbacks of existing repetitive scheduling visuals.

1.3 Research Objectives and Scope

This research introduces an efficient framework for scheduling linear and scattered infrastructure projects to meet both deadline and resource constraints, while minimizing project cost, optimizing resource use, and presenting the schedule in a clear, legible and easy to understand format. To automate the proposed framework and facilitate its use in practice, the research proposes a simplified implementation tool that is as easy-to-use as CPM and Gantt charts. The following are the detailed objectives of this research:

1. Investigate current practices and necessary features for scheduling linear, vertical, and scattered repetitive projects and identify the unique challenges and constraints that apply to scheduling each of these types,
2. Develop a comprehensive scheduling framework with flexible scheduling options that are suitable to both linear and scattered repetitive projects to meet deadline constraints,

3. Develop an integrated resource optimization procedure that efficiently resolves resource constraints not only on the available crews, but also on the individual resource availability limit. The optimization procedure efficiently minimizes project cost and duration,
4. Develop a prototype tool of the proposed framework equipped with enhanced and modifiable visualizations that offers a clear and legible representation of all schedule details; and
5. Test the proposed tool on case-study projects to refine the tool and validate its effectiveness.

The proposed framework offers decision support that helps project managers to systematically generate practical near-optimum schedules with best arrangement of construction methods and resources, in addition to legible reports to facilitate efficient communication among project stakeholders. This will ultimately lead to time and cost savings, in addition to full control over the execution of large infrastructure projects.

1.4 Research Methodology

The methodology for achieving the above objectives is described as follows:

1. Literature review: Conduct a comprehensive literature review of the theoretical and practical scheduling requirements for the construction of linear and scattered repetitive projects, which represent the majority of infrastructure projects. Attention would be given to investigating the prevalent challenges and the unique constraints that apply to each type. In addition, existing resource-constrained scheduling and optimization for these projects will be explored.
2. Current Industry Practices: Investigate the prevalent practices adopted by small and large construction companies for scheduling and optimization of repetitive projects to identify the trend of scheduling techniques and tools used in the industry and determine the perceived advantages and disadvantages and the barriers to utilizing more advanced tools.

3. **Integrated Scheduling:** Based on the identified characteristics of repetitive infrastructure projects, an integrated scheduling framework will be developed utilizing a mathematical formulation to determine necessary crews and their assignment along the units, to meet project deadlines. This scheduling engine is generic enough to consider a variety of practical situations of linear and scattered projects, including non-identical units and varying execution orders among scattered units.
4. **Resource-Constrained Scheduling:** For resource management, the scheduling engine will be enhanced to handle resource constraints both at the activity crew level and the individual resources as well.
5. **Visuals Enhancement:** With the advanced features of the proposed schedule improvement framework completed, a detailed yet flexible and easy to understand visualization layout will be developed to effectively present the different decision parameters and communicate the project schedule in a highly legible manner among all stakeholders, to promote acceptance and easy integration within the industry.
6. **Prototype Development:** A computer prototype that integrates the proposed framework and formulations for the optimized scheduling of resource-constrained repetitive projects along with the enhanced visuals will be developed.
7. **Validation:** The developed prototype will be tested on multiple case-study scenarios to validate the functionalities of the proposed scheduling framework as well as the resource allocation and optimization features. The potential integration of the proposed tool for repetitive infrastructure projects in the industry will be discussed.

1.5 Thesis Organization

The remainder of the thesis is organized as follows:

Chapter 2 presents a detailed literature review to identify similar characteristics between linear, vertical, and scattered repetitive projects as well as determine their unique characteristics, challenges and constraints when seeking to plan and schedule such projects. The capabilities and limitations of existing scheduling, optimization and resource management approaches, models and tools for repetitive projects are also explored.

Chapter 3 discusses the different decision variables and schedule parameters that affect the duration of repetitive projects. A combined scheduling framework is then presented that incorporates these schedule parameters and integrates them with the most appropriate scheduling method for repetitive projects. This comprehensive framework is tested to validate its efficacy in implementing each of the integrated project scheduling decision parameters with the project schedule.

Chapter 4 explores the integration of resource management with the improved scheduling framework described in Chapter 3, in order to address the common MRCSP challenges faced by the majority of repetitive projects. A unified scheduling framework that can meet project deadlines and resource constraints while incorporating comprehensive project scheduling features is then presented.

Chapter 5 presents the developed scheduling tool prototype that is equipped with the unified scheduling framework introduced in Chapter 4 along with enhanced visualizations. The chapter describes the benefits of the proposed tool in providing a familiar yet powerful interface that can easily be used without advanced or sophisticated training and features a clear and legible representation of the project details and schedules for quick assimilation, easy manipulation, and

adequate decision-making support. Each of the integrated scheduling features is tested with different scenario examples to demonstrate these benefits.

Chapter 6 introduces validation case-studies representing the complexity of a real-world repetitive project and the proposed comprehensive tool is tested to validate the proposed benefits and highlight the scheduling contributions in terms of robustness, flexibility, integrated resource management and cost savings.

Chapter 7 summarizes the research work, highlights its contributions, and provides recommendations for future research.

Chapter 2

Literature Review

2.1 Introduction

This chapter first briefly introduces the broad scope of projects in the construction sector followed by a detailed review of the unique characteristics of repetitive infrastructure projects. This is followed by a comprehensive review of the recent literature in traditional scheduling and repetitive scheduling methods and optimization models. Finally, a review of resource management, allocation and optimization techniques for resource-constrained projects is presented along with a quick overview of current techniques of interest dedicated to future advancements in complex repetitive project scheduling. The chapter concludes with a summary of the research gaps in the presented literature that is to be addressed in the proposed research.

2.2 Types of Repetitive Projects

Most civil infrastructure projects are generally repetitive projects with synchronized execution of construction activities across multiple repetitive units. These projects, like large assembly line projects, are very resource demanding and can be classified into three groups, as shown in Figure 2-1: (1) Linear horizontal projects such as pipelines and roads with many sections; (2) Non-Linear Scattered projects such as multi-bridge rehabilitation programs or multiple housing units; and (3) Non-Linear vertical projects such as high-rise buildings. The first two types, cover the wide range of infrastructure projects, either new projects or rehabilitation projects. Though each type of repetitive project has its unique challenges as shown in Table 2-1, they share some common challenges and traits, particularly the need for efficient resource and work synchronization to benefit from the economy of scale, much like assembly lines in manufacturing.

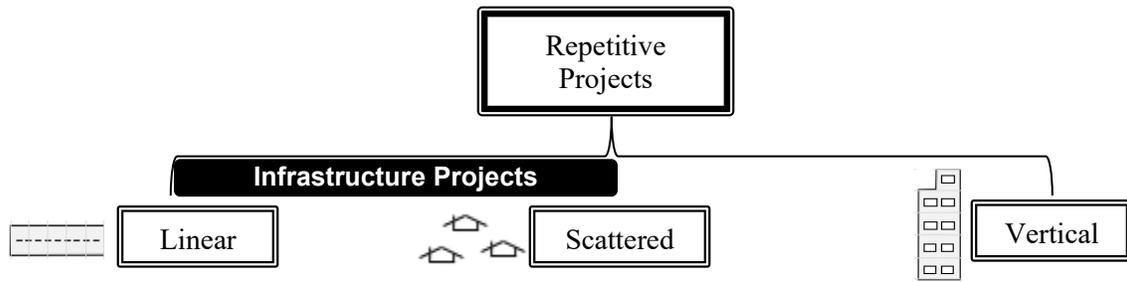


Figure 2-1 - Types of Repetitive Projects

The difficulty of scheduling repetitive construction projects arises due to the complex relationships among activities, repetitive units, and resources. Unlike the case of a non-repetitive project, e.g., a single detached house or a mall, repetitive construction work demands that the work crews repeat similar tasks while moving from one location to another, one floor to another, or one building to another. Some construction tasks need to be completed only once (e.g., the roof of a building for a vertical project is only completed once), hence repetitive projects can sometimes also be a combination of both repetitive and non-repetitive tasks (Tomar & Bansal, 2019).

Table 2-1 - Unique challenges of repetitive projects

Linear Projects	Scattered Projects	Vertical Projects
<p>Tasks can be completed at multiple units simultaneously (e.g., having two crews working from both ends of a road to save time).</p> <p>All tasks are completed in a certain sequence.</p>	<p>Each task can be completed with its unique unit sequence across the different units of the project.</p> <p>The time and cost to move the crews among the different geographical units should be considered to achieve a realistic and reliable project schedule.</p>	<p>Structural tasks must be completed from bottom to top.</p> <p>Finishing tasks can be completed in any sequence – bottom-up or top-down.</p> <p>Vertical relationships between a task in one unit and another task in another unit can exist.</p> <p><u>These projects will not be addressed in this research.</u></p>

2.3 Scheduling of Repetitive Projects

Despite the extensive literature work to tackle construction project scheduling, many projects are still completed late, resulting in a subtle lack of confidence in methods and solutions used to plan these projects, especially among general site personnel (Kenley, 2004; Moreno et al., 2020). It is clear from the literature and investigations that the lack of appropriate and reliable initial project planning most often is the cause of the delays and variability in these projects (Moreno et al., 2020). To tackle the complexity of scheduling large repetitive projects, optimization has garnered a strong research direction as well as mathematical methods such as linear, non-linear, and dynamic programming, though they can mostly only find exact solutions for small sized projects with a few activities, small number of crews (i.e. small number of constraints and decision variables) (Selinger, 1980; Reda, 1990; Senouci & Eldin, 1996; El-Rayes & Ramanathan, 2002).

Typically, the Critical Path Method (CPM) has been the most widely used scheduling tool in different industries (Kenley, 2004) and has been applied to construction projects for more than half a century. A typical non-repetitive project schedule calculated using CPM is done using a network diagram of the project activities that shows the relationship and precedence between the activities. A simple activity-on-node network diagram of 6 sequential activities in a one-unit (i.e., non-repetitive) project is shown below in Figure 2-2. The earliest start time (EST), earliest finish time (EFT), latest start time (LST), and Latest Finish Time (LFT) for each activity can then be calculated using CPM equations (Tomar & Bansal, 2019). The EFT and LFT of the last activity in the activity network diagram is always the same and represents the last day of the project (i.e. project duration) (Tomar & Bansal, 2019). In the case of a repetitive project, the CPM of the first unit, calculated just like the above example, is then copied or repeated for other units in order to calculate the overall project duration across the different units. CPM is an adequate and proven scheduling technique for non-

repetitive projects but has well documented shortcomings when applied to repetitive projects (Tomar & Bansal, 2019; Olivieri et al., 2018; Hassan & El-Rayes, 2020; Mazars & Francis, 2020; Tomczak & Jaškowski, 2020; Vanhoucke, 2006; O'Brien, 1975).

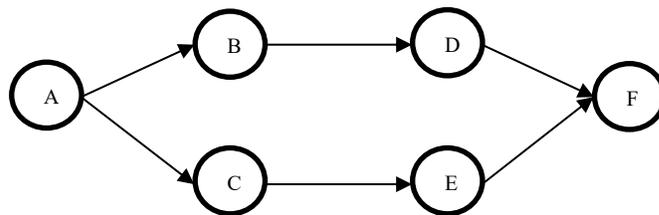


Figure 2-2 - Simple activity network diagram showing precedence relationships

CPM does not have computational formulations to maintain continuity of work among units and activities nor visualization capacities to present the large amount of schedule information in these projects associated with the differences in tasks' rates or the crew movements among the work locations (units). For repetitive projects, the CPM calculations schedule each activity after the conclusion of its predecessor(s), whenever that may be and overlooks the importance of having the crews maintain work continuity as they move from one unit to another. For example, from one unit to the other, faster crews would be idle for a period of time while waiting for predecessor activities that employ slower crews to be completed. To address the CPM drawbacks, techniques have been developed in an attempt to synchronize resources, maintain work continuity, incorporate non-repetitive tasks within repetitive projects, respect project deadlines, and account for learning curve effects. Examples of the developed techniques include the Line Of Balance (LOB) (Arditi & M.Z., 1986); the Linear Scheduling Model (LSM) (Harmelink & Rowings, 1998); and the Repetitive Scheduling Method (Harris & Ioannou, 1998) Productivity Scheduling Method (Lucko, 2008), Location-Based Management and Scheduling (LBMS) (Kenley & Seppänen, 2010), and other recent variations (e.g. Su and Lucko (2016); Shah (2014)).

The LOB technique, introduced in 1962, is a scheduling approach that addresses the assessments, selections, and presentations in graphical form, of the driving factors involved in a production process as measured against time. Originally adopted in the manufacturing industry, it generally ensures compliance with work and resource continuity for all the identified factors in the production process. In the construction industry, LOB methods have been developed to provide more accuracy and flexibility in scheduling repetitive activities for a construction project. Since it is better suited for spatial planning, more so than CPM, it provides better considerations for the different units/locations, activities and resources that need to be considered (Firat et al., 2009; Hyun et al., 2020). Usually on an LOB chart, the activity schedule is calculated and developed by means of a specified production rate. As shown below in Figure 2-3(a), the production rate of an activity is shown by the linear connection between the activity's units and the buffer time between the activities is also easily depicted (Hyun et al., 2020; Yi & Lucko, 2015).

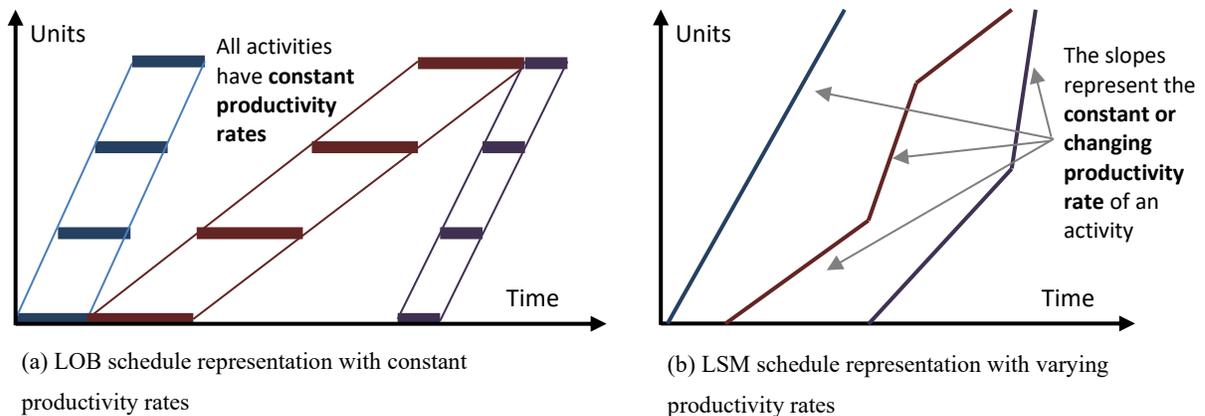


Figure 2-3 - Comparison of LOB & LSM graphical scheduling methods

An important improvement of LOB over CPM is its clear representation of the project progress as the start and finish times of each activity at each unit is shown and the progress of the crews from one unit to the other is easily observed. The LOB method, however, is suitable primarily for sequential activities or activity networks such as those found in simple small repetitive projects.

While being an improvement from the CPM technique, LOB charts represent each unit on a vertical index, without showing distances or exact locations, which are necessary for linear projects. As an alternative representation to LOB, therefore, Johnston (1981) introduced the Linear Scheduling Method (LSM) where activities are plotted with the vertical axis representing distances and locations of the repetitive units. The activities are plotted as straight lines and the productivity rate is represented by the constant or changing slopes as depicted in Figure 2-3(b). In Figure 2-3(b) a different project (from Figure 2-3(a)) is shown and the first activity is completed with the same productivity rate (i.e., constant slope) while the second & third activities having varying productivity rates while being completed (i.e., changing slopes). However, it is primarily a graphical method and thus lacks numerical computations (Chzanowski & Johnston, 1986). Also, the linear chart does not easily show the durations of the tasks at the various units. To combine the benefits of the two representations, Hegazy et al. (2020) introduced the Duration-Distance chart representation shown in Figure 2-4, with the vertical axis shows the distance measure of each unit in proportion to the others. The duration of the activities is clearly shown as well as the productivity rate. As such, this representation is the one used in the developments proposed in this research.

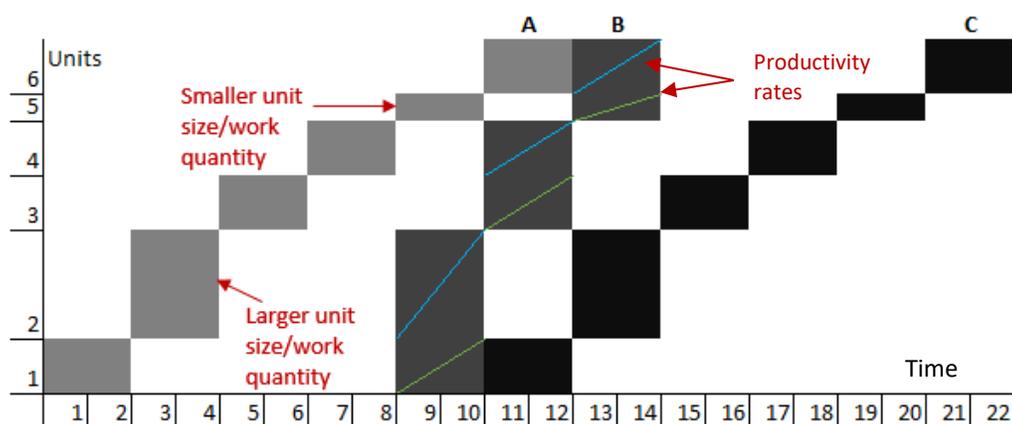


Figure 2-4 - Duration-Distance representation of a repetitive schedule

2.3.1 The CPM/LOB Scheduling Formulation

The cornerstone of repetitive scheduling methods is ensuring crew work continuity across the repetitive locations/units and over the project duration (Shim & Kim, 2014). This continuous workflow helps to minimize the required mobilizations and demobilizations as the crews move from location to location, establish a good work momentum and increase or maintain the crew productivity as the number of repetitions increase which leads to both time and cost savings (Olivieri et al., 2018; Altuwaim & El-Rayes, 2018; Bakry et al., 2014).

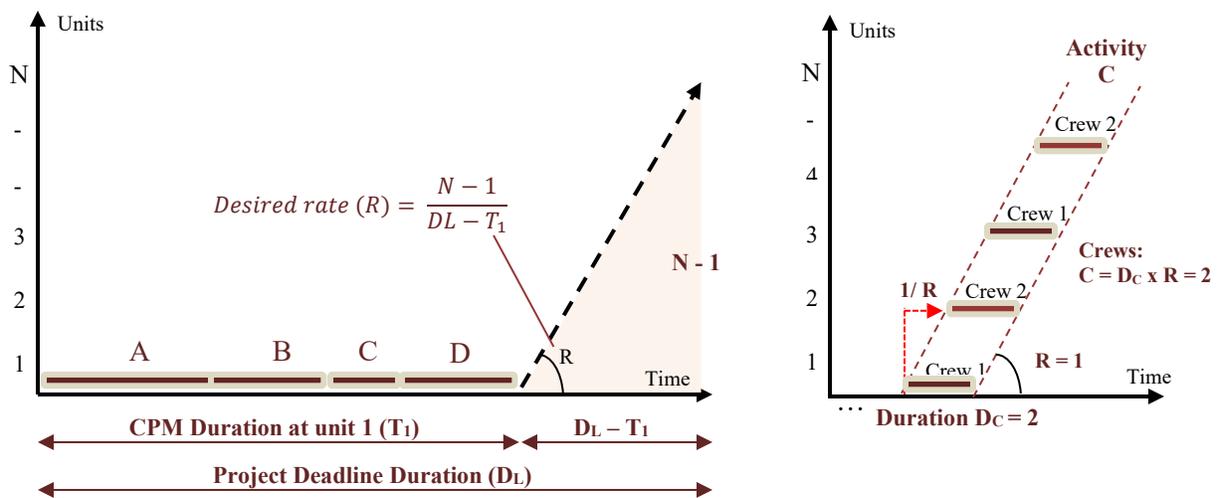


Figure 2-5 - CPM/LOB Computations for shifted crews

Because CPM network analysis can consider the logical relationship within each repetitive unit, Suhail and Neale's research (1994) presented one of the first mathematical CPM/LOB formulation that combines the CPM network analysis and LOB method for repetitive scheduling. The formulation is used to determine task delivery rates and thus the required crews that meet a specified deadline.

For a project with a specified deadline (D_L), existing CPM/LOB calculations begin with conventional CPM formulations to calculate the duration of one unit (T_1), as shown in Figure 2-5

(Hegazy, 2002). After completing unit 1, the shaded triangle on the left side of Figure 2-5 shows that the remaining N-1 units will need to be delivered in the remaining $(D_L - T_1)$ days, at a desired progress rate calculated in (2.1).

Equation (2.1) also includes the total float of the activity (TF) which acts as a flexible adjustment factor to reduce the delivery rate of non-critical activities. Thereafter, the number of required crews is calculated based on the desired rate of delivery (R) and the activity durations (D) using (2.2). The adjusted delivery rate using the integer value of the crews (C) is recalculated through (2.3). This calculation results in a schedule with shifted crew arrangement (right side of Figure 2-5). In this schedule, for activity C with a duration D_C , crew continuity is maintained, and crews are arranged so that each unit (all are identical) starts at a $(1/R)$ timeframe after the previous unit. The key drawback of this computation is that crew start times are not integer, thus being impractical and unrealistic to implement as multiple crews cannot easily be planned to start at different times in the middle of the day.

$$\mathbf{Desired\ Rate\ for\ task\ } i \mathbf{ (} R_i \mathbf{) = } \frac{(N-1)}{(D_L - T_1 + TF_i)} \quad (2.1)$$

$$\mathbf{Task\ Crews\ (} C_i \mathbf{) = Roundup}(D_i \times R_i) \quad (2.2)$$

$$\mathbf{Adjusted\ Task\ Rate\ (} R_i \mathbf{) = } C_i / D_i \quad (2.3)$$

Because the crews can be arranged in a parallel, rather than shifted, manner, a revised CPM/LOB formulation was introduced by Hegazy et al. (2020) for the case of parallel crews. The crews are scheduled as S cycles of C crews that achieve the desired delivery rate using (2.4) to (2.6). These equations are demonstrated in the example provided in Figure 2-6, where the number of crews of task ‘C’ is 3 crews engaged in 5 cycles to complete all 15 units.

$$\text{Initial cycles } (S_i) = \frac{(D_L - T_1)}{D_i} + 1 \quad (2.4)$$

$$\text{Number of parallel crews } (C_i) = \text{Roundup}\left(\frac{N}{S_i}\right); 1 \leq C_i \leq N \text{ and } C_i \leq \text{Crew Limit}_i \quad (2.5)$$

$$\text{Actual cycles } (S_i) = \text{Roundup}\left(\frac{N}{C_i}\right) \quad (2.6)$$

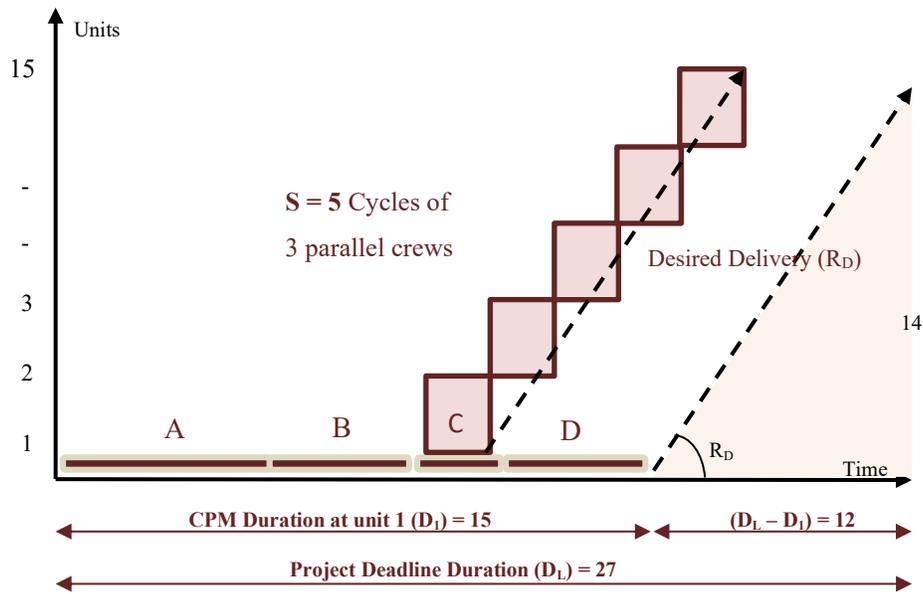


Figure 2-6 - Updated CPM/LOB computations for parallel crews

2.3.2 Persistent CPM/LOB Scheduling Challenges

While the CPM/LOB formulation is simple and effective for simple projects with identical units, it requires additional enhancements for more practical and complex scenarios, as will be addressed in later chapters, particularly due to the rounding of the number of activity crews (Zou et al., 2018a). Dolabi et al. (2014) introduced the Heuristic Line of Balance (HLOB), as an improvement to the CPM/LOB scheduling methodology. The HLOB calculates a schedule that satisfies deadline constraints despite the rounding of the number of crews for repetitive projects. Firat et al. (2009) proposed a similar improvement – the Advanced Line-of-Balance (AloB) approach, that improves the

LOB schedule visualization and caters to repetitive projects with varying unit sizes by grouping activities with similar production rates.

Using CPM/LOB for simple projects with identical units can meet deadlines and maintain work continuity, leading to an ideal repetitive schedule with synchronized task speeds that leaves no time gaps among the tasks, as shown in Figure 2-7(a). However, in more practical situations with non-identical units and crew availability constraints, task speeds will differ (Figure 2-7(b)), thus, the schedule will exhibit time gaps that lead to deadline violation. For example, using fewer crews on some tasks (e.g., A and C in Figure 2-7(b)) due to crew availability limits leads to unsynchronized task delivery rates and thus schedule gaps and a delayed project duration. This is a simple example of the considerations that must be made to obtain an optimal repetitive schedule. Another one of the factors that leads to schedule gaps is when the activities have non-identical units. In this case, the scheduling successive activities and assigning which crew to which unit becomes a very challenging task that can affect project duration and the amount of schedule gaps.

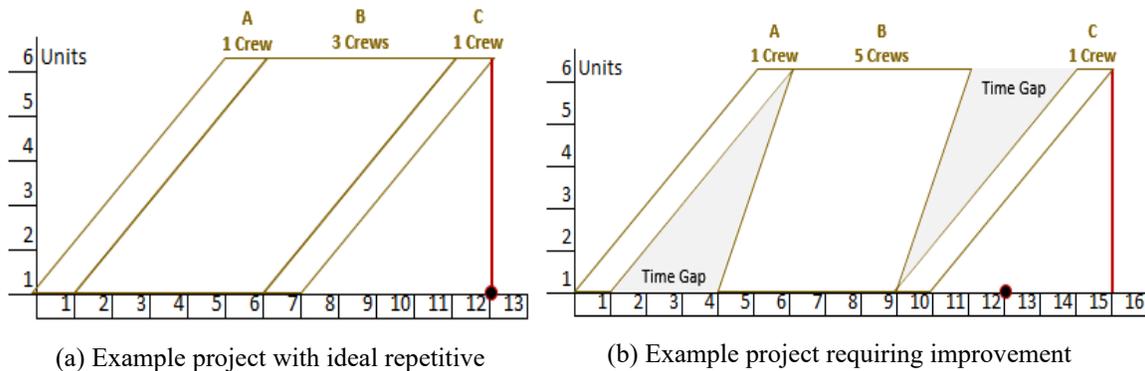


Figure 2-7 - Schedule time gaps due to unsynchronized task delivery rates

In the typical CPM/LOB formulation, once the number of crews is calculated, the schedule is drawn one activity at a time, following the CPM network. To schedule and draw a successor

repetitive task after its predecessor, given that the two activities have different speeds and unit durations, researchers (e.g., Hegazy and Kamarah (2008); Laramée (1983)) utilize an approach whereby the successor task is plotted to start at a time in the future (Figure 2-8), then shifted backwards to start immediately after the predecessor. This approach has been termed the “Delta-Shift” approach.

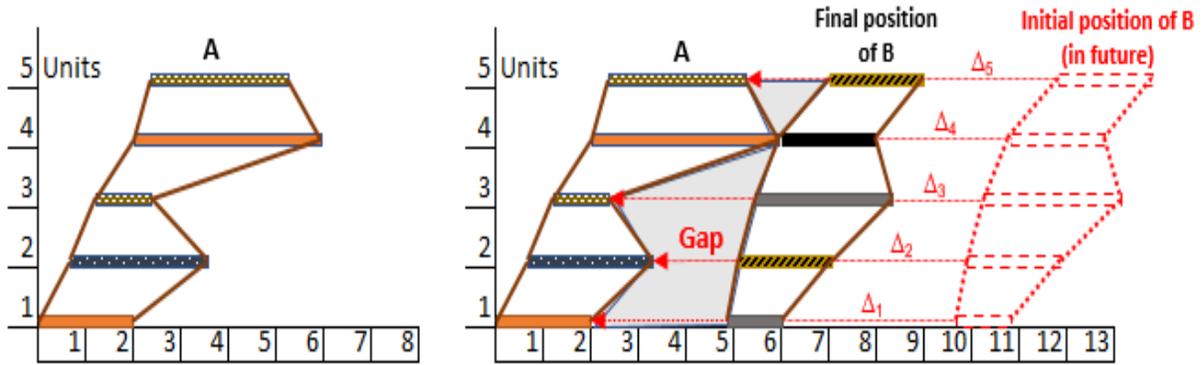


Figure 2-8 - Delta-Shift approach for non-identical units

Another variation of the delta-shift method used by other researchers (e.g., Long and Ohsato (2009)) is to draw the successor task at time zero and then calculate a required Delta-Shift time to move the task immediately following the predecessor. A third variation used in this thesis where the initial position of the successor is drawn at the start time of the predecessor. Then, the maximum shift time among the units (Figure 2-9) is calculated using (2.7) and (2.8), where task A has C_A crews and identical unit durations D_A . The successor B also has C_B crews and identical durations D_B along N units, where x is the unit with the maximum delta-shift value.

$$\Delta Shift_N = \text{Max} \{f(x): x = 1, 2, \dots \text{unit } N\} \quad (2.7)$$

where, $f(x) = \text{Predecessor Finish}(x) - \text{Initial Successor Start}(x)$

$$\Delta Shift_N = f(x) = \text{Roundup}\left(\frac{x}{C_A}\right) \times D_A - \left(\text{Roundup}\left(\frac{x}{C_B}\right) \times D_B\right) \quad (2.8)$$

In Figure 2-9(b), the initial position of activity B starts at time 0, then the delta-shift for each unit (arrows) is calculated, with the maximum delta-shift shown at the 7th unit (3 days), thus, task B is shifted forward 3 days. The Delta-Shift process provides an effective scheduling method for the parallel crews calculated with the CPM/OB method and respects logical relations at each unit, thus provides an effective formulation for non-typical activities. Though the delta-shift scheduling process in combination with parallel crews is effective for scheduling tasks with different crews/durations, it creates schedule time gaps between tasks, as shown in Figure 2-8 and Figure 2-9(b). These gaps are a result of the delta-shift process which treats the tasks as large blocks that are placed next to each other regardless of the gaps that may form due to the non-identical units or crews.

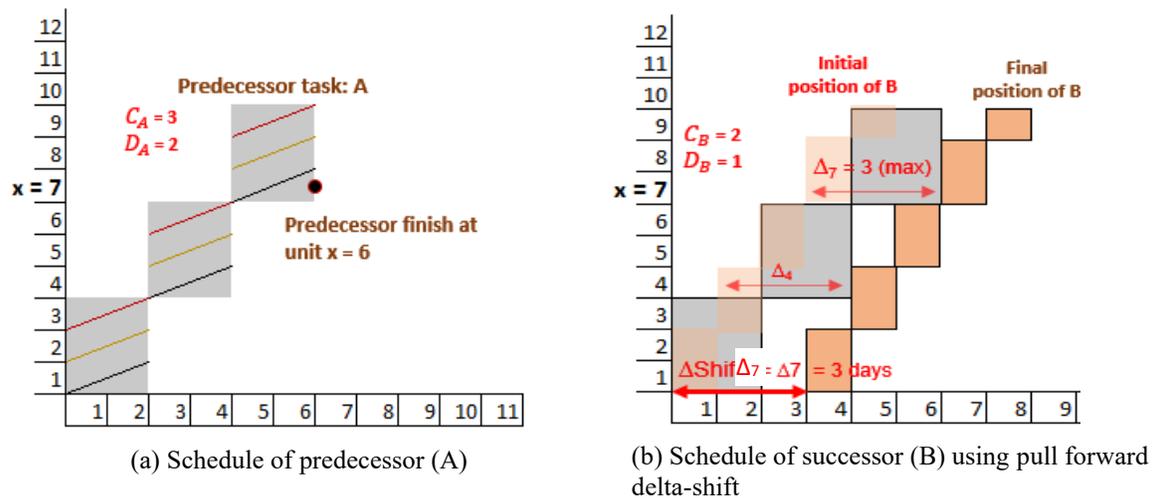


Figure 2-9 - Sample project schedule using Delta-Shift computation

Another drawback of the typical CPM/LOB formulation is its inconsistencies and inaccuracies with calculating the activity crews, which are often underestimated leading to deadline violations. These inaccuracies and schedule delays can arise due to a number of factors including crew rounding, using integer start and finish dates and crew limits etc. Unexpected deadline violations can also result from relaxed deadlines due to activity crew underestimation using the CPM/LOB calculations as proven by Hegazy et al. (2021). To help meet the deadline under complex situations, a crew adjustment loop

proposed by Mostafa (2021) utilizes an iterative recalculation of the number of crews based on (2.1) and (2.2). The calculated crews are calculated based on the difference between the project deadline (D_L) and the CPM duration of a unit (T_1). Thus, the smaller the difference (i.e., $D_L - T_1$), the larger the number of crews calculated for the tasks. The proposed crew adjustment loop increases the activity crews if the project deadline is violated by iteratively reducing the ($D_L - T_1$) difference by 1 until the schedule no longer exceeds the set deadline.

2.3.3 The First-Come-First-Served Crew Assignment

The key concept of the FCFS (Hegazy et al., 2020) is to handle each crew individually, rather than each task as a block, thus being more flexible in the crew assignment process, which reduces schedule time-gaps and can arrive at shorter schedule durations. If the project shown in Figure 2-10, with two activities A & B over 9 units, is taken as a sample, the FCFS crew assignment process to schedule the successor activity B, is as follows (illustrated in Figure 2-11):

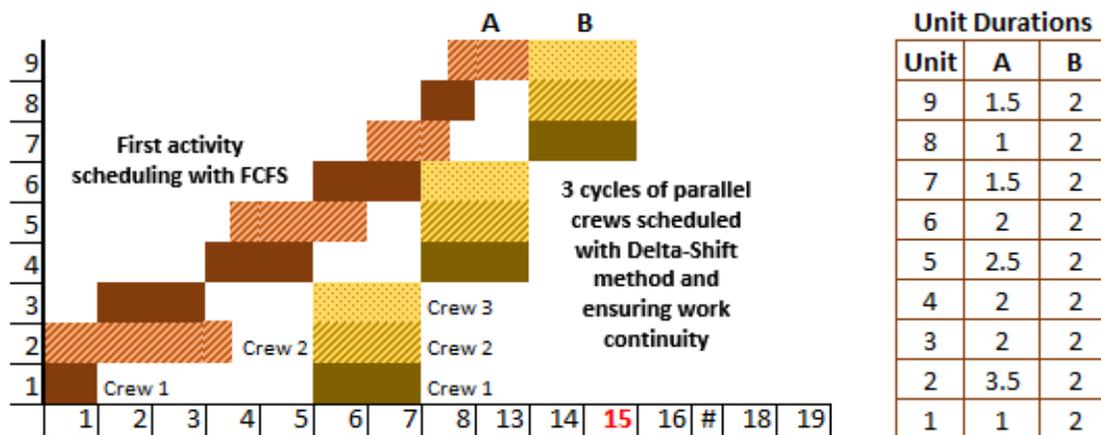


Figure 2-10 - Sample project scheduled with parallel crews and Delta-Shift

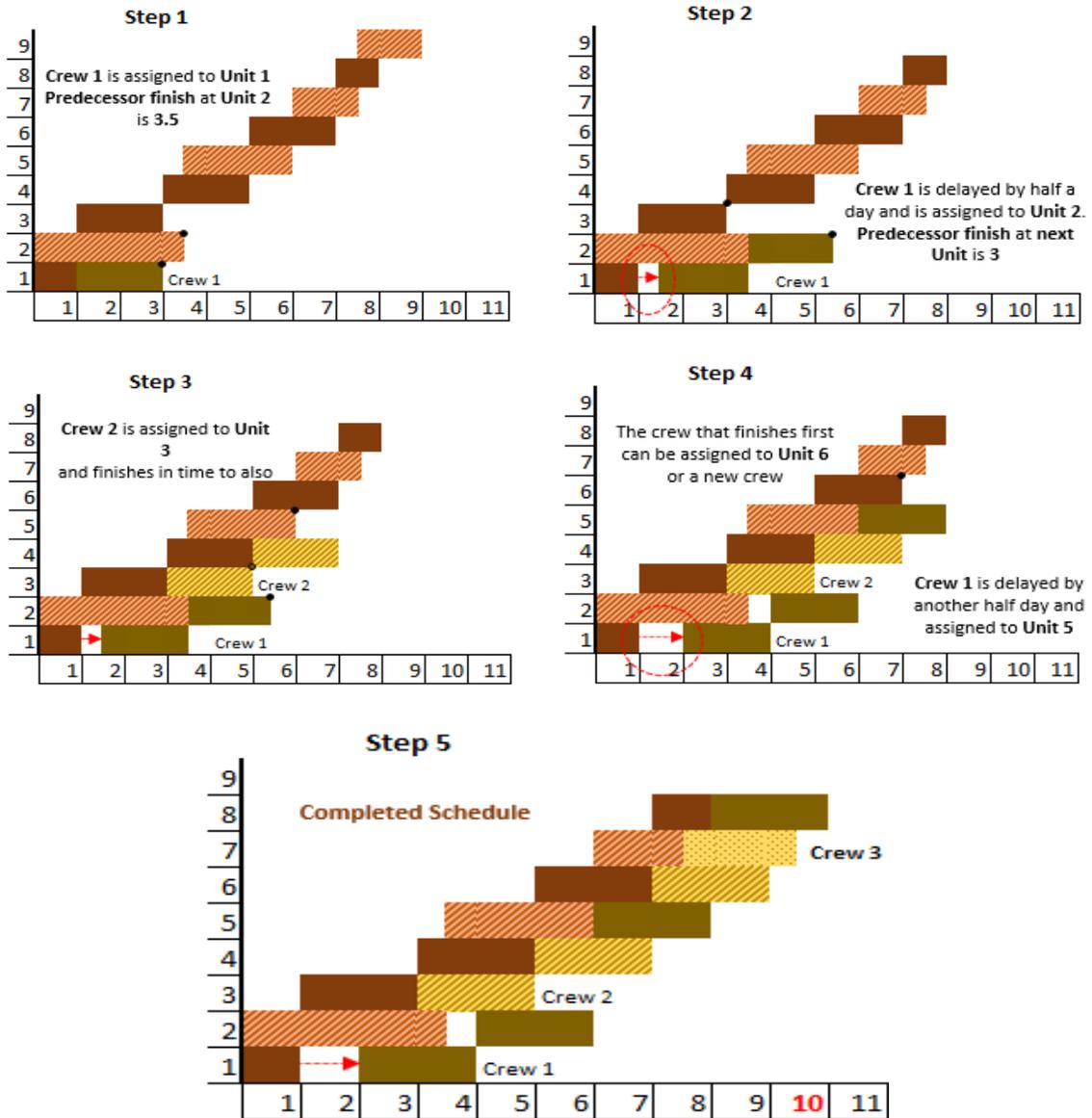


Figure 2-11 - Schedule generated using FCFS

1. In the first step, all crews of activity B (2) are available. Crew 1 of activity B can thus be assigned to the first unit after the Predecessor (A) at unit 1 (Step 1 in Figure 2-11).

2. At unit 2, the finish time of predecessor (A) is greater than the current finish of crew 1. Hence, crew 1 is available to work when unit B2 can start. To maintain work continuity and avoid crew idling between unit 1 and 2, Crew 1 is delayed by 0.5 day (Step 2).
3. In step 3, the predecessor finish is day 3, Crew 1 will not be available until day 5.5. Since another crew is available, a new Crew 2 can be assigned to complete activity B at unit 3.
4. At unit 4, based on the predecessor finish (Day 5), Crew 2 will be the earliest available crew at day 5, thus Crew 2 is assigned to unit 4 at time 5.
5. For unit 5, following the predecessor finish (Day 6), Crew 1 will be the earliest available at time 5.5, accordingly, Crew 1 is assigned to unit 5 and its previously assigned units (1 and 2) are delayed half day to ensure work continuity.

Following this process, the final schedule is shown in Figure 2-11.

As shown in this example, the FCFS schedule (Figure 2-11) has multiple benefits over the delta-shift schedule (Figure 2-10): (1) Much fewer time gaps; (2) Better synchronized tasks, hence continuity within each unit is improved; and (3) Better crew utilization as Crew 3 for task B is only needed for one unit. In addition, FCFS is generic and can minimize gaps due to non-identical units, and also produces optimal crew assignments. The efficacy of the FCFS is in maintaining the continuity of each crew individually, from unit-to-unit, by assigning the earliest available crew to a unit, and adding new crews only when necessary. Though the FCFS enhances CPM/LOB computation, it does not guarantee meeting deadlines and does not consider the availability limit of the individual resources that form the crews, nor accommodate practical crews' strategies that are needed for linear and scattered projects, such as variable unit sequence. Thus, several efforts to enhance resource management for repetitive scheduling have been investigated in the literature.

2.3.4 Repetitive Scheduling with Flexible Unit Order

With the flexibilities of the FCFS in allocating crews individually, different approaches to improve a project schedule and duration can be introduced. One such robust crew assignment strategy is having varying unit orders for the project activities. With the FCFS crew assignment, a non-serial unit order can easily be implemented and scheduled. This flexibility is particularly useful for scattered projects, whereby the order of the different geographical work sites can greatly affect the total project duration or resource management, as it allows each activity to follow its own non-standard sequence among the units, rather than pure sequential from unit 1 to unit N.

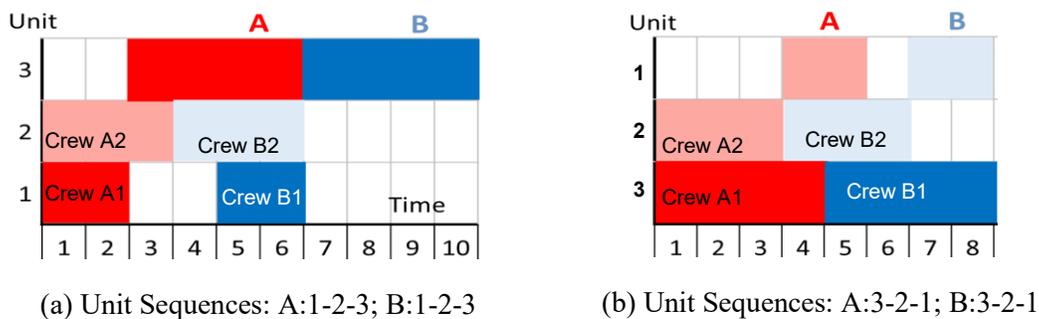


Figure 2-12 - Effect of flexible unit order on Crew Assignment and Project Duration

The effectiveness of this approach is presented by Hegazy and Kamarah (2022) along with the benefits of considering unit order optimization for better project scheduling and resource management (Kamarah, 2018). Figure 2-12 demonstrates the effectiveness of flexible unit orders for a sample project with two activities along three non-identical units that increase in size (and duration) from unit 1 to 3. With two crews in each task, a schedule using unit sequences of “1-2-3” for both tasks is shown in Figure 2-12(a), with 10-day duration.

Changing the unit order to a descending sequence based on unit size (or duration) would result in a unit sequence: “3-2-1” for both tasks. The new duration with this sequence is shorter, finishing in 8-days (Figure 2-12(b)). As such, it is possible to try different unit sequences to reach a more optimal schedule. As testing different unit sequence combinations can become complex or require sophisticated optimization tools for larger projects with multiple activities and units, a simple heuristic of following a descending sequence as introduced by Mostafa (2021) is a reliable strategy.

2.3.5 Resource Management

Based on the above discussion, CPM/LOB repetitive scheduling is not an easy task, particularly under strict deadlines, crew availability limits, non-identical units, and required different sequence of units in various tasks. Typically, resource limits are considered in terms of available task crews, but not the availability limit of individual resources that form the crews (e.g., laborers, carpenters, etc.). In the literature, various research efforts present scheduling improvements to handle either resource limits or strict project deadlines, while efforts that combine both are limited. Repetitive scheduling optimization, therefore, has attracted the attention of many researchers who developed models with different focus points.

Constrained Resource Scheduling (CRS) methods (e.g., Siu et al. (2016); Tran et al. (2016)) resolve resource overallocations by assigning resources to top priority tasks, based on a specific priority rule, and delaying the others, with an objective to reduce the consequent delays to the project. In recent years several advanced efforts have been developed to optimize the repetitive schedule considering a variety of conditions and constraints. Zou et al. (2018a; 2018b) presented a mixed-integer linear programming model for solving deadline satisfaction problems while considering

varying crew productivity and cost. Eid et al. (2018) developed a multicriteria optimization model that provides planners with a set of non-dominated solutions. Heravi and Moridi (2019) used particle swarm optimization to consider the effect of idle resources on the project cost. Monghasemi and Abdallah (2021) developed a linear programming model that determines the optimal execution order of units, which is especially useful for scattered projects. Ammar and Abdel-Maged (2018) incorporated the crews' momentum and learning curve effects. Alagha et al. (2021) used evolutionary algorithms to create repetitive schedules with minimum resource fluctuations.

2.4 Other Scheduling Techniques

Other research efforts have aimed at addressing different aspects of the multimode resource constrained scheduling problem (MRCSP). MRCSP refers to the optimization problem faced by repetitive projects that have multiple construction modes available as well as multiple resource constraints. Hence the MRCSP is one with numerous decision variables and optimization constraints. While some are also based on improvements to the CPM/LOB computation, others utilize mathematical modeling or other complex optimization models that address very specific optimization objectives. While this aims to introduce a comprehensive scheduling solution that is easily adapted and utilized for various repetitive scheduling problems, these scheduling techniques can potentially benefit from incorporating solutions from this research.

Hassan and El-Rayes (2020) presented a novel scheduling model, also roughly based on the LOB approach, that analyzes and quantifies the impact of activity delays on not just the project completion time, but also on the work continuity of its successor activities and thus overall project cost and work productivity. Moreno et al. (2020) also proposed a fixed start method (FSM) for repetitive project scheduling as an alternative to the traditional CPM approach. They highlight the sizeable benefits of building a scheduling model or method that efficiently utilizes or prioritizes historical data from

various projects that provides data on activities, completion times, crew sizes by activity etc. The FSM strategy itself is possible because of the more accurate activity duration estimations based on the historical data and probability distributions hence creating more reliable and implementable project schedules.

Poor material management can also negatively impact crew productivity rates and project duration, increasing the latter by up to 130% in some cases (Liu & Lu, 2018). Liu and Lu (2018) proposed an analytical methodology that is able to consider material logistics constraints along with the general resource constraints for scheduling and optimization. The solution quantified the impacts of variations in material demand and supply on the project costs.

Another scheduling consideration of interest is batch-sized scheduling Figure 2-13. Often, employed contractors or subcontractors are assigned work packages that may include multiple construction activities across multiple units. They may also be required to repeat this work package over the course of the project (Shim & Kim, 2014). Hence it may prove difficult or futile for the project owner or manager to schedule the individual units these contractors are responsible for as the estimations may be grossly inaccurate. A scheduling approach based on batch production can be employed.

Shim and Kim (2014) proposed a mathematical and heuristic computation to address the scheduling of repetitive projects using batch-size optimization. Existing methods for developing project schedules with batch-sizes involve mostly graphical approaches. These approaches are not quick and require re-drawing of the graph whenever a change is made in project variables. The mathematical and heuristic method proposed provides a model that can be used to calculate or adjust a project schedule, taking the various batch-sizes of the activities into consideration.

Other scheduling approaches also tackle the need to consider the topographical and environmental constraints and integration in repetitive project scheduling. Tomar and Bansal (2019) proposed a scheduling tool that combines 4D building models with GIS in order to take the geographical information of the construction site into consideration when developing the execution strategy and sequence for the project schedule. Elbeltagi and Dawood (2011) similarly proposed a 4D BIM + GIS based system that provides more real-time tracking and visualization of the progress and performance of repetitive projects as it is being completed.

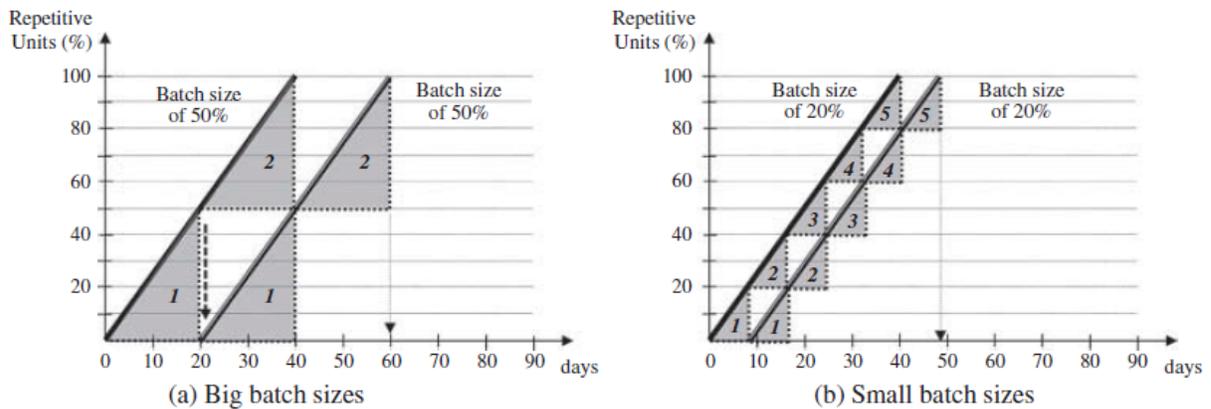


Figure 2-13 - Batch crew scheduling for repetitive projects (Shim & Kim, 2014)

Considerations of the locations (units) or workspaces where construction activities are completed is mostly neglected in construction project scheduling approaches which generally leads to workspace congestion and/or conflict and thus project delays and incurred costs (Francis, 2019; Mirzaei et al., 2018). Mirzaei et al. (2018) proposed a 4D-BIM scheduling approach that utilizes a developed project schedule to detect time-space conflicts between the scheduled activities, especially those scheduled to occur concurrently with multiple crews sharing a common workspace (e.g., parallel crews). Another workspace planning and scheduling method, suggested by Tao et al. (2018), makes use of a mathematical model to solve the space-time scheduling problem with repetitive projects.

Crashing a schedule without carrying out workspace evaluation may seem effective on paper but during implementation these workspace constraints and congestion make it difficult for multiple activities and crews to work in the same unit concurrently. To address this, Francis and Morin-Pepin (2017) investigated the impacts of resources and workspace management on activity float computations. Activity float is the widely used indicator for the potential for a project scheduled to be crashed. Hence inaccurate float computations can lead to unreliable project schedules that result in higher risks of completion for the project or unplanned costs.

Traditional repetitive scheduling methods group work locations into units (e.g., floors of a building) as discussed earlier. This approach typically addresses the scheduling optimization objectives of work continuity and resource allocation. However, to better address non-identical units as seen in more diversified real-world construction projects, an alternate approach introduced is the non-unit or workgroup-based scheduling. A non-unit-based scheduling model proposed by Huang and Sun (2006) groups similar activities across units into ‘activity groups’ with inherent logical relationships still present between the activity groups. This approach mostly allows a much better analysis of the resource chains and availability as some scheduling methods already allow for varying activity duration across units.

2.5 Summary and Research Gap

Developing executable repetitive project schedules that can be efficiently implemented in the real-world in consideration of the many practical and flexible situations related to linear and scattered projects is the key challenge in repetitive scheduling. CPM based methods, though effective for simple non-repetitive projects and extensively used, have serious drawbacks. Primarily, the CPM formulation when applied to repetitive projects is unable to respect project deadlines. CPM techniques are also not equipped to consider resource limits as resources are by default assumed to

always be available, leading to schedules requiring more resources than are available. Due to the large daily fluctuations also seen with these schedules, individual resource-leveling efforts are often required to avoid excessive mobilization and demobilization of resources and overall improved resource utilization. Although the CPM/LOB computations provide solutions to the drawbacks of the CPM method alone, they also do not address resource limits and are also prone to creating schedules with considerable gaps as the activities are scheduled as blocks and hence inefficient in the case of non-identical units.

Proper geometric arrangement of adjacent activities is the key to creating a schedule that is short and tightly packed with no gaps. This point thus indicates the importance of optimal geometric arrangement of the tasks and the flexibility of parallel crew arrangement to reduce schedule time gaps in the case of identical repetitive units. These optimal geometric adjustments can be achieved using the FCFS whereby crews are assigned non-sequentially to minimize time gaps. However, the FCFS approach also does not consider the very crucial aspect of repetitive project scheduling – resource management. In practical real-world projects, multiple resource constraints exist, both at the crew level and the individual resources levels (e.g., laborers, equipment etc.). A comprehensive framework that addresses these project constraints as well as resource constraints while being flexible enough to allow for non-identical units and work productivity through a mix of interruptions, batch sizes and speed changes to the activities' crews to achieve maximum synchronization between the project activities is not present in the literature. Despite their benefits, more complex mathematical and metaheuristics optimization models to address these project, activity and resource constraints in repetitive scheduling have some difficulties namely: the need of specialized software, black box processing (i.e., when the exact technique used by the model to attain its results are not known or easily replicated), frequent parameter tuning, and large processing time; making them suitable more

for improving, rather than generating, a solution. The generalized and comprehensive approach in this research can instead provide a starting solution for use by these optimization models.

Chapter 3

Improved CPM/LOB Computation to Meet Deadlines

3.1 Introduction

This chapter introduces the various proposed computational improvements for addressing the highlighted drawbacks and challenges of scheduling linear and scattered infrastructure projects. Critical drawbacks of existing approaches are presented to isolate the specified needs and areas of improvement. New heuristic formulations and logic have been developed to address these areas of improvement have been developed and are described as stand-alone or integrated solutions.

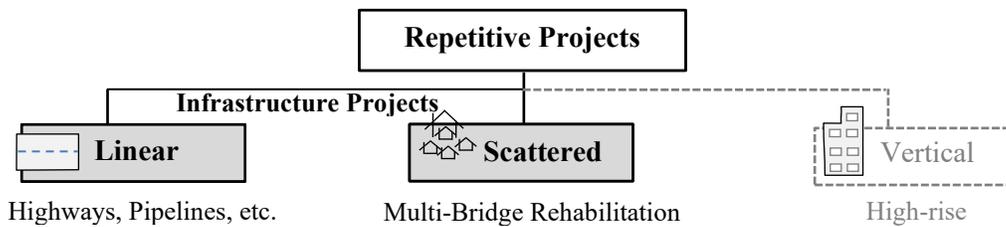
3.2 Scheduling Requirements

In addition to addressing the general requirements of repetitive project scheduling highlighted in Figure 3-1, the proposed computational improvements intend to address the unique requirements that apply to practical linear and scattered projects. Linear projects require fully flexible crew assignments, interruptions, and management to allow the crews to proceed from multiple units simultaneously and optimally. Scattered projects, in addition to needing fully flexible crew assignments that can be tailored from one activity to the other, also involve unique cases of batch crew assignments where multiple units are completed by a crew over the same time period as in the case of sub-contractors.

From 2.3.2, it is apparent that conventional CPM/LOB computation for repetitive scheduling are still challenged by complex situations that cause schedule gaps, and consequently schedule delays and/or resource violations. In addition to strict deadlines and resource shortages, most common schedule complexities of linear and scattered infrastructure projects include:

- Non-identical units or limited crews that disturb task synchronization and result in large variations in tasks' delivery rates.
- Tasks requiring crews to follow non-sequential orders.

These common project situations lead to large time gaps in the schedule and project delays; thus it is not intuitively or computationally easy to determine the correct number and best arrangement of activity crews to meet deadlines and eliminate these gaps.



- General Requirements:** (1) Meet deadlines, crew limits, resource limits, and crew continuity.
 (2) Produce schedules with synchronized speeds and minimum gaps.
 (3) Consider non-identical units and produce legible schedule visuals.

Unique Requirements:

- Any task can proceed at multiple units simultaneously (e.g., using two sets of crews working from both sides of a road to save time), following certain sequence.	- Each task can proceed with its unique sequence among units. - Need to consider the time and cost to move crews among units.
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Figure 3-1 - Scheduling Requirements for Linear & Scattered repetitive projects

Unsynchronized activity delivery rates arise when activities have very different durations, non-identical units, or the available crews to the activity are limited. Figure 3-2 shows two very simple cases of schedule gaps due to unequal activity durations and differing crew availabilities that lead to project delay. In Figure 3-2(a) all activities have one crew but have varying durations while in Figure 3-2(b) though the activities have the same duration, they have different number of crews available, A (1), B (3) and C (1) and as such the delivery rate of B is thrice that of A and C. The severity of the

project delay or schedule gap caused increases as the number of units increase. Other project cases with delays due to non-identical units have also been presented in chapter 2 (Figure 2-10).

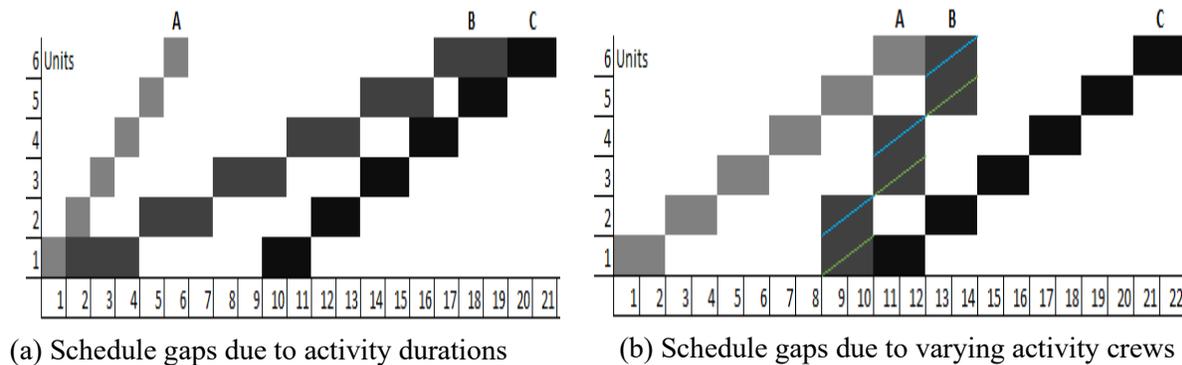


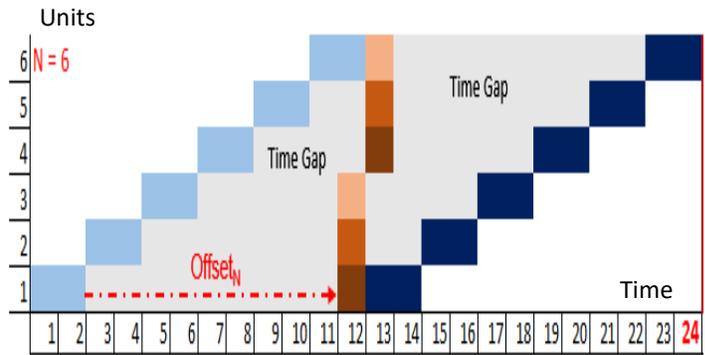
Figure 3-2 - Schedule time gaps due to unsynchronized activity delivery rates

Arriving at a solution with synchronized activity delivery rates (i.e., making them as parallel as possible) can be a difficult task due to the different project and activity logic and resource constraints. A quicker and reliable solution is introducing an interruption as shown in Figure 3-3. Different approaches to incorporate designed interruptions have been studied by many researchers (Hyari & El-Rayes, 2006; Long & Ohsato, 2009; Altuwaim & El-Rayes, 2018). The project case in Figure 3-3(a) with 6 units (i.e. $N = 6$) as an example can be improved by including a work interruption for activity B at mid-unit ($N/2 = 3$), which allows activity C to start earlier thereby reducing the gap and allowing the project to finish earlier. Currently most approaches to determine schedule interruptions is done by trial and error or complex optimization models. A simpler mathematical formulation was also developed by Hegazy et al. (2020) whereby the interruption is calculated at mid-unit and is based on total gap between an activity and its predecessor. This formulation requires the delta-shift (2.7) and starts with a calculation of the offset distance using (3.1). The interruption calculation is illustrated in

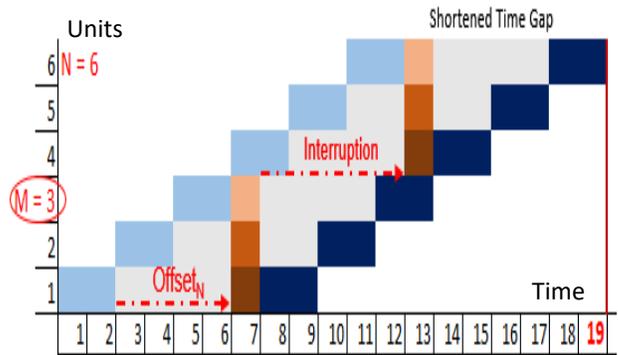
Figure 3-3 which shows a project with 6 units and 3 repetitive activities having different crews and durations (Hegazy et al., 2020; 2021):

$$Offset_N = \Delta Shift_N - D_{Predecessor} \quad (3.1)$$

$$Interruption\ time\ at\ unit\ M = Offset_N - Offset_M \quad (3.2)$$



(a) Original with unsynchronized activity rates and time gaps



(b) Designed interruption to reduce schedule delays

Figure 3-3 - Impacts of designed interruption for synchronizing activity delivery rates

The calculated offset distance ($Offset_N$) for activity B in Figure 3-3 is 9 days. The offset distance at the interruption unit, which is chosen as the mid-unit ($M = 4$) is then calculated with the same (3.1). The total interruption time at unit M can then be calculated using (3.2), which is 5 days, removing the need for trial-and-error attempts to arrive at a suitable interruption. The resulting schedule is shown in

Figure 3-3(b). and with an interruption of 5 days, the successor activity C can start earlier on day 8, saving project time (from day 24 to day 19).

The mathematical formulation though an improvement from time-consuming trial & error approaches and complex model optimization, is ineffective for the practical case of non-identical units and interruption of individual crews of an activity is not explored. Therefore, improvements are needed to optimize the interruption implementation.

Another schedule intervention to reduce time gaps and synchronize activity delivery rates is to introduce mid-activity changes, as shown in Figure 3-4. This can be done by either adding or removing some crews after a specific unit of the task thus changing the activity rate. In Figure 3-4, the slopes of the activity bars in the schedule are adjusted to fit closer together. Determining the appropriate unit to adjust the activity rate and how many crews to add or subtract usually requires some trial and error after a schedule has been calculated. A heuristic procedure to maximize tasks synchronization using this rate change strategy is also discussed later in this chapter.



Figure 3-4 - Changes to activity delivery rates to reduce schedule gaps

Some other practical situations that create schedule time gaps and can benefit from these schedule intervention methods are shown in Figure 3-5. Figure 3-5(a) illustrates a project case where multiple

predecessors (C & D) cause time gaps, while Figure 3-5(b) presents another project case whereby the unit order of a predecessor activity leads to schedule time gaps between it and its successor.

To address the drawbacks of existing interruption formulations and optimally address other schedule challenges, the following procedures are proposed:

- An improved heuristic process for determining optimal interruption for flexible crew-focused scheduling approaches such as FCFS which are better suited for linear & scattered projects.
- A flexible and comprehensive heuristic process to determine optimal activity speed changes that also allows for the co-existence of multiple construction modes.

These simplified heuristic processes provide improvements to scheduling of projects with identical and/or non-identical units or varying unit orders.

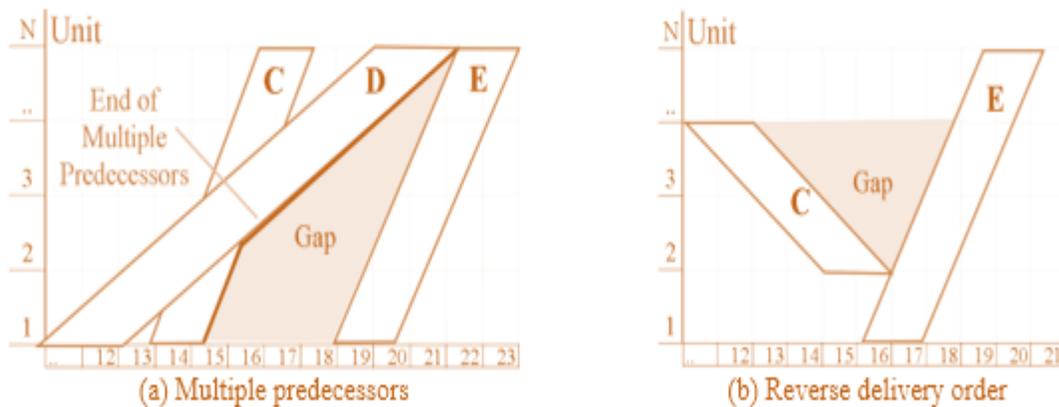


Figure 3-5 - Project situations causing schedule time gaps

3.3 Designed Interruption Formulation

In determining the optimal designed interruption for crew-focused scheduling, the following need to be considered: (1) Finding the optimal unit at which to apply the interruption; and (2) Deciding the number of crews that should be interrupted. Each of these is discussed next.

3.3.1 Determining Optimal Interruption Unit

Work interruptions used strategically can help reduce project duration with comparatively minor cost implications. Any associated costs could also be offset by the resulting schedule having less indirect cost and reduced penalties due to the earlier project finish date. The interrupted crew could also potentially be put to work on another project/task during that period, as an alternative cost offset. Introducing smaller interruptions such as those shown in Figure 3-6 could further result in a better synchronization of activities and shorter project duration but the cost of such interruptions such as idle crews, crew mobilization & demobilization and loss of productivity must be evaluated against the potential cost savings of finishing the project earlier.

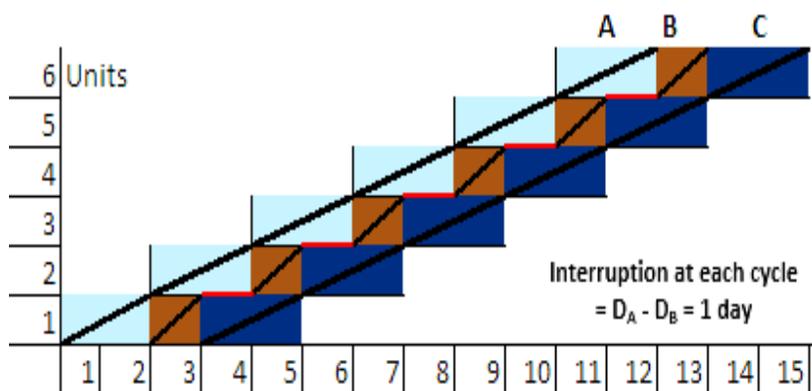


Figure 3-6 - Multiple activity interruption for tighter schedule

Finding the optimum amount of interruption by trial & error is time consuming, while using mathematical formulation applies to a predefined unit. A simple heuristic process is therefore proposed in this research where the benefits of interruptions are examined at different interruption units. Figure 3-7. shows three activities and the effect of interrupting the second activity at three preset locations: (1) at 25% of total worked units, (2) at 50% of total worked units, i.e., mid-unit, and (3) at 75% of total worked units. Depending on how strict the deadline of the project is, or the duration and crew formation of the activity's successors, an interruption at these different locations

has their different advantages. For the proposed interruption framework, a comprehensive set of six preset interrupt locations are considered (Table 3-1). These six interruption locations provide a robust and effective selection of possible interrupt locations while searching for the optimal interruption/project duration balance.

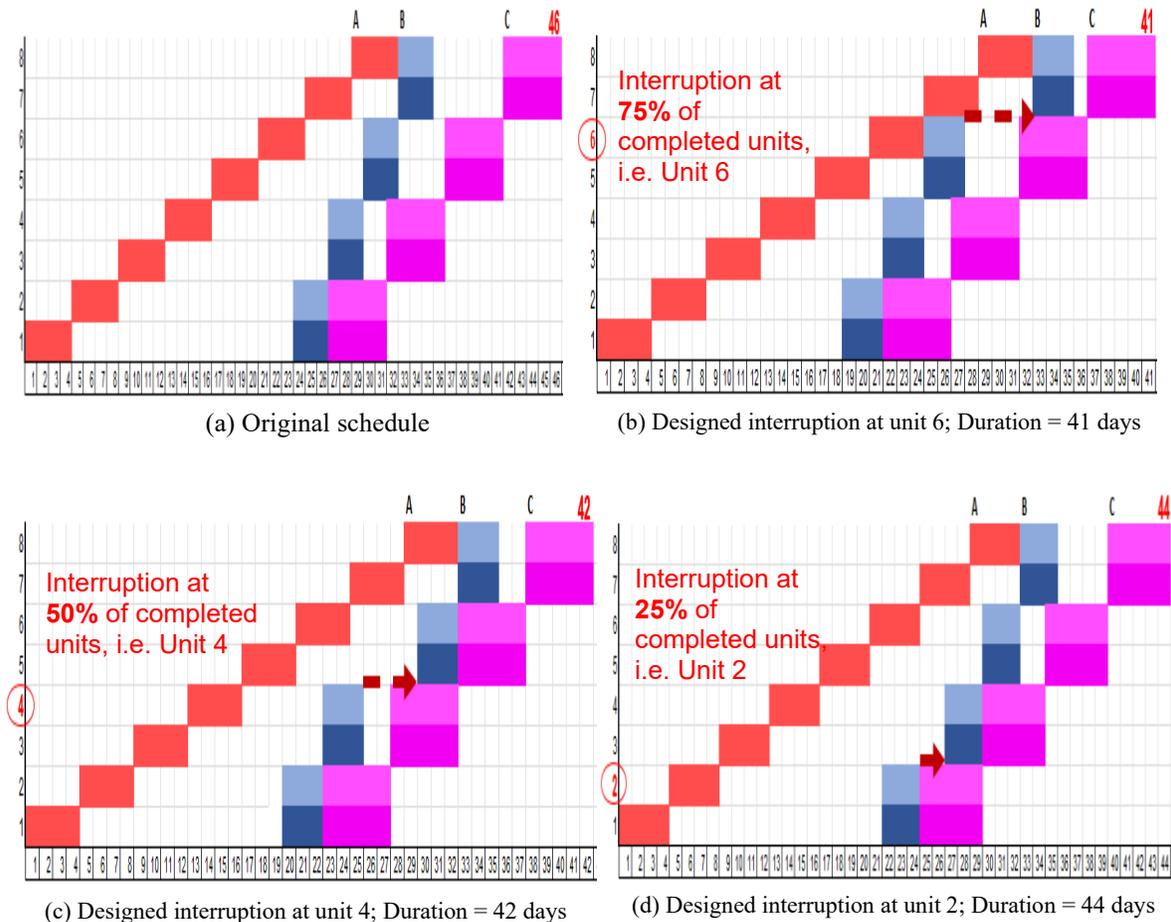


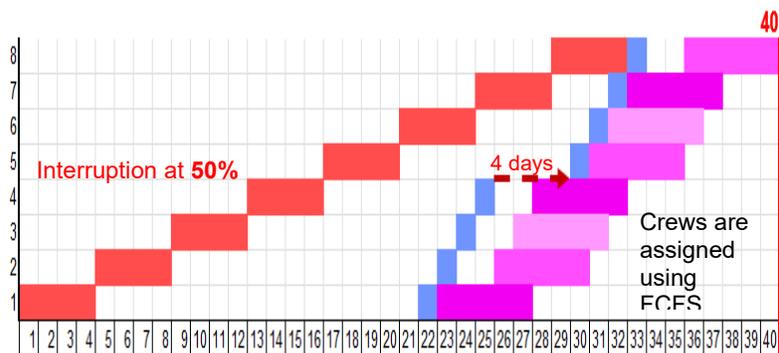
Figure 3-7 - Impacts of interruption at different units of an activity

The effectiveness of these preset interrupt locations is illustrated in Figure 3-8, which shows the interruption at unit 2 as providing the optimal interruption for the second activity. Although interrupting the second activity at both the 25% & 50% locations provides the same project duration,

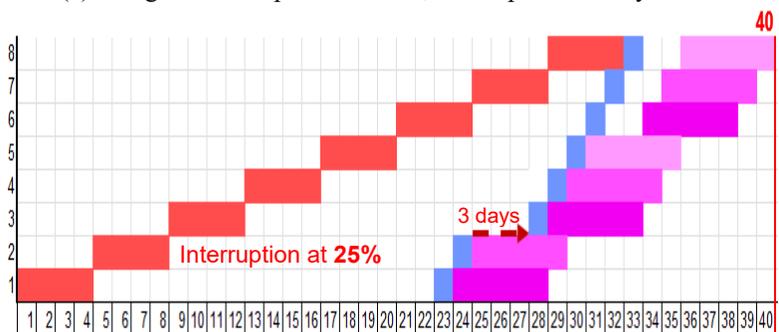
the framework selects an interruption at 25% as this provides the least amount of interruption for the same reduction in project duration. Any unnecessary interruption is also removed once an optimal solution is found. Determining this trade off in interrupt days versus saved project days is a key contribution of this interruption framework.

Table 3-1 - Preset Interruption Locations

Preset Interruption Locations	Shown in Figure 3-7
75% of worked units	(b)
50% of worked units	(c)
25% of worked units	(d)
75% & 50% of worked units	-
75% & 25% of worked units	-
50% & 25% of worked units	-



(a) Designed interruption at unit 4; Interruption = 4 days



(c) Designed interruption at unit 2; Interruption = 3 days

Figure 3-8 - Optimal interruption reduces schedule delays with least interruption time

3.3.2 Determining Optimal Crew Interruption

As discussed in chapter 2, the FCFS scheduling approach is most suitable for linear and scattered projects as it applies a crew-focused assignment that helps to minimize gaps between activities and caters to identical or non-identical units. In order to benefit from this crew-focused scheduling technique, the activity interruption must also take on a crew-focused approach. The optimal interruption for each crew of an activity would be calculated independently as interrupting each crew would have different impacts on the project schedule. However, when an activity is interrupted at a particular interrupt location, though this approach calls for each crew to be interrupted independently and does not calculate interruption using (3.2), benefits for the overall project duration might not be realized if only the crew at that unit is interrupted. This is illustrated in Figure 3-9. If only the crew at the interruption unit is interrupted, then the work schedule of crew 1 keeps the start of the successor activity at the same date. Thus, when determining the optimal interruption for an activity, the best combination of crew interruptions must be found.

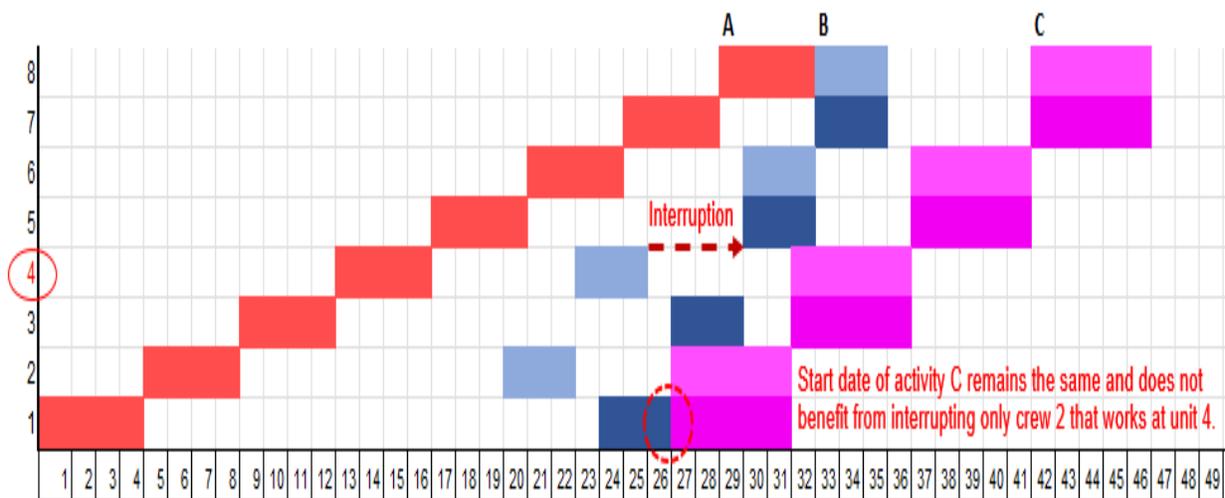


Figure 3-9 - Considerations for individual crew interruption

To develop a crew-focused interruption framework, each crew that works on an activity must be managed individually and interrupted individually using the unique interrupt locations for each crew. When an activity has multiple crews, each crew is assigned to a particular set of units thus the 6 preset locations, as defined above, for each crew would differ. To calculate which unit a crew should be interrupted based on its assigned units, (3.3) is used; where $intU_{iL}$ is the interruption unit(s) for the crew at the iL location and $MaxU_C$ & $MinU_C$ are the highest and lowest unit number the crew works on. For example, if a crew is to be interrupted at 75% of its worked units, (3.3) finds the unit at 75% for this particular crew based only on the units the crew works on not all the units of the project; because the unit at 75% will differ from one crew to the other based on the units each crew works on.

$$intU_{iL} = Rounddown(MaxU_C - MinU_C + 1) * iL + MinU_C \quad (3.3)$$

where $iL \in (25\%, 50\%, 75\%)$

$$Total\ interruption\ options_i = 6 \times C_i \quad (3.4)$$

In the case of a simple activity with 2 crews, the number of interruption possibilities based on the 6 preset interrupt locations would be 12 (3.4). Of these options, the best tradeoff between total interrupt days and project duration is selected. If interrupting only crew 1 does not lead to an improvement in the project schedule, it is generally unlikely that interrupting only crew 2 would result in an improvement. As shown in Figure 3-9 if interrupting only crew 1 leads to no improvement then interrupting only crew 2 would likely also not result in an improvement, both crews need to be interrupted. Hence why the total interruption possibilities are limited to (3.4) to reduce the complexity of the problem. With this added flexibility in the calculation of the activity interruption by considering individual crew interruption, a FCFS scheduling approach integrated with optimal interruption selection is possible.

Table 3-2 - Interruption values for sample project using existing and new frameworks

Interrupt Location	Crew	Interrupt Unit	Interrupt days with Existing Methods	Interrupt days with new framework	
			Activity Block	Parallel	FCFS
75%	C1	10	5	2	6
	C2	11	5	2	1
	C3	12	5	-	1
25%	C1	7	6	9	9
	C2	8	6	9	9
	C3	9	6	6	9
Average Interruption			11	9.33	11.67
Project Duration			52	52	48

Figure 3-10(a) shows a project case with 3 activities over 15 units. Out of the eighteen possible interruptions, an interruption at 75% & 25% of the worked units gives the best schedule. If the activity was to be interrupted as a block at these units, as is done with existing methods, the resulting schedule would be as shown in Figure 3-10(b) with a duration of 52 days. However, using the proposed framework, the individual crew interruption days are shown in Table 3-2 and it can be seen that ‘Crew 3’ only needs to be interrupted once to still achieve the best solution found when activity C has parallel crews. Figure 3-10(c) and Figure 3-10(d) show the best schedules if activity C’s crews are parallel or FCFS respectively. The proposed framework also ensures that the solutions found have had any unnecessary or inconsequential interruptions removed. The developed crew-focused interruption framework provides a heuristic process for determining an activity interruption that is applicable even to cases with non-typical activities, non-identical units, or varying unit orders. It can also be applied to any crew formation. Though it is evident in Figure 3-10(d) that a FCFS crew assignment approach yields the least gaps and better schedules as it is able to allow more strategic interruption.

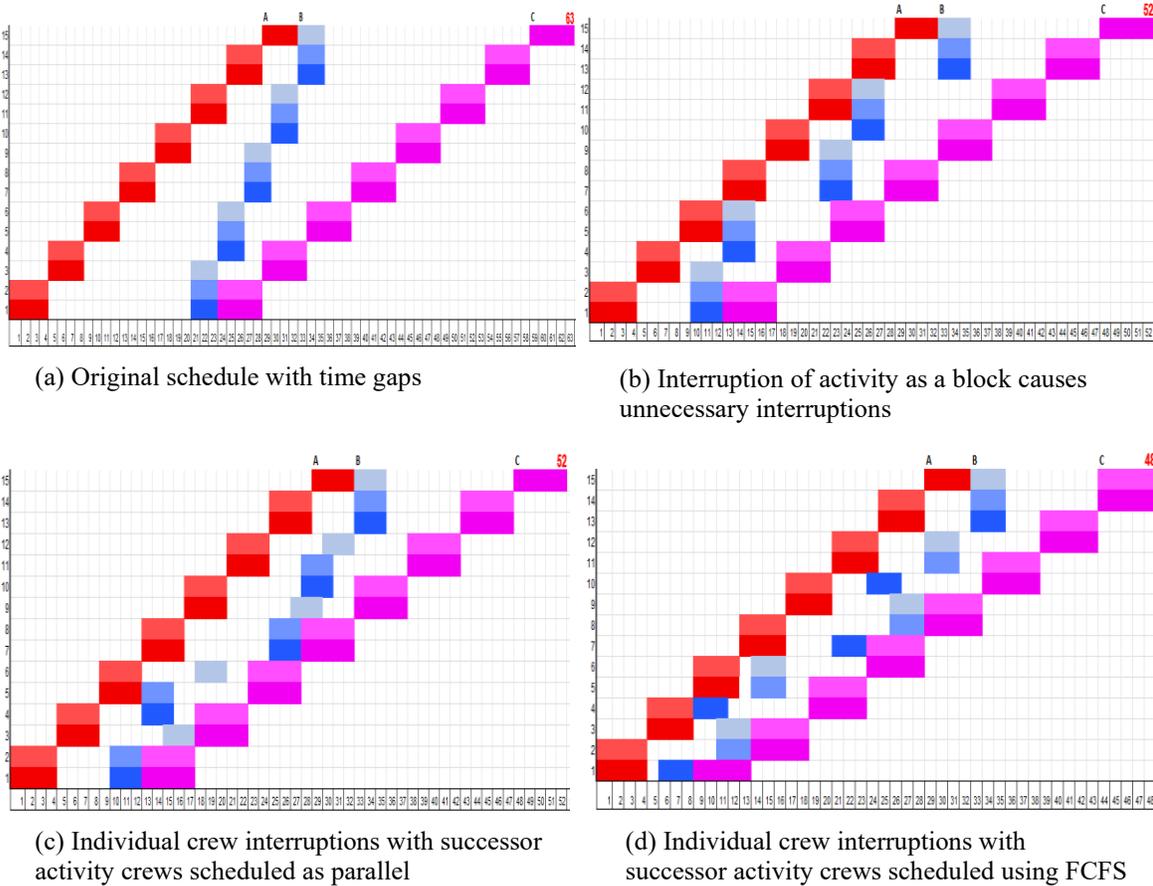


Figure 3-10 - Example using Crew-focused interruption

3.4 Activity Speed Manipulation

Rather than using an interruption time for faster activities, changing activity rates is an alternative technique to speed up slow tasks and reduce the schedule time gaps, particularly when extra crews are available. Ideally the maximum number of crews required to finish an activity in the shortest amount of time would be used if it was possible. However, in practical real-world situations, this is not the case as resource constraints dictate the number of crews that can be assigned to an activity. The LOB/CPM computations provide good estimates for the number of crews an activity should use in order to best utilize the total crews available while meeting the project deadline. However, often times the gaps caused by the unsynchronized activity rates can be improved by changing the activity speed

mid activity. This is beneficial as it does not require the higher completion rate for the full duration of the activity and thus those resources can be used elsewhere before being assigned to the activity.

These activity speed changes can be achieved by either:

- Increasing the number of crews assigned to the unit,
- Changing to a faster construction method.

It is fairly common to speed up an activity by assigning more crews, as is available, to the activity in order to complete it faster. However, if planned correctly, this speed change can also be achieved by switching to a faster construction mode mid-activity. Determining at what point of execution to speed up the activity and the optimal number of crews to add, or construction method to use to achieve the largest impact in project duration reduction often requires trial and error or estimation by experienced project managers. However, the proposed process to determine the optimal speed change for the activity helps to provide a reliable and simplified framework for determining an optimal speed change solution for an activity. The proposed heuristic process can be summarized as follows:

1. Check the activities' rates and identify the eligible activities for speeding their delivery rates.

Eligible activities are ones that:

- a) have faster successors; and
- b) their rates are less than 0.75 of the desired rate for the project (i.e. Equation (2.1)).

Note: These conditions are to ensure that the selected activities that are sped up are ones that would reduce the project duration. If a successor activity is slower, speeding up the current activity would not reduce the project duration. This is the same if the rate of the current activity is already close to the desired completion rate (i.e., Equation (2.1))

2. For each eligible activity, depending on the number of units the project has, the unit at which to apply a speed change varies:
 - a) If the number of units, N , is 2 or 3, then activity is interrupted at the second unit worked on.
 - b) If $N = 4$, then a speed change at the 2nd and 3rd units are compared to choose best solution.
 - c) If $N > 4$, then 3 preset locations for speed change are accessed: (a) at 25% of the worked units; (b) at 50% of the worked units and; (c) at 75% of the worked units.

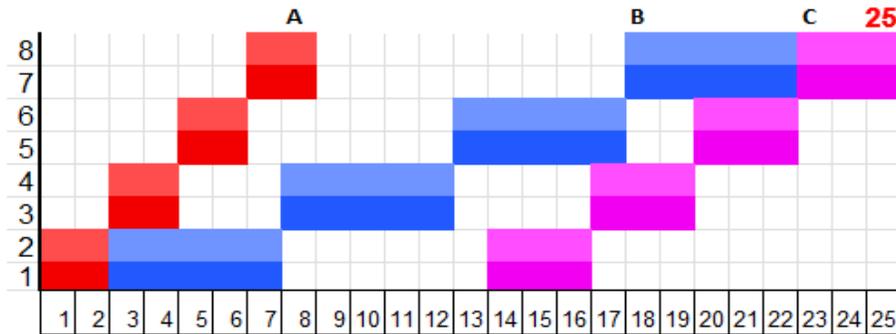
3. For each eligible activity, determine the number of crews to add or construction mode to use. To determine this the following are considered:
 - a) If adding crews: No more than 2 additional crews, or total available crews/resources can be added, whichever is less.
 - b) If changing construction modes: No more than 2 additional construction modes, or total construction modes available can be considered, whichever is less.
 - c) If the CPM duration at the first unit (DC_1) is already greater than the total project duration (D_P), then 1 or 2 crews can be added, or 2 faster construction modes can be considered. The best solution is chosen.
 - d) Otherwise:
 - i. If the rate of the activity's successor (R_S) is greater or equal to three-quarters of the desired completion rate (R_D) - as described in chapter 2 – then only 1 crew can be added or only 1 faster construction mode can be considered.

- ii. Or else, If the rate of the activity's successor (R_S) is less than three-quarters of the desired completion rate (R_D), then 1 or 2 crews can be added or 2 faster construction modes can be considered, and the best solution is chosen.
4. The new crews are added, or the construction mode is changed, at each of the 3 speed change locations and the schedule is recalculated (using FCFS) to determine if an improvement is achieved.

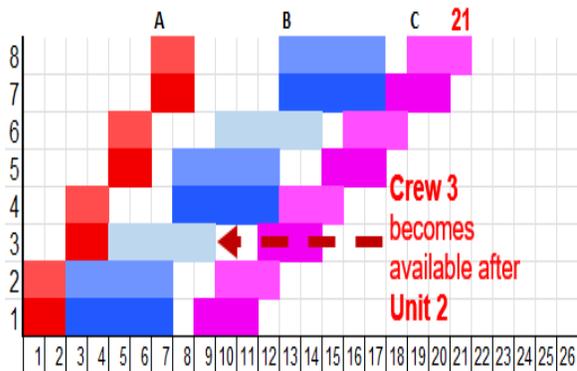
An example of this process using additional crews or faster construction methods is shown below.

3.4.1 Activity Speed Change Through Increased Crews

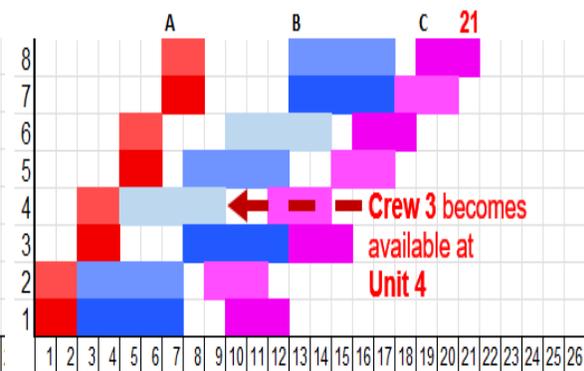
With the initial schedule (Figure 3-11(a)) and a project deadline of 20 days, the speed change process starts by adding one extra crew to activity B at 75% of the worked units, then the schedule is recalculated, and the crews are reassigned. The computation checks other locations (i.e., 50% & 25%) to identify the best solution. Figure 3-11(a) & (b) show that the schedule has the same duration with a speed change at 25% & 50%, hence any solution can be chosen based on associated cost implications. The current algorithm is developed to choose speed change at a later unit since mobilizing additional crews at a later unit would generally cost less but this added decision flexibility is up to the project owner/manager to decide and can be changed. The rate of the activity's successor is greater than three quarters of the desired completion rate, R_D (2.1), and the deadline has been met, hence no additional crews are needed to check for further improvements. As described earlier, the extra crews added are assigned using the FCFS crew assignment technique and hence schedule gaps are naturally minimized in the recalculated schedules.



(a) Original schedule



(b) Speed change at 25% of worked units. Crew 3 is introduced after unit 2



(c) Speed change at 50% of worked units. Crew 3 is available at unit 4

Figure 3-11 - Activity speed change using additional crews

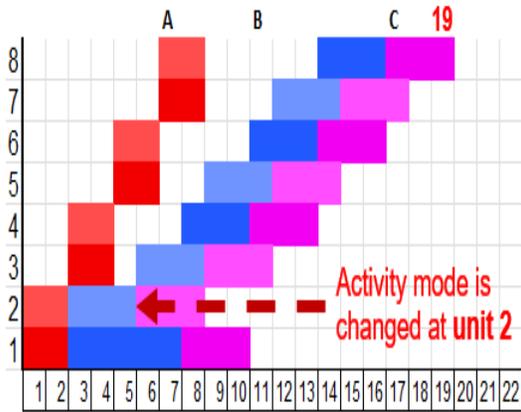
3.4.2 Activity Speed Change Through Construction Mode Change

An alternative to the above speed change approach is to change the construction mode of an activity to a faster method. As seen in Table 3-3, activities have their unique construction mode options.

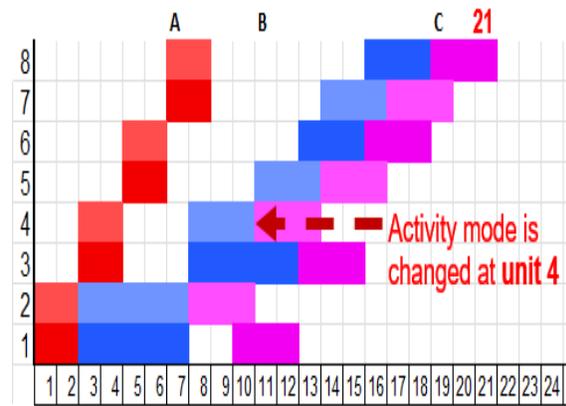
Starting with the same initial project schedule from Figure 3-11(a), the construction mode of activity B is changed to Mode 2 (Table 3-3) at 75% of the worked units and the schedule is recalculated. Of the three speed locations, 25% is the best location found to change the construction mode, as shown in Figure 3-12(a) - as compared with Figure 3-12(b) - with an improvement of 6 days in the project duration. Again, since the deadline is met and the rate of the activity's successor is in line with the desired completion rate, R_D a faster construction mode does not need to be explored.

Table 3-3 - Sample project construction modes

Construction Modes	Mode 1: Slowest, Cheapest			Mode 2: Faster, More Cost			Mode 3: Fastest, Most Expensive			
	Activity	Cost	Duration	Crews	Cost	Duration	Crews	Cost	Duration	Crews
A	\$ 2,000	2	2	\$ 4,000	1	2	-	-	-	-
B	\$ 10,000	5	2	\$ 15,000	3	2	\$ 19,000	2	3	3
C	\$ 4,000	3	2	\$ 7,000	2	2	\$ 10,000	1	3	3



(a) Speed change at 25% of worked units. The activity duration becomes shorter with construction mode 2



(b) Speed change at 50% of worked units.

Figure 3-12 - Activity speed change with faster construction modes

3.5 Batch-Unit Scheduling

Another practical situation that creates schedule time gaps is the occurrence of batch crews. A scheduling approach based on batch production can be employed though this approach is not common in current repetitive scheduling methods (Saad et al., 2017; Shim & Kim, 2014) as the consideration of different batch sizes amongst activities does further complicate the repetitive scheduling problem. Batch crews may be required for different reasons for example an activity that can only be completed multiple units at a time (e.g., finishings) or when a batch of units are assigned to a subcontractor. Figure 3-13 provides a clear representation of the complexities varying batch-sizes can introduce to a project schedule and illustrates the need for better batch-scheduling techniques.

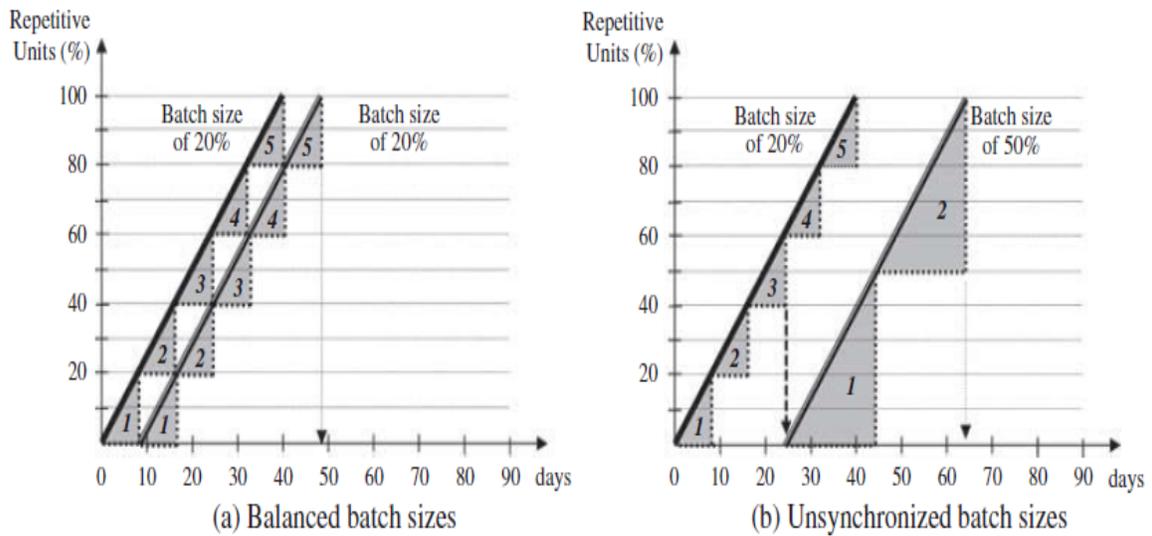


Figure 3-13 - Batch scheduling challenges (Shim & Kim, 2014)

In order to cater to the real-world situation of batch unit assignments as is commonplace in scattered and linear projects, the FCFS crew assignment technique was improved to support batch crew assignment. As outlined in chapter 2, while assigning crews, two key schedule components are used:

- The finish time of the predecessor activity at the current unit being scheduled - FT_p and,
- The earliest finish time of all crews available - F_{er}.

To support batch crew assignment, a third schedule component must be considered:

- Batch size, S_B

With the batch size, S_B, available, when a crew is to be assigned, it would be assigned by batch as opposed to by unit, hence the FT_p of all units that fall under the same batch will be considered as shown in (3.5). For example, if S_B is 2 then the FT_p at Batch 1 would consider the max FT_p value

between Unit 1 & 2 when assigning a crew to these units, then Unit 3 & 4 will be considered together when assigning the next batch crew etc.

$$FTp \text{ at Batch } b = \text{Max}(FTp_x) : x = S_B(b - 1) + 1, \dots, S_B b \quad (3.5)$$

where FTp_x is the finish time of the predecessor at unit x . With the same project schedule as Figure 2-10, the modified FCFS crew assignment technique for batch scheduling can be summarized as follows (Figure 3-14):

- (1) The batch size for activity B is 3, i.e., each crew of activity B is assigned to 3 units at a time.
- (2) In the first step, all crews of activity B (2 crews) are available, hence Fer for all crews is Day 0. However, the FTp at unit 1 is Day 1, and the FTp at unit 2 is Day 3.5, hence Crew 1 of activity B will have to be assigned to start its batch assignment on Day 3.5.
- (3) At units 3 and 4, the finish time of predecessor (A) is Day 3 and Day 5 respectively. As the current finish time of crew 1 is greater than Day 5 and another crew is available, a new crew, (Crew 2) can be assigned to complete activity B at units 3 & 4.
- (4) At units 5 and 6, the finish time of predecessor (A) is Day 6 and Day 7 respectively, both greater than the current finish time of crew 1, which finishes earliest on day 5.5 hence crew 1 is available to work when these units can be started. To maintain work continuity, crew 1 is delayed by 1.5 days as shown in the figure.
- (5) At units 7 and 8, the finish time of predecessor (A) is Day 7.5 and Day 8 respectively, both greater than the current finish time of crew 2, which finishes earliest on day 7, hence crew 2 is available to work when these units can be started. To maintain work continuity, crew 2 is delayed by 1 day as shown in the figure.
- (6) At unit 9, based on the predecessor finish ($FTp = 9$), Crew 1 will be the earliest available crew at day 9, thus Crew 1 is assigned to Unit 9 at Day 9. This is the last unit of the activity, hence crew 1

would have just 1 unit in its batch assignment. The completed schedule is thus achieved while minimizing schedule gaps and providing support for batch crew assignment when required.

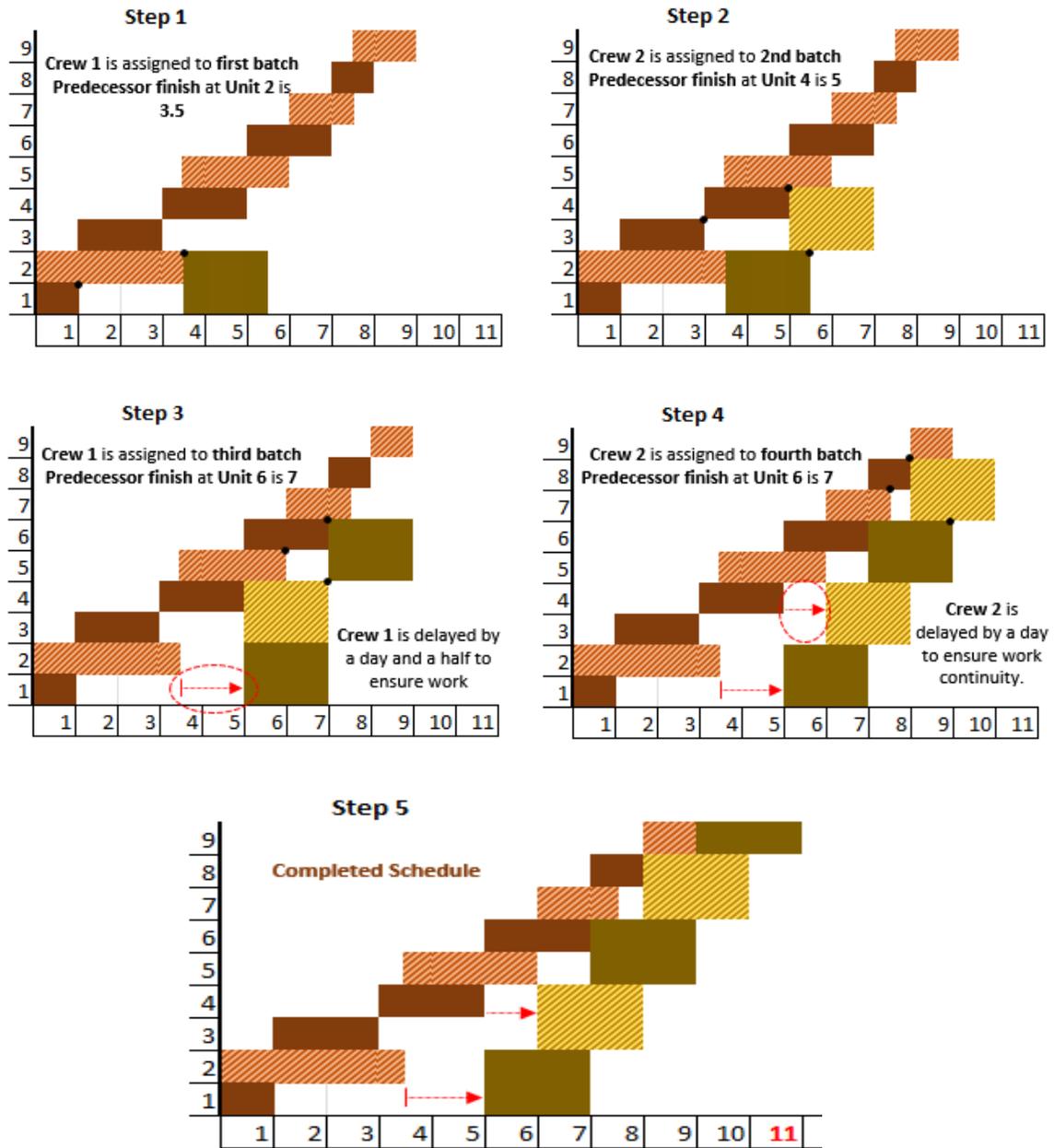


Figure 3-14 - Batch scheduling using updated FCFS process

3.6 Conclusion

Repetitive projects inherently are characterized with numerous schedule delaying traits, from non-typical activities to non-identical units to the type of crew formation used for its activities. As introduced in chapter 2, achieving an optimal schedule for a repetitive project requires fulfilling often times conflicting project constraints while maintaining work continuity across the project units. The benefits of work continuity include better productivity from the works, less mobilization and demobilization costs and creation of a schedule that is realistic and reliable. Efforts to schedule repetitive projects however either exacerbates the schedule time gaps or do not address the added requirement to attain activity delivery rate synchronization. Synchronizing activity delivery rates reduce time gaps in the project schedule, improve resource usage over the duration of the project and reduce the overall project duration.

To achieve such an optimum schedule for repetitive projects, this chapter introduces the developed heuristic process framework for tightening repetitive project schedules and reducing time gaps. This process provides several benefits over existing schedule improvement approaches. The enhanced interruption time and location computation and the proposed heuristic process for determination of optimal mid-activity rate changes can be easily implemented to many different type of project constraints and activity types. The efficacy and flexibility of the proposed schedule intervention framework to reach an optimal schedule while respecting constraints was demonstrated using simple project cases. More complex case study cases will be introduced and examined in a later chapter.

Chapter 4

Integrated Resource Management for CPM/LOB Scheduling

4.1 Introduction

As previously outlined, efficient and effective resource management is a crucial aspect of reliable and accurate repetitive project scheduling. This chapter focuses on the resource management module of the schedule improvement framework presented in this research. Improved computations for individual resource limit considerations are first introduced followed by an evaluation of resource levelling activities and techniques for repetitive schedules. Finally, an enhanced FCFS computation with integrated resource management is presented. The proposed computation is then evaluated to highlight the benefits as compared to typical resource levelling methods.

4.2 Enhanced First-Come-First-Served (eFCFS)

Recent research efforts to consider resource limits can produce good schedules, however due to their nature, either mathematical formulation or complex optimization models, it is usually difficult to formulate a reliable model that includes all the flexible options for infrastructure projects. Project characteristics such as non-sequential unit sequences or individual resource limits (e.g., labor, trucks etc.) are not considered, and if they are other aspects such as non-identical units or flexible crew formulations are absent.

As opposed to non-repetitive projects that involve activities in one unit or work, repetitive projects include an additional level of complexity due to the multiple units involved and the possible use of multiple crews for each task. In repetitive projects, the number of task crews is a key activity decision that governs project duration and resource use, in addition to the activity method. Typically, repetitive

projects handle resource constraints in terms of the number of available activity crews for the activity's construction method. However, handling individual resource limits at the more detailed level (e.g., laborers, trucks, etc.) adds another level of complexity that the initial CPM/LOB and FCFS computations were not designed for. Resource levelling would typically be done after the schedule is calculated. Applying this same concept of levelling resources after a schedule has been developed, though useful for non-repetitive projects, is greatly ineffective for resolving over allocation in repetitive projects as it can produce large schedule gaps.

Figure 4-1 illustrates a simple schedule case of two activities with resource levelling performed after the schedule is calculated. The figure shows two tasks A and B over 7 identical units, each uses two crews, where each task crew requires one resource, while the overall availability limit is only 2 per day. The standard FCFS schedule without resource allocation (Figure 4-1(a)) shows a resource overallocation. Using a task delay of 6 days to resolve the overallocation (similar decision strategy used for non-repetitive projects), as shown in Figure 4-1(b), leads to an extended project duration and large time gaps. Therefore, it is necessary to enhance the FCFS scheduling process to incorporate CRS functionality, reduce time gaps, and generate more efficient schedules.

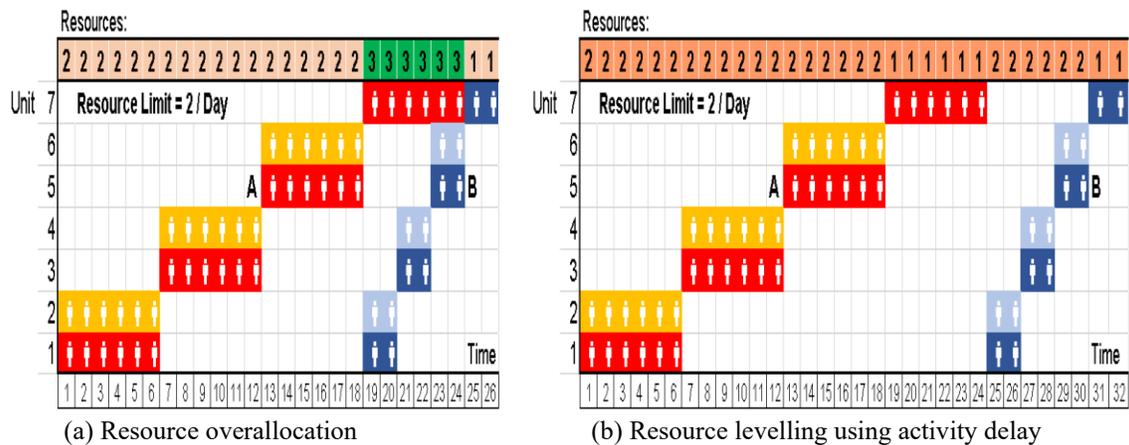


Figure 4-1 - Inefficiencies with resource levelling on a completed project schedule

Integrating resource management with FCFS consists of two key enhancements to the original FCFS process (Hegazy et al., 2020) to resolve the overallocation of the individual resources: (1) Adjusting activity crew limits from CPM/LOB calculations, based on any specified individual resources limits; and (2) Enhancing the FCFS crew assignment in a manner that avoids both resource overallocation and unnecessary resource downtime by maximizing the total daily resource use subject to constraints. These two aspects are discussed in the following subsections. A detailed flowchart of this enhanced FCFS (i.e., eFCFS) process is shown in Figure 4-2.

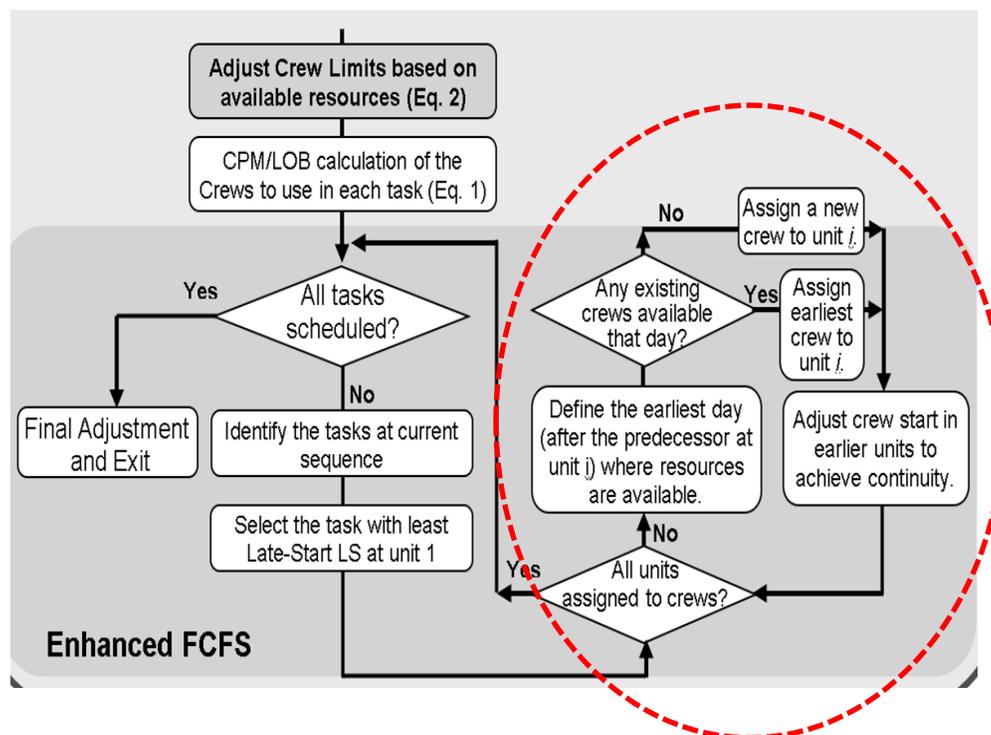


Figure 4-2 - Enhanced FCFS heuristic process (eFCFS)

4.2.1 Revised Crew Limits

To improve the CPM/LOB calculations, in the case of limited individual resources (1 to R resources), a simple adjustment to calculate the number of crew constraints for each task (x), based on the individual resource limit, is as follows:

$$Crew\ Limit\ (L_x) = Min \left\{ L(x_j)_0, \frac{C_{Ri}}{U(xj)_{Ri}}, \frac{C_{Ri+1}}{U(xj)_{Ri+1}} \dots \frac{C_{RR}}{U(xj)_{RR}} \right\};$$

for $i = 1$ to R (4.1)

Where, $L(x_j)_0$ is any user defined crew limit for the activity (e.g. max crews that are able to work simultaneously in the unit space), C_{Ri} is the daily project limit for resource R_i , and $U(x_j)_{Ri}$ is the amount of individual resource R_i required for activity 'x' by its current construction method 'j'. As such, using (4.1), the number of crews available to an activity is not only limited by the associated CPM/LOB calculations, but also by the availability of the individual resources that form the crew. Based on (2.2) and (4.1), the resulting crew limit for an activity is consistent with available resources, thus avoiding resource overallocation, particularly when parallel crews are to be assigned to the activity; the total number of parallel crews would thus not outnumber the available individual resources.

4.2.2 Resource Allocation Strategy

To allow the FCFS algorithm to efficiently resolve resource overallocation, the algorithm has been revised, as shown in Figure 4-2. The enhanced process performs resource allocation and levelling within the FCFS. For the case of a project with 11 activities as shown in Figure 4-3, the process would start by selecting the first activities to schedule based on the project network. In this case the first sequence of activities (i.e., activities with no predecessors) are activities A, B, and C. For these first three activities in the first sequence, the algorithm prioritizes the available resources to the activity with the least Late-Start (LS) time as calculated with the CPM/LOB formulations. In this case activity B would be scheduled first with the available resources (Table in Figure 4-3) as it has a LS value of 0. The next activity in this sequence could be activity A as it has a lower LS value. If

activities A & C were to have the same LS value, then the activity with the smaller ID number (A) would be scheduled based on available resources followed by activity C.

Combining the sequence priority with the LS priority rule improves resource allocation and respects logical relationships across units and across activities as predecessor activities will always be given the resource they need, before allocating to their successors that can be delayed as necessary.

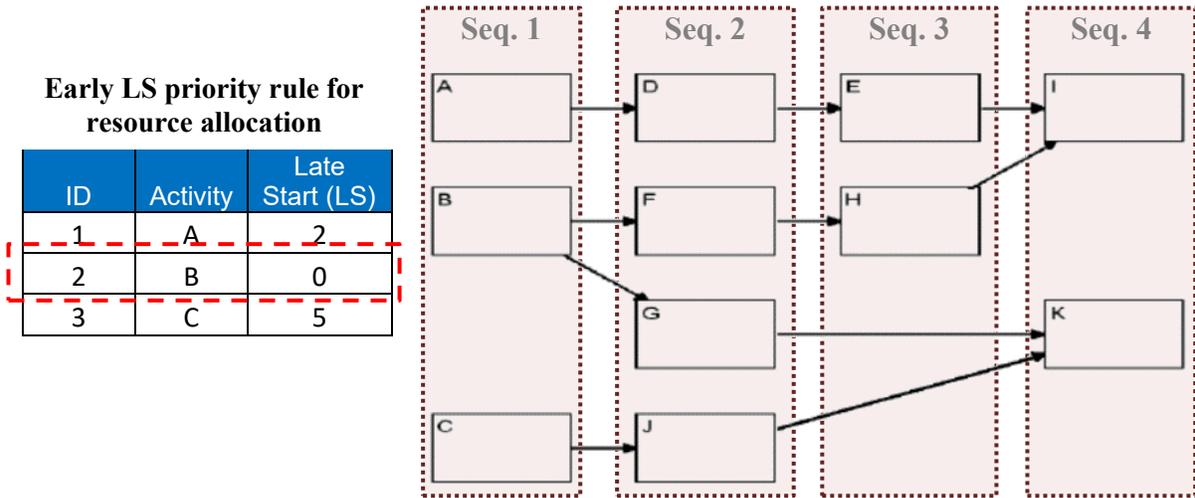
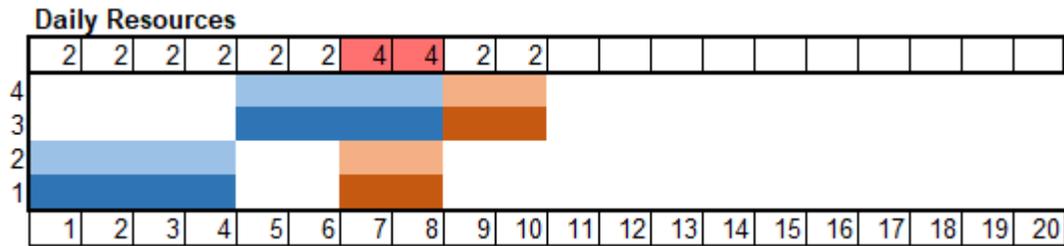


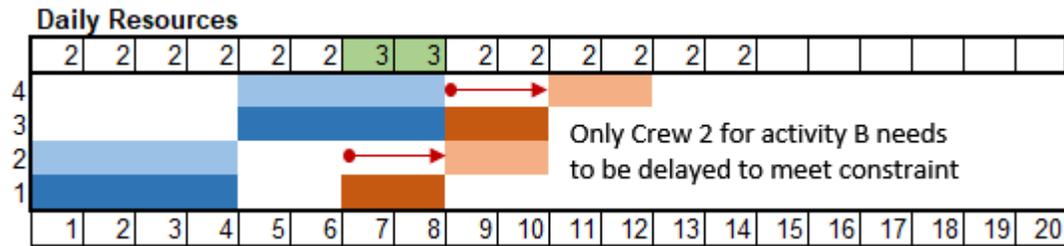
Figure 4-3 - Activity prioritization based on activity network

4.2.3 FCFS with Resource Allocation Using Crew Delays

Levelling resources to meet resource constraints is an inevitable part of project scheduling that must be done in order to create reliable and implementable project schedules. Introducing resource levelling with the FCFS scheduling allows each crew to be considered individually and not the whole activity block. With the multiple crews and multiple units present in repetitive projects, it can be concluded that to meet resource constraints, each crew of an activity can be delayed exclusively in order to meet resource constraints as illustrated in Figure 4-4 where the daily resource limit is 3.



(a) Original schedule with resource limit violations



(b) Modified schedule with resource allocation

Figure 4-4 - Individual crew delays for resource overallocation

ID	Name	Duration	R1	Crew Limit
1	A	6	1.0	2.0
2	B	2	1.0	2.0

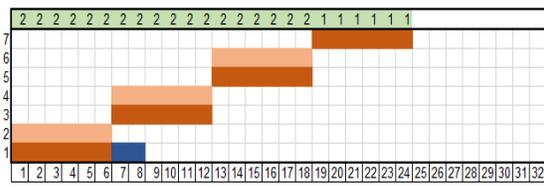
Figure 4-5 - Resource constrained sample project

To better illustrate the FCFS with crew delays, a simple 7-floor building project case will be used. The project has 2 activities to be completed on each floor. It is assumed that the two activities use a resource, R1, with a daily availability limit of 2 per day. The duration and resource requirements of each activity, A and B, are shown in Figure 4-5, as well as the activity crew limits.

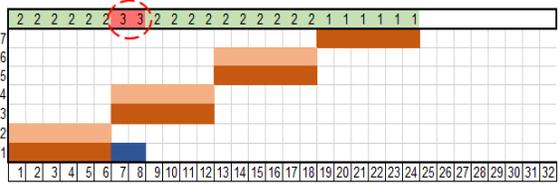
Individual crew delays combined with FCFS for resource levelling approach is illustrated in Figure 4-6 and can be explained as follows:

1. A crew is assigned to each unit sequentially, hence starting at unit 1, since no other crew has been assigned, crew 1 is assigned to unit 1. (Figure 4-6(a)).

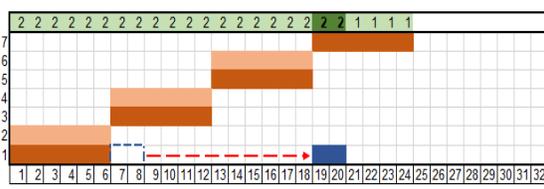
2. The daily resource usage for each day crew 1 works at unit 1 is checked to ensure there are no resource violations (Figure 4-6(b)).
3. It is found that there are not enough resources for crew 1 to work at unit 1 from **day 7 – 8**, thus crew 1 is delayed by 12 days to start on **day 19** (Figure 4-6(c)).
4. Since crew 2 is available and has not been previously assigned, crew 2 is thus assigned to unit 2 to start on **day 7** (Figure 4-6(d)).
5. However, repeating Step 3 for crew 2 working at unit 2 shows that the earliest start day that does not violate the resource constraints is day 21. Thus crew 2 is delayed by 14 days to start on **day 21** (Figure 4-6(e)).
6. At unit 3, activity A finishes on day 12, but the crew that finishes earliest is currently crew 1, so crew 1 is assigned to unit 3 to start immediately after finishing unit 1 on **day 21** to preserve crew work continuity (Figure 4-6(f)).
7. Repeating step 3 for crew 1 shows that in order to avoid resource constraint violations, while preserving work continuity, crew 1 at both units 1 and 3 must be delayed by 4 days to start on **day 23 & day 25** respectively (Figure 4-6(g)).
8. At unit 4, activity A finishes on day 12 also, and the crew that finishes earliest is currently crew 2, so crew 2 is assigned to unit 4 to start immediately after finishing unit 2 on **day 23** to preserve crew work continuity (Figure 4-6(h)).
9. However, repeating step 3 again for crew 2 shows that to avoid resource constraint violations, while preserving work continuity, crew 2 at both units 2 and 4 must be delayed by 4 days to start on **day 25 & day 27** respectively (Figure 4-6(i)).



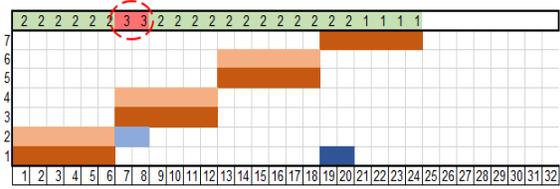
(a) Unit 1 allocation



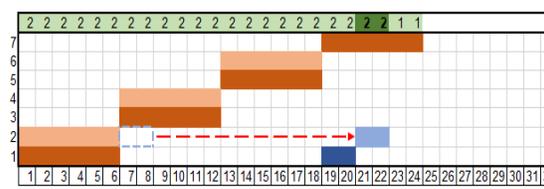
(b) Resource constraint violations at unit 1



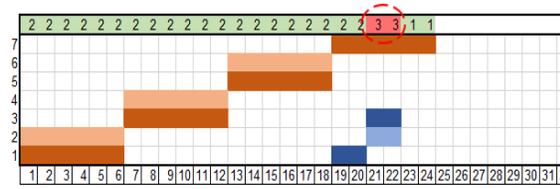
(c) Resource levelling at unit 1



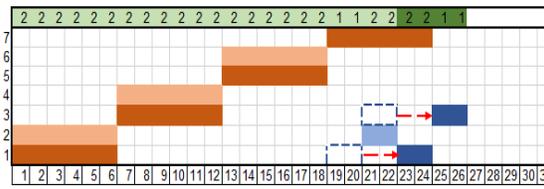
(d) Crew allocation at unit 2 and resulting resource constraint violation



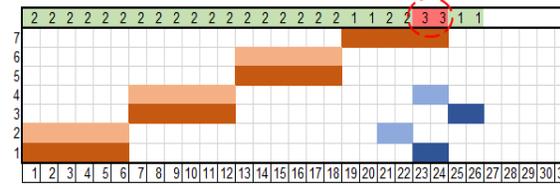
(e) Resource levelling at unit 2



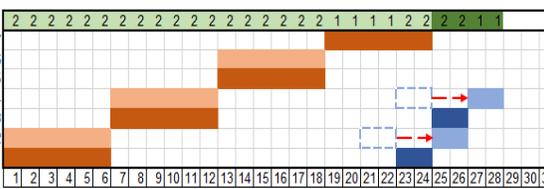
(f) Crew allocation at unit 3 and resulting resource constraint violation



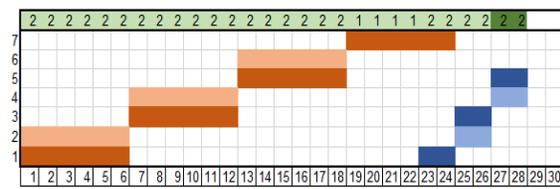
(g) Resource levelling at unit 3



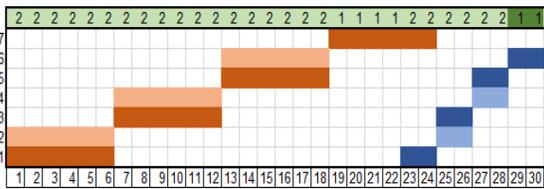
(h) Crew allocation at unit 4 and resulting resource constraint violation



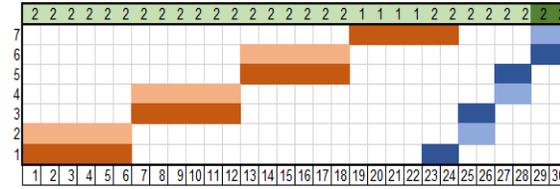
(i) Resource levelling at unit 4



(j) Crew allocation at unit 5 with no resource constraint violations



(k) Crew allocation at unit 6 with no resource violations



(l) Crew allocation at unit 7 with no resource violations

Figure 4-6 - Sample project case with resource overallocation resolved with crew delays

10. At unit 6, activity A finishes on day 18. Both crews finish on the same day thus crew 1 is assigned to unit 6 to start immediately after unit 5 is finished on **day 29**. Repeating step 3 for crew 1 at unit 6 shows that there are no resource constraint violations, thus no delay is necessary (Figure 4-6(k)).
11. At unit 7, crew 2 is the crew with the earliest finish and is assigned to unit 7. There are no resource violations. The final schedule (Figure 4-6(l)) has a 30-day duration, with the resource profile shown in Figure 4-7.



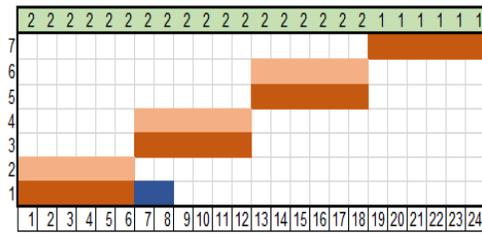
Figure 4-7 - Final project schedule and resource profile using crew delays

4.2.4 eFCFS for Enhanced Resource Management

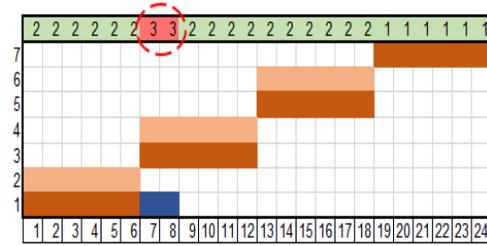
The crew-delay approach highlighted above can be shown to effectively schedule the project while ensuring all resource constraints are met. However, analyzing the final project schedule resource

profile (Figure 4-7), it can be seen that there are some days in which the daily resource usage is below the maximum available. From day 19 to 21, only 1 unit of the resource is scheduled to be used, resulting in excess inventory and cost during those days that the resources are not maximized. Therefore, an enhanced FCFS (eFCFS) algorithm has been developed to maximize resource usage. The eFCFS has an extra resource levelling step within the first-come-first-served crew scheduling (Circled in the flowchart of Figure 4-2). Applying this enhancement to the previous example is shown in Figure 4-8. In this process, once an activity is selected for scheduling, the activity crews are assigned to the units step by step. To schedule activity B, for example, the steps are as follows:

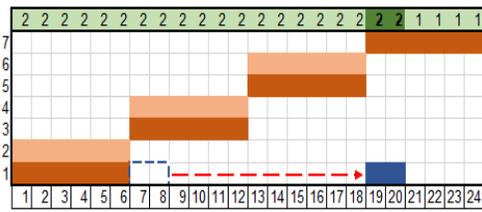
1. Crew 1 of B is assigned to unit 1, immediately after the predecessor at unit 1 (Figure 4-8(a)) and The daily resource usage is checked to see if a resource violation exists (Figure 4-8(b)).
2. Because a resource violation exists on days 7 and 8, thus Crew 1 is delayed day-by-day until day 19 (Figure 4-8(c)), where it does not have overallocation, finishing on day 20.
3. Since, due to resources constraints, resources will be free only on day 21, i.e., after Crew 1 is done with unit 1, it is more beneficial to re-use Crew 1 in unit 2 than to use a new crew. Thus, Crew 1 is assigned to unit 2 (Figure 4-8(d)) and will finish on day 22.
4. Similarly, Crew 1 is assigned to unit 3 (Figure 4-8(e)), then unit 4 (Figure 4-8(f)).
5. Crew 2 can then be assigned to unit 5 (Figure 4-8(g)) on day 25, to avoid project delays. Afterwards, both Crew 1 and Crew 2 can be assigned to unit 6 and unit 7, respectively.
6. The final schedule, therefore, is 28 days, as shown in Figure 4-8(h).



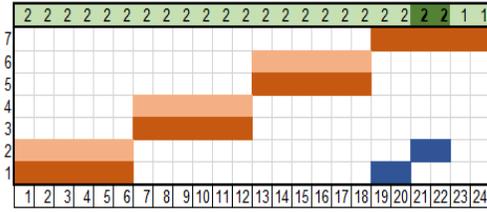
(a) Crew 1 of task B assigned to unit 1.



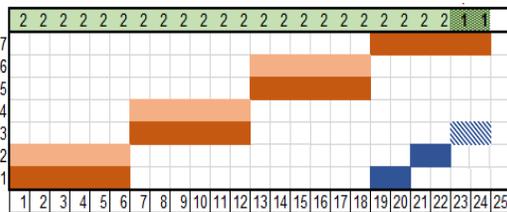
(b) Resource constraint violations at unit 1.



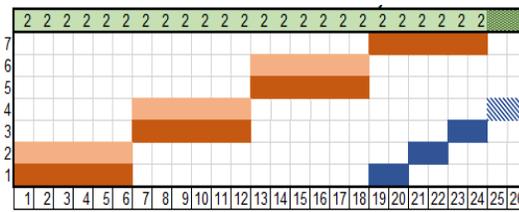
(c) Crew 1 delayed at unit 1 until day 19.



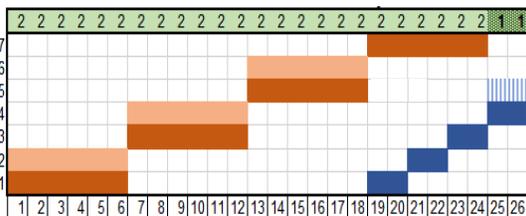
(d) Assigning Crew 1 to unit



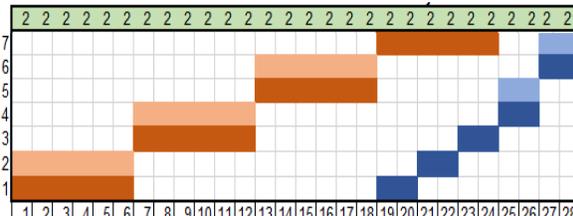
(e) Assigning Crew 1 to unit 3.



(f) Assigning Crew 1 to unit 4.



(g) Assigning Crew 2 to unit 5.



(h) Assigning Crew 1 to unit 6 and Crew 2 to unit 7.

Figure 4-8 - eFCFS for resource allocation produces less project duration.

This small example shows that the eFCFS is efficient and could reduce the 30-day resource-constrained schedule of Figure 4-6 to 28 days by assigning the crews more efficiently. The result is that the resource-constrained schedule of the eFCFS has only a two-day delay from the original schedule (without resource constraints). The eFCFS is able to efficiently resolving resource

constraints with minimal gaps between tasks, leading to minimum project extension due to these constraints. The eFCFS also produces a more compact and optimized project schedule that ensures maximum resource utilization along the duration of the project.

4.3 Conclusion

Resource levelling for repetitive projects, though inevitably necessary to achieve reliable and implementable project schedules, can be difficult to consider while the project schedule is being developed. The schedules are usually created, and the resource constraints are considered and dealt with afterwards. The FCFS scheduling approach provides a unique opportunity to create a scheduling algorithm that is able to consider resource constraints while creating the most optimum project schedule. With the core of the FCFS being independent crew allocation across the different units and activities, the resource levelling can also be done at the micro level across the units and activities.

The traditional FCFS along with the resource allocation strategy, though capable of building a resource optimized schedule, still created pockets of resource underuse within the project's duration. To tackle this, the eFCFS procedure enhances resource allocation by allowing the maximum possible utilization of the resources on each scheduled day of the project. Applying the eFCFS to an example project showed that the eFCFS generated a shorter project duration, as it can find the minimum project delay due to resource constraints. This leads to an optimal utilization and minimization of project crews, cost savings from a shorter project duration, as well as avoiding the underuse of available resources.

Chapter 5

Integrated Scheduling Tool for Linear and Scattered Projects

5.1 Introduction

In an effort to compile the different scheduling features as discussed in the previous chapters, this chapter introduces the final component of the proposed framework; a comprehensive, flexible and easy-to-use repetitive scheduling tool. The tool presented provides essential scheduling calculation functionalities integrated with the enhanced critical schedule optimization features as presented in the previous two chapters. The chapter starts by introducing the various aspects and features of the scheduling tool, including the inputs, calculation approaches as well as the various outputs the project owner can benefit from. Two implementation cases are then presented to demonstrate the effectiveness of the proposed tool and the simple, yet comprehensive output provided to the user.

5.2 Integrated Scheduling Tool

To implement the repetitive scheduling framework discussed in chapters 3 and 4, considering all the necessary flexible options needed for linear and scattered projects, a comprehensive tool was developed that encompasses all the variable for scheduling repetitive projects. The tool is developed to provide reliable and accurate scheduling for meeting deadline durations, minimize cost, and handle resource-constrained projects that have varying types of activities and/or units. The developed tool was built on the Microsoft Excel platform and consists of user interface functionalities and computational scripts. An overview of the developed tool is shown in Figure 5-1, with four main parts: (a) General project data and constraints; (b) Data of the project activities and repetitive units; (c) Scheduling decisions that govern schedule computation; and (d) Various visual results representing the calculated schedule and legible crew assignments. Each of these is discussed next.

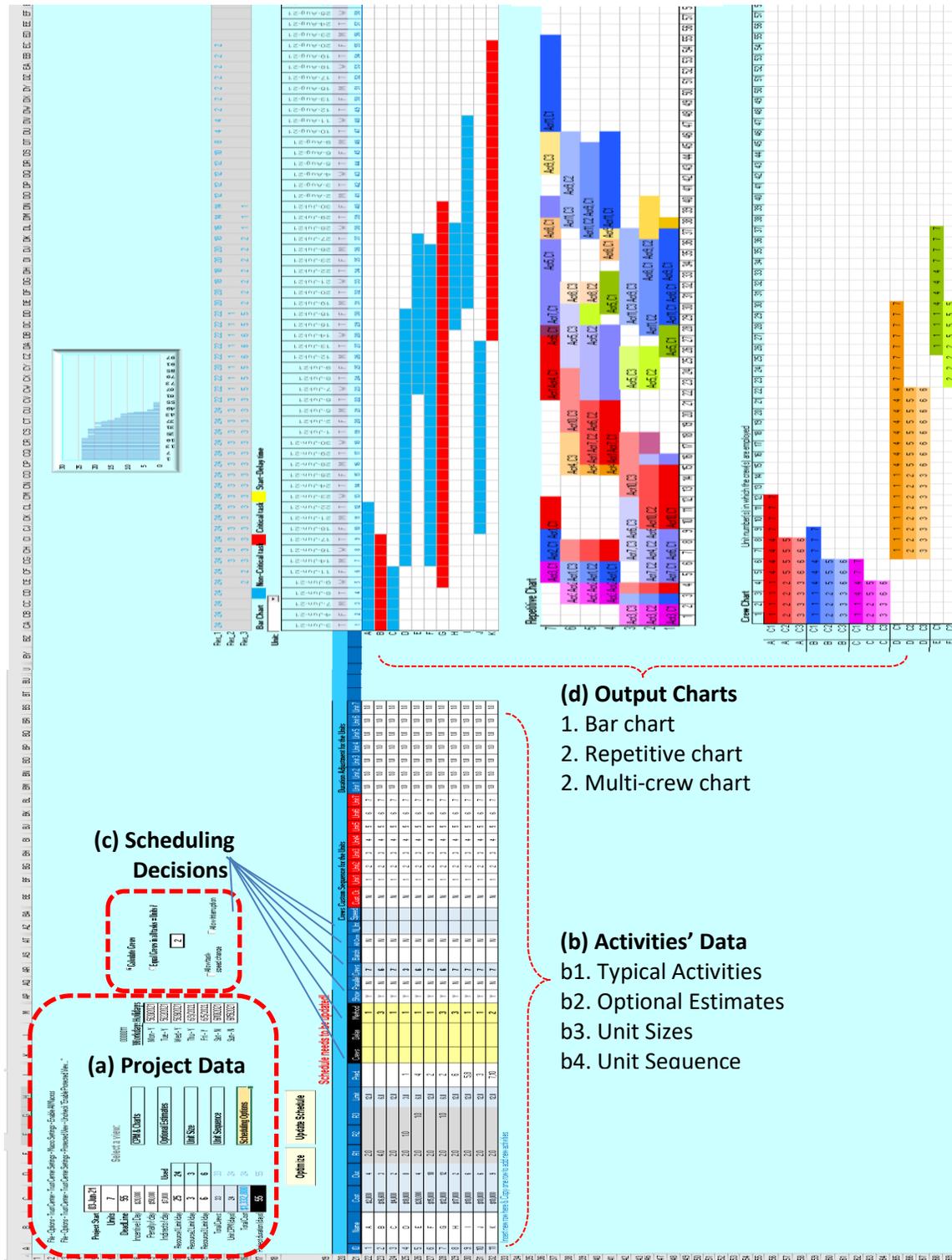


Figure 5-1 - Overview of the repetitive scheduling worksheet

5.2.1 Part (a): General Project Data and Constraints

All project data required to calculate the schedule can be entered into the worksheet (Figure 5-2). The project data refers to all project related constraints and data such as the project deadline, total number of units (e.g., sections of a road, schools in a refurbishment project), project costs implications and project workdays. The worksheet is versatile enough to cater to single-unit projects (i.e., non-repetitive). If the number of units entered by the user is 1, then the schedule calculations would be primarily based on the CPM/LOB calculations. In this part of the sheet also, the user can specify the daily availability limit of three key resource categories. Figure 5-2, for example, shows a limit of 45 R1 individual resources per day.

		Repetitive Units			
General project constraints	Units	12			
	DeadLine	105			
	Incentive / Day	\$20,000			
	Penalty / day	\$50,000			
	Indirects / day	\$7,000			
Project Resource Constraints	Resource1 Limit /day	45	42		
	Resource2 Limit /day				
	Resource3 Limit /day				
Results of current schedule	Total Crews:	7			
	Unit CPM (days)	22			
	Total Cost	\$1,320,000			
	Project duration (days)	88			
				Workdays	Holidays
				Mon - Y	2021-05-20
				Tue - Y	2021-05-22
				Wed - Y	2021-05-28
				Thu - Y	2021-06-03
				Fri - Y	2021-06-05
				Sat - N	2021-06-10
				Sun - N	2021-06-15

Figure 5-2 - General Project Constraints

5.2.2 Part (b): Data of Project Activities and Repetitive Units

This represents the data of the project activities and the repetitive units. Different types of activity data are accessed via different views, as shown in Figure 5-3. All activity data such as duration, cost, unit/section size, resource requirements and any imposed constraints like crew limits are provided. Figure 5-3(a) shows the list of activities in a typical unit and their logical relationships, to be used to

Figure 5-3(c) shows the data input for specifying the unit size, which is important for the scheduling of non-identical units. In this representation, a size of 1.0 represents a unit with a duration and cost equal to that provided in the construction method estimate (Figure 5-3(b)). Consequently, a value of 0.5 represents a unit that is completed in half of the time of the default construction method estimate and costs half as much as the default unit size. And evidently a value of 2 means the unit is twice the size and cost of the default unit.

Figure 5-3(d) also shows the data input for specifying any desired sequence for the activity units, which is an important consideration for linear and scattered projects. This allows for an optimal dispatch of crews to different locations (in scattered projects) or different sections (in linear projects). Thus, an activity can have a different unit order compared to another activity. These characteristics of the project activities are considered to create the required project schedule.

ID	Name	Crews	Method	Show	Parallel	Crews	Batch	All Crew	N_Int	Speed
1	A		2	Y	N	1		N		
2	B		2	Y	N	1		N		
3	C		1	Y	N	1		N		
4	D		2	Y	N	1		N		
5	E		2	Y	N	1		N		
6	F		2	Y	N	1		N		
7	G		1	Y	N	1		N		

Figure 5-4 - Activity flexible decisions

5.2.3 Part (c): Flexible Scheduling Decisions

The power of the developed tool is shown through the flexible decisions the user is able to set for each activity in order to arrive at a desirable project schedule. Decisions such as using a particular

number of crews for an activity, limiting an activity to a specific construction method (Figure 5-4), minimising schedule gaps through interruption, and/or applying speed changes to an activity.

In addition to the above activity decisions, there are several decision options that the user can use to improve the schedule, or that a project owner decides to implement, namely: parallel crews or batch crews (Figure 5-4). The governing crew assignment format is FCFS, thus, if a parallel crew formation is specified, all crews of that activity would be scheduled to start in parallel (i.e., all starting on the same day) and thereafter, each crew would be scheduled on a FCFS basis. The same applies to batch crews, though each crew is scheduled to a batch of units, the crew assignment to each batch still follows a FCFS basis. In addition, the user can decide if the schedule should allow interruption or an activity speed change if the deadline is not met. The activity interruption has two forms (Figure 5-5):

- Individual crew interruption: Each crew is treated as an individual entity of the activity and can be interrupted. The resulting schedule can thus have multiple crews that are interrupted, or just 1 crew interrupted if the project deadline is met: or
- Group interruptions: If the activity uses parallel crews, then all crews of the activity can be interrupted as a group.

On the other hand, the activity speed change can take on two forms:

- Speed change through additional crews: In this case, the completion rate of the activity is increased by adding more crews to the activity at a given unit. Hence, the increased number of crews is available to the activity until the activity is completed; or
- Speed change through faster construction mode: This change is achieved by changing the method of the activity to a faster construction mode at a given unit. From the specified unit

to the last unit of the activity, it is thus completed with a different mode, which would mean a different activity duration, resource usage, and/or crew limit.

Although these decisions are designed to be used to calculate an optimal schedule that meets all project constraints (Figure 5-5), they can also be used as activity inputs (Figure 5-4). The user can specify a desired interruption or speed change to an activity by entering a value in the corresponding column. This interruption could be foreseen changes or circumstances the project manager has decided to plan for (e.g., break from construction due to planned outage, change in activity construction mode due to receipt of additional equipment, etc.). This flexibility allows the user of the tool to also enter project features not necessarily related to the schedule optimization but rather planned changes to the project.

Flexible crew calculation

Speed Change Optimization

Schedule Interruption Optimization

Calculate Crews
 Equal Crews in all tasks = Units /

2

Allow task-speed change
 By crews
 By method

Allow Interruption
 Allow Interruption of Parallel Crews

Figure 5-5 - Schedule intervention controls - User interface

5.2.4 Part (d): Resulting Schedule and Visualization Options

Strategic visualization is vital in simplifying the repetitive project planning as the large amount of information must be presented in a way that is easy to understand, analyse and fully shows all aspects of the project schedule. Improved visualization options include:

- An updated activity Gantt chart for repetitive projects. This chart can thus be used for single unit projects (non-repetitive) or repetitive projects and provides flexibilities to show the progress of specific units (Figure 5-6).
- Repetitive Schedule chart. This repetitive chart (Figure 5-7) allows the use of a variable unit order axis as well as showing any delays in the start of a crew due to resource constraints (as is commonly depicted in non-repetitive charts). When a variable unit axis is used, the unit number is shown at the bottom right corner of the unit bar. This would be illustrated in the case study 1 below.
- A multi-crew Gantt chart (Figure 5-7) that provides a very easy analysis and representation of the project's crews as they advance from one unit to the other. This information is highly useful in aiding project workspace and resource management in order to maximise the use of the project's crews as well as avoid workspace conflicts.



Figure 5-6 - Repetitive project Gantt chart

(Monghasemi & Abdallah, 2021; Altuwaim & El-Rayes, 2018) the best solution found is a 150.63-day schedule with the activities having a unit order of: 1-5-4-3-2-6 and some calculated interruptions.

The resulting schedule using the proposed interruption framework of this research is a 149-day schedule with designed interruptions for activities 2, 4 and 5 (Figure 5-8 & Figure 5-9). Without any additional crews, this relatively low-cost interruption framework is able to arrive at a better schedule. Another option is also available to the user as they can choose to improve the schedule by speeding up some tasks instead of using interruptions. Figure 5-10 shows the result of this choice whereby the project finishes in 143 days with only the first activity having an extra crew introduced at unit 2 (i.e., 25% of total units – 25% of 6 \approx 2), as speeding up some of the successor tasks led to no improvement.

Table 5-1 - Case study 1 - Project activity data

"Duration / Cost" of Non-Identical Units						
	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
A	11 / \$39,926	18 / \$65,333	12 / \$43,556	12 / \$43,556	12 / \$43,556	16 / \$55,896
B	9 / \$13,732	9 / \$13,732	11 / \$16,784	11 / \$16,784	6 / \$9,155	11 / \$16,784
C	10 / \$81,672	13 / 106,174	13 / 106,174	9 / \$73,505	15 / \$12,508	9 / \$73,505
D	10 / \$67,175	13 / \$87,328	10 / \$67,175	15 / \$100,763	10 / \$67,175	16 / \$107,480
E	14 / \$60,012	20 / \$85,731	17 / \$72,872	17 / \$72,872	20 / \$84,017	10 / \$42,866

The integer values of the activity durations and interruptions of the proposed interruption framework makes a search for near-optimum solutions difficult, however, it represents a more practical solution as opposed to the double-digit values obtained in the literature, which realistically cannot be enforced during the project implementation. While this example demonstrates the ability of the developed tool to calculate schedules with varying site orders and determine ideal interruptions using a simple case of one crew per activity and a single execution mode, it is also capable of handling more complex cases with multiple crews, interruptions, multiple construction modes, and

unit orders. Thus, providing a wider array of decision variables available to optimize project schedules with stricter and diverse constraints. Also, the flexibilities of this tool to cater to different types of crews has also been briefly covered in chapter 3 whereby the interruption and scheduling of batch crews can also be achieved.

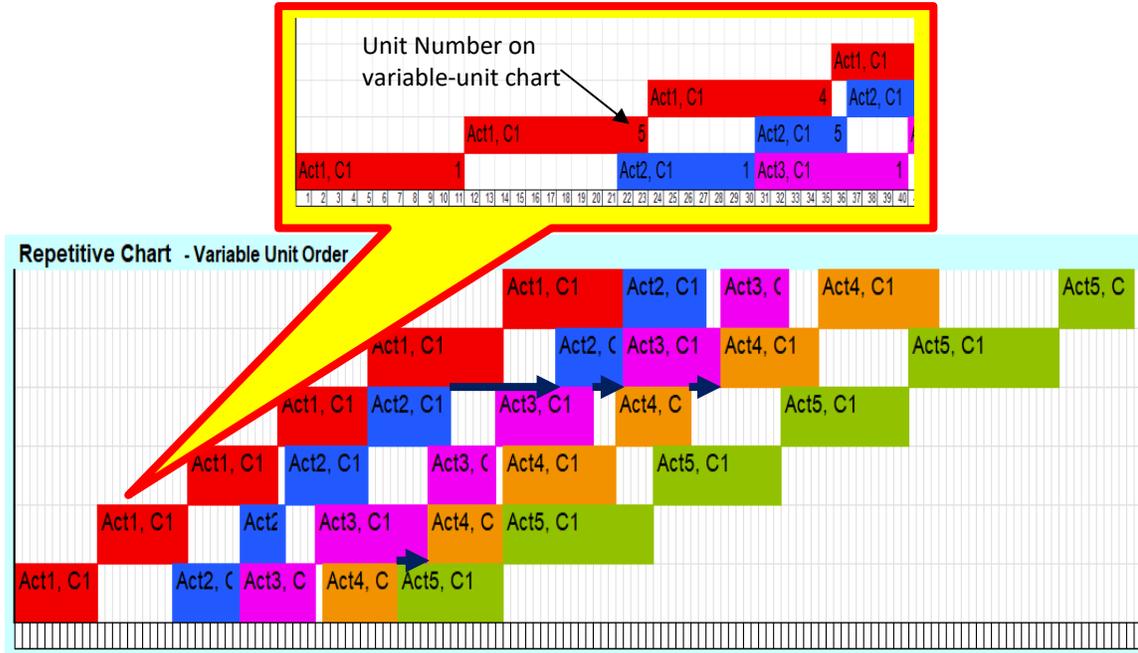


Figure 5-8 - Improved case study 1 project schedule with proposed interruptions (149 days) - Tool Output

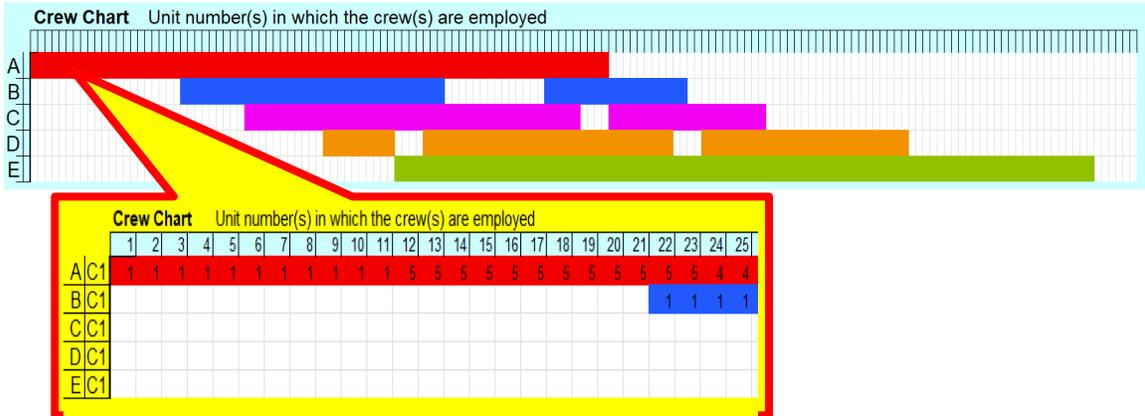


Figure 5-9 - Improved case study 1 project crew chart - Tool Output

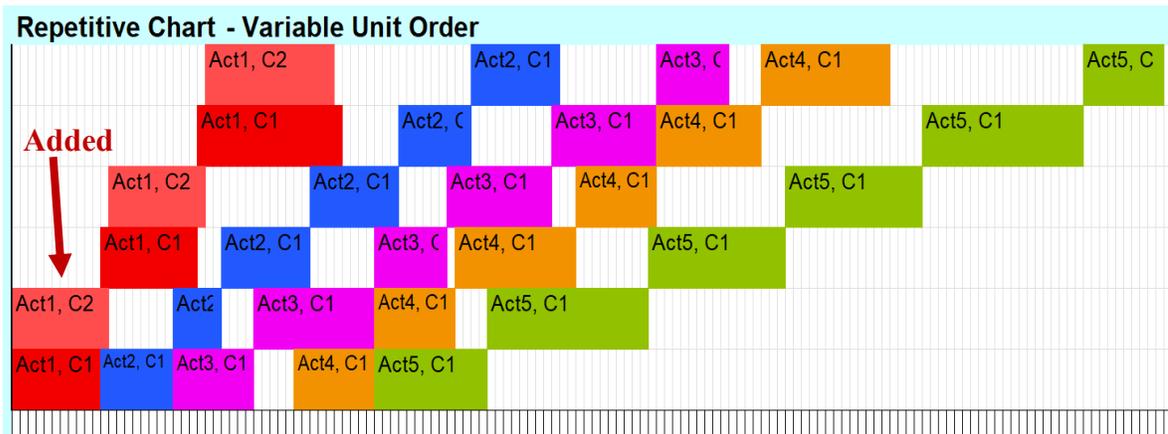


Figure 5-10 - Improved case study 1 project schedule with speed change - Tool Output

Table 5-2 - Case study 2 - Project data (Damci et al., 2013)

Activity name	Required worker hours to finish unit	Number of workers in optimum crew	Daily working hours	Duration (days)	Number of crews	Start-to-start productivity rate (km/day)
(A) Locating and clearing	96	6	8	2	2	1
(B) Excavating	64	8	8	1	2	2
(C) Laying aggregate	80	10	8	1	3	3
(D) Laying pipes	84	7	8	1.5	2	1.33
(E) Testing	80	10	8	1	4	4
(F) Backfilling	96	6	8	2	5	2.5
(G) Compacting	144	9	8	2	2	1

5.3.2 Case 2: Linear Project

Tang et al. (2018) verified their LOB-based resource leveling constraint programming optimization model on a pipeline construction project that consists of 7 macro-activities along 26 units (26 km).

The project deadline constraint used is 65 days. The original project case as originally presented by

Damci et. al. (2013) is shown in Table 5-2 with the project information such as the manhours, number

of crews and unit durations. The best schedule found by Tang et al. (2018) is a 65-day project schedule with a maximum daily manpower requirement of 47 - a significant improvement from the manpower requirement peak of 102 found by Damci et al. (2013) in the original solution. This project case is used as a validation case to test the robustness of the integrated resource management framework introduced in chapter 3 and the excel schedule tool developed.

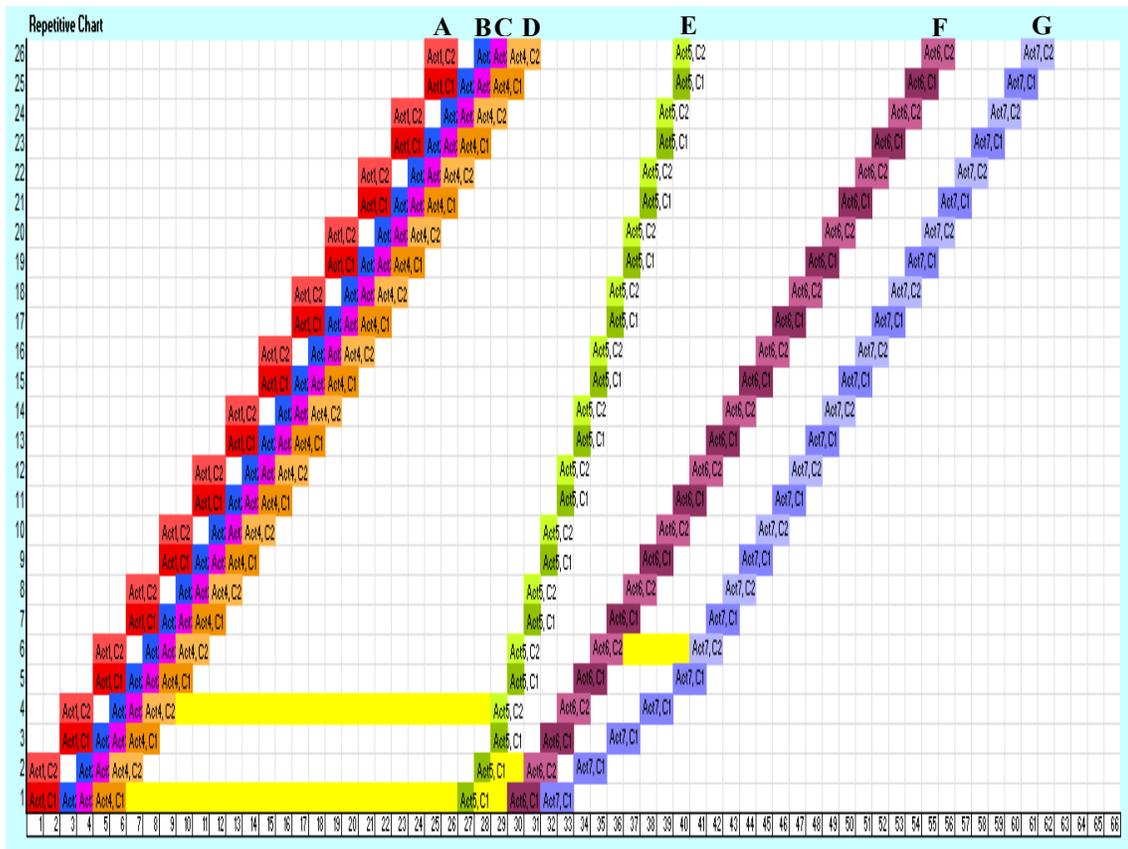
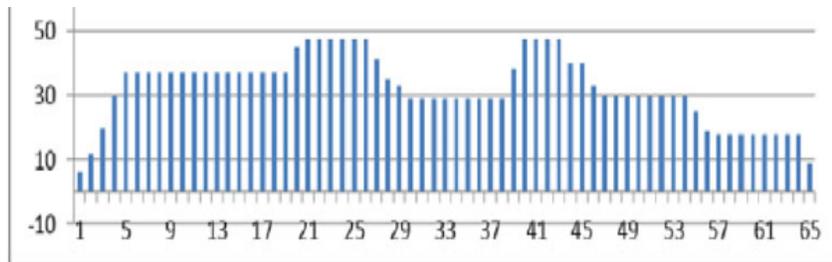


Figure 5-11 - Improved schedule of Case study 2 project - Tool Output

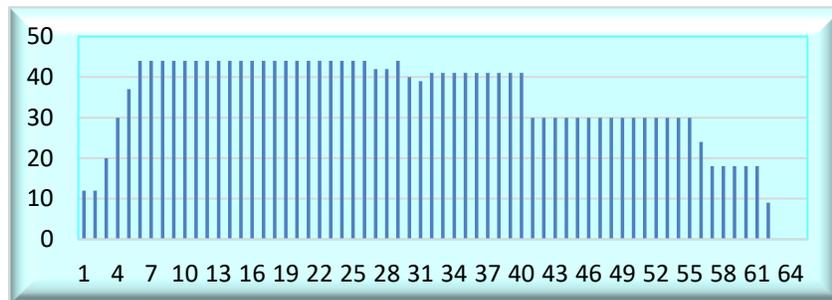
Due to the nature of the original project data (Table 5-2), some slight revisions were made when entering the project data in the tool:

- The duration of activity D was rounded up from 1.5 to 2 to eliminate non-integer activity unit durations. Despite this change, an improved schedule was still achieved.

The resulting schedule from these changes is a 62-day schedule (Figure 5-11), which is 3 days shorter when compared to the results of the more complex constraint programming model (Tang et al., 2018). Not only is a shorter duration achieved, but the peak resource use was also reduced from 47 to 42 (Figure 5-12). The calculated total deviation from average for the resource profile was also reduced by 1 from 531 to 530 thus indicating a better levelling of resources with less peaks. This is important because a project manager generally wants to use the same, or close to the same amount of resources everyday without large variations in the day-to-day resource requirements. Due to the strict resource constraints, schedule improvements to reduce gaps would not be useful in this case as most of those gaps are due to the daily resource limits (Yellow bars in Figure 5-11).



(a) Tang et al. (2018) resource profile for Case study 2



(b) Calculated resource profile for Case study 2 project – Tool output

Figure 5-12 - Improved resource profile comparisons for Case study 2 project

5.4 Conclusion

This chapter presented the development of a repetitive scheduling tool that contributes to effective planning and scheduling of linear and scattered repetitive projects in a simple and computationally powerful manner. As a larger portion of the construction business becoming repetitive (especially the increase in rehabilitation works), such tools can help projects to capitalize on the potential for time and cost savings of repetitive projects and reduce delivery backlog. Use of this tool also helps project owners and managers to arrive at the most cost-effective schedule that meets project deadline and resource constraints. The Excel-based prototype tool can be further developed into a commercial-level tool to support more individual resources, and faster processing speed.

Chapter 6

Conclusion and Future Research

6.1 Summary

Civil infrastructure projects are typically large in size and involve construction activities that are repeated across a large number of units. There are generally three types of repetitive projects: linear horizontal projects such as pipelines and highways; scattered projects such as multiple housing or multiple-bridge rehabilitation projects; and vertical projects such as high-rise buildings. While each type has its unique characteristics, linear and scattered types cover the largest majority of civil infrastructure projects, and as such are the ones this research focused on. These repetitive projects require construction crews to repeat the same activity in each of their assigned units, ideally with each crew scheduled to work continuously from unit to unit without interruption. Maintaining work continuity realizes a large benefit by establishing a good work momentum (i.e., learning) and ultimately saving time and cost. In addition to crew-work continuity, an ideal repetitive schedule exhibits several other key characteristics such as having proper crews in all tasks; meeting deadlines; having all consecutive tasks progress with an almost parallel delivery rate to establish synchronized work cycles; optimal resource use and clear schedule visuals showing all crew assignment details. With these often times conflicting objectives, arriving at an optimal or reliable schedule is difficult for large projects.

While different research efforts and solutions exist such as mathematical formulations, optimization models or heuristic approaches, more research is needed to find a solution or model that includes all the flexible options for infrastructure projects. Complex metaheuristics or mathematical formulations are usually overly complex or involve some black box processing that make them

difficult to apply to large infrastructure projects. Other simpler scheduling methods continue to produce schedules with significant gaps unable to meet deadlines, or overly positive schedules that are unreliable during implementation. Some other resource-related efforts, for example, do not handle non-sequential unit sequences, which are necessary for scattered projects, and vice versa.

To provide an effective schedule improvement framework, this research first discussed the special requirements of scheduling repetitive projects and then specifically linear and scattered projects. Computational enhancements to current scheduling calculations is then presented followed by an integrated resource management framework. To aggregate all the efforts, a specialized and tailored tool was developed that incorporates the various repetitive project scheduling calculations, schedule improvement interventions, resource management integration as well as updated and clear schedule visualizations. Such a tool would greatly improve the chances of completing projects successfully with minimal deviation from the plans.

6.2 Research Contribution

The main contribution of this study are the key schedule improvement interventions to not only produce more tightly packed and synchronized project schedules but to also develop a tool that would provide advanced decision support for optimized scheduling and resource management that is tailored to the unique characteristics of linear and scattered infrastructure projects.

The various challenges this research aims to address, as highlighted in the comprehensive literature study, include providing a scheduling framework that accommodates flexible unit sequence, individual resource limits and resource levelling, and updated schedule visualizations.

6.2.1 Enhanced Scheduling Formulation

To address the scheduling challenges, an effective scheduling intervention framework was presented to provide sufficient improvements to default schedules created using a CPM/LOB + FCFS formulation. The framework provides accommodation for the often present batch crews for repetitive project and also consists of heuristic approaches to designing interruptions or activity rate changes into the project schedule.

The current FCFS served crew assignment technique is centered around a unit-to-unit approach and as such the formulations do not provide accommodations for batch crews. This research not only presented appropriate calculations to enable a FCFS crew assignment for batch crews, but the developed tool is also able to implement these formulations and properly present the batch crews in updated visualizations.

A heuristic approach for determining the optimal interruption of activities in a project was also developed that helps to create a schedule that not only minimizes schedule gaps to increase task synchronization and work efficiency but in many cases also reduces overall project duration. The crew-focused heuristic approach allows for a truly flexible and comprehensive solution to be found while minimizing unnecessary interruptions to ensure a balance between task synchronization and work continuity.

The heuristic approach was also applied to determine optimal speed changes for activities as an added schedule intervention option to achieve the same benefits as interruption. A flexibility to change an activity speed using either through additional crews or faster methods was explored and implemented successfully. Due to the same crew-focused approach used, the successful co-existence of multiple construction modes within an activity's implementation was achieved. These schedule intervention techniques were proved to be highly effective for creating schedules better able to meet

strict deadlines without expensive or time-consuming time-cost trade-off analyses thus providing better decision support to project owners or managers.

6.2.2 Integrated Resource Management

Resource levelling for repetitive projects, though inevitably necessary to achieve reliable and implementable project schedules, can be difficult to consider while the project schedule is being developed. The schedules are usually created, and the resource constraints are considered and dealt with afterwards. The FCFS scheduling approach provides a unique opportunity to create a scheduling algorithm that is able to consider resource constraints while creating the most optimum project schedule. With the core of the FCFS being independent crew allocation across the different units and activities, the resource levelling can also be done at the micro level across the units and activities.

The traditional FCFS, though capable of building a resource optimized schedule, still created pockets of resource underuse within the project's duration. To tackle this, the updated crew limit calculations for each activity and the enhanced FCFS technique introduced in this research, combines the crew allocation strategy of the FCFS with resource levelling at the crew level, allowing each scheduled day of the project to maximize the available resources as much as logically possible. Hence not only is resource overallocation avoided by checking resource availability at each crew assignment but resource under-utilization is avoided by ensuring crews are assigned based on what daily resources are available not only based on number of crews the activity can use.

Thus, the integrated resource management framework achieves an optimal utilization and minimization of project crews, cost savings from a shorter project duration as well as from avoiding an underuse of available resources.

6.2.3 Comprehensive Scheduling Tool

This research also introduced a fully equipped scheduling tool that successfully incorporates the CPM/LOB calculations, FCFS crew assignments, schedule improvement interventions, integrated resource management and clear yet comprehensive visualizations for linear and scattered projects. The tool is applicable to both repetitive and non-repetitive projects and allows the use of different construction methods, variation of work quantities among different sites, different crew assignments strategies such as parallel or batch crews, activity-specific unit orders (all activities do not need to have the same unit/site sequence) as well as specified individual resource limits for resource allocation. Equally important is the visualization solutions the developed tool provides: a familiar schedule bar/Gantt chart properly adjusted to legibly depict repetitive projects, a familiar duration-distance chart equipped to accommodate variable unit order as required, a resource profile chart for easy resource management and usage analysis, and a new multi-crew chart to provide visual representation of how and where the crew's work progresses over time. The various charts the tool provides help represent the large project data associated with repetitive projects of this nature in a clear and legible manner that is usually missing in repetitive project scheduling solutions as discussed in the literature study. This comprehensive representation can help improve the capability of the project team or managers to understand, analyze, and communicate the schedule information to all involved parties.

To demonstrate the usefulness and effectiveness of the developed tool and its capabilities and features two case study projects previously analyzed were presented. The results of the implementation cases proved the reliability and suitability of not just the developed tool but also the schedule intervention techniques presented for linear and scattered repetitive projects.

6.3 Future Research

The proposed repetitive scheduling framework provides decision support to determine the best combination of construction methods, crews, interrupt times, and activity site sequences that minimize total cost and meet deadlines, while considering individual resource limits as well as general crew limits. To demonstrate the usefulness of the framework introduced and the developed tool, a validation case of a real-life renovation project was presented. Following on from this research some exciting areas of future research can be identified as follows:

- Improving the FCFS. Currently the decision logic of the FCFS works to maximize the use of existing crews while ensuring work continuity. This core of the FCFS process was also applied to integrate it with resource allocation. However, there are no considerations to ensure minimal or unnecessary delays whenever a crew is delayed for work continuity reasons. Minimizing these delays due to continuity would also ensure an even tighter packed schedule where successors are able to start earlier.
- Improving the activity duration estimates by considering the productivity factors that affect workers' productivity levels. This can be done by introducing task-specific productivity factors that refine task durations based on weather conditions (e.g., winter/summer) or other factors such as crew skill level, etc. It is also possible to use duration modifiers for each scattered site if the working conditions are not favourable (e.g., a school is operational during rehabilitation work). The improved duration computation would provide a more realistic schedule that factors in practical work conditions.
- Evaluating project duration under uncertain activity durations can be considered in future work. As a form of risk analysis, it is possible to determine a probability distribution for the project duration, by considering individual probability distributions for the variability in each

activity duration (instead of being fixed/deterministic as is currently). This can be done using Monto-Carlo simulation analysis which can depict what impact the uncertainty levels in the activities' durations would have on the overall project duration. Accordingly, it is possible to answer questions related to the probability of meeting a certain deadline duration, under uncertainty.

- The current tool considers availability limits for only 3 individual resources. This can be expanded to include many more to truly represent the real-world nature of construction crews which are made up of many different resources.
- A more user-friendly Graphical User Interface can be developed for the tool to further simplify the working interface the user interacts with and avoid unwanted behavior or errors.
- The performance of the tool can be further improved if written in a faster processing language instead of the integrated Excel Programming Language
- Integrating a cost optimization functionality with the developed Excel tool. Time-Cost Trade-Off (TCT) analysis and provides a more in-depth analysis of the different cost implications of many of the schedule improvement frameworks presented in this research. Though the interruption and speed change frameworks are relatively cost-effective, they may however come with costs associated with either the demobilization and remobilization of the resources or otherwise. A cost analysis framework to find the optimal schedule intervention would greatly increase the worth of the proposed framework. Also, deadline constraints may not be respected with the available resources and in which case, faster construction methods would need to be analyzed using TCT analysis. To provide project owners and managers more decision support, integrating the current tool with these cost optimization objectives would greatly increase the reliability and accuracy of the schedule created.

- Extending the developed tool for scheduling of multi-project portfolios in which a combined pool of resources must be used across the different projects. With the extensive suite of features, the tool is capable of accommodating and extending these functionalities to also include multi-project considerations.

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