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LEVELING RESOURCES AND ALLEVIATING CONGESTED AREAS OF LINEAR SCHEDULES

by
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AN ABSTRACT OF THE THESIS OF

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The fluctuations in the daily aggregate human resources and the overloading of workspaces have been two undesirable issues encountered by managers during construction, in particular on repetitive projects. The former imposes additional costs on the project resulting from idle workforce and release and rehire factors as well as leads to improper distribution of the contractor's payments. The latter creates congestion that negatively affects labor productivity. However, these two issues could be mitigated through resource leveling and proper space planning during the early project phases.

Few attempts were made to level resources in linear schedules by changing production rates or the slopes of linear lines. However, this has led in some instances to a decrease in productivity. Moreover, the existing leveling techniques did not account for congestion after leveling. Therefore, this research study presents an automated mathematical model targeted at generating a leveled-least congested linear schedule.

Results revealed that the proposed model is effective and yields a more efficient resource and cost profiles under a less congested schedule. The study contribution lies in providing project planners and practitioners with a resource leveling tool that can be applied on linear schedules to account for congestion without altering production rates. It also adds to the literature through amending the traditional linear schedule to accurately represent two-dimensional workspaces and rapidly visualize conflict areas.

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ABBREVIATIONS

$A.D$	average deviation of data points from their mean
$\Delta d_{(i,i')}$	overlap in duration between activities i and i´
$E.D(i)$	end date of activity i
$F(i)$	float days of activity i
I_i	interference of activity i workspace
$L(i)_X$	location of activity i on day X
$M_E(i)$	Maximum end day of activity i that won't delay its successor s
$M_S(i)$	Maximum start day of activity i that won't delay its successor s
n	number of project days
R	remainder of an equation
R_i	number of resources used for activity i
ρ_i	average resource density for activity i
RIC	resource improvement coefficient
$S.D(i)$	start date of activity i
$TtlDur(i)$	total duration of activity i for all units
$U(i)_X$	the unit that activity i is occupying on day X
$U.D(i)$	unit duration of activity i
$U.D(s)$	unit duration of activity i's successor
υ_k	space volume occupied by one unit resource k
$\upsilon(\omega_i)$	volume of workspace ω allocated to activity i
$\upsilon(\omega_i \cap \omega_{i'})$	intersection in workspaces between activities i and i´
ω_i	workspace allocated to activity i

y_i	resource usage on day *i*

CHAPTER 1

INTRODUCTION

1.1 Introduction

At the heart of every construction project lies planning and scheduling. Several attempts are made to define these two terms, but the most convenient for construction are the following. Construction project planning is defined as the process of selecting the unique method and sequence for conducting work from the many other orders and ways that could be adopted to complete the project. The proper plan is the series of steps necessary to realize optimum outcomes. As for scheduling, it is defined as determining the timings of individual processes involved in the project and combining them to determine the overall project duration. Scheduling usually comes after developing a specific plan for carrying the works. (Antill & Woodhead, 1990).

However, Scheduling is not restricted to the planning phase, rather it is done before, during and after the construction period. In the first phase, scheduling is done to determine the timings of the activities, as mentioned earlier, and to quantify the daily resource (labor, materials, equipment and money) demand in order to properly allocate these resources. As for during construction, the schedule serves as a guideline for carrying out the works and it is used as a control tool that allows comparing the actual performance of the project relative to the schedule. This is necessary for early pinpointing of any potential deviation from the planned performance and taking corrective measures accordingly. Finally, the as-planned versus as-built schedules are developed after construction and would be used in analyzing the claims and disputes if they arise. The as-built schedule also serves as a historical database that could be used and analyzed for planning and scheduling of future projects. (El Rayess,1997).

Planning and scheduling are considered crucial requirements in construction projects. They are meant to achieve project goals within budget and without delays. One of the many scheduling methods used in construction is linear scheduling or the line-of-balance (LOB), which is a powerful planning and scheduling technique used to handle repetitive projects such as pipelines and high-rise buildings. It is a system that focuses on the connection between location and the work activities to be executed while ensuring workflow continuity. Network techniques such as CPM proved shortcomings in scheduling repetitive projects because they become very complex as the number of units and activities increase.

Scheduling is usually accompanied with resource allocation, or assigning various resources (humans, equipment, materials, money and information) to scheduled tasks. However, one of the undesirable issues that face managers during construction phase is the fluctuations in the daily number of human resources. This imposes additional costs on the project resulting from idle workforce and release and rehire factors (Atan & Eren, 2018). It leads also to rough fluctuations in the contractor's cash flows since they include payments allocated for laborers. Contractors must have continuous liquidity to pay for subcontractors, suppliers and day-to-day running of the business. Improper cash flow handling might render contractors unable to fairly finance the work. Robust financial management is necessary for the endurance and longstanding economic success of construction contractors (Lucko, 2010). Another undesirable issue that face managers is when the workspaces become congested. Space is one of the intrinsic project resources that is exhaustively consumed by the trades and dynamically changing layout during construction and finishing phases. Congestion of workspaces occurs when space requirements for different activities interfere with each other's, resulting in decreased worker productivity and potential safety hazards (Akinci et al., 2002).

Resource leveling has been applied as a solution to the first issue. It aims at diminishing the fluctuations in the daily resource requirements throughout the project and accordingly the fluctuation in the daily aggregate laborers cost. The most widely used resource leveling technique is the one established by Harris (1973), however it is applied on CPM networks. As for congestion, it has been shown that accounting for space requirements during planning results in extra benefits such as reduced conflict between laborers, improvement in safety and quality, decrease in project delays and decrease in crew waiting times and work interruptions (Chua et al., 2010).

The main objective of this thesis lies in providing project planners with a congestion minimization resource leveling tool to use in linear schedules. The study employs MATLAB in developing an easy-to-use Graphical User Interface (GUI) that offers many options. The aim of this study is to better manage a schedule for repetitive projects by diminishing fluctuations in daily resource aggregates and the corresponding fluctuations if their costs while ensuring minimal levels of congestion. This research's contribution to the industry lies in providing resource leveling method for linear schedules while ensuring uncongested workspaces and without altering production rates.

1.2 Research process

Planning for this study is done through setting a design for the research process, ensuring thereby a smooth transition from the beginning until completion of the work. The initial stage involved extensive and thorough research on all the subjects tackled in the study in order to highlight potential problems and gaps in the area. Then, a set of research questions is well formulated and supported by corresponding study motivation and objectives. The conducted background research and highlighted gaps serve as a guideline in developing the methodology and methods adopted to carry out the work. A conceptual model is elicited through the suggested methodology and transformed to a computational model that will be tested and analyzed through a case study. Finally, the study is ended with putting forth of conclusions, limitations and recommendations.

1.3 Organization of the thesis

The structure of the thesis is summarized in Figure 1. Chapter 2 covers the literature pertinent to linear scheduling and other scheduling techniques, resource leveling and workspace congestion. Chapter 3 pinpoints the gaps in literature based on the conducted research and provides a clear problem statement along with the declaration of significance and objectives of the research. The discussion of formulating a conceptual model for resource leveling in linear scheduling while minimizing congestion is explained in chapter 4 and followed by a case study that demonstrates how the model works in chapter 5. Results from testing the model through the case study are analyzed and summarized also in chapter 5. Chapter 6 offers conclusions, discussion on the limitations of the work and recommendation for future studies.

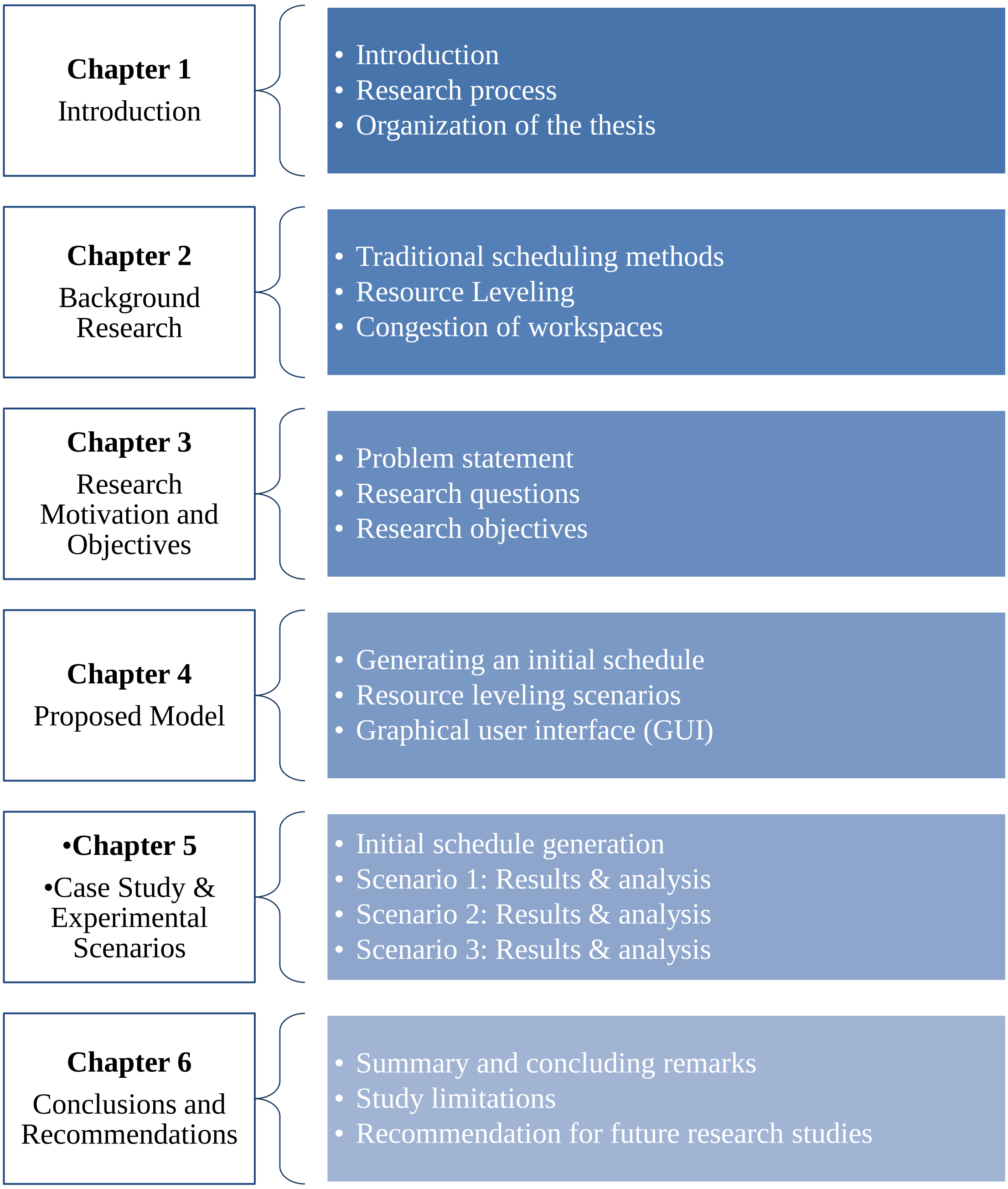


Figure 1 Thesis Organization

CHAPTER 2

BACKGROUND RESEARCH

There are plenty of research studies in literature that separately address line of balance scheduling, leveling and congestion but very few are the ones that tackle two of them together and no research is found to address all three simultaneously. The literature presented hereafter covers the traditional scheduling techniques and some of the research studies pertinent to linear scheduling in construction projects, resource leveling and alleviating congestion generally and in repetitive projects in particular.

2.1 Traditional Scheduling Techniques

Several scheduling techniques have been established throughout the years. The most commonly used ones in construction are the Bar (Gantt) Chart, Program Evaluation and Review Technique (PERT), Critical Path Method (CPM), and Line of Balance (LOB). Each of these scheduling methods has its own advantages and disadvantages.

2.1.1 Bar (Gantt) Chart

In 1917, Henry L. Gantt developed the bar chart which is a graphical representation of the activities as bars spanning a defined length of time and which shows no relationship or links between the activities. The bar chart quickly gained popularity because of its simplicity in representing the tasks on a time scale. Before constructing the bar chart, the project has to be broken down into tasks or activities with defined durations. Each activity then is presented on the chart as a bar having its own start and end points that represent the actual start and end days of the specific task. The advantages of using the bar charts are their ease of use and simplicity in conveying timely data. They are especially appealing for people with no technical background such as upper-level managers and some clients. However, the main disadvantage of the bar charts is their inability in displaying relationships between the activities. Even though few programmers tried to incorporate the links in the charts, the results are not always clear. The relationship lines would become tangled and the bars cannot be moved around to make the graph clearer. Also, the bar chart is not practical to use for large and complex projects. Though the bar chart is an insufficient scheduling tool to use solely in construction scheduling, it has a supporting role to other scheduling methods (Saleh, 2010).

2.1.2 Critical Path Method (CPM)

The first thing to do when talking about the critical path method is to draw the logical network of activities. A network is composed of a set of activities connected by logical and chronological relationships. The logical network of activities has two aspects. It is either an Activity on Node (AoN) network or an Activity on Arrow (AoA) network as shown in Figure 2 and Figure 3 respectively. In the AoN, the activities are hosted in nodes and the links or arrows between these nodes represent the logical relationship between the tasks. (Saleh, 2010). For each link, the activity to the left is the predecessor and the activity to the right is the successor, meaning that the successor cannot start until the predecessor has finished if the relationship between them is finish-to-start. If the relationship is start-to-start, then then the successor can start only when the predecessor has started and some time has elapsed. If the relationship is start-to-finish, then the predecessor must start before the successor can finish. Finally, if the relationship is finish-to-finish, then the successor cannot finish until the predecessor has finished. As for the AoA network, the activities or tasks are stationed on the arrows connecting the nodes, whereas the nodes represent the events i.e. the points in time where an activity starts and ends

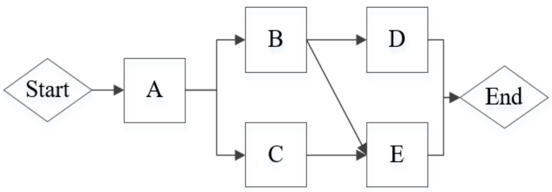


Figure 2 Activity-on-Node

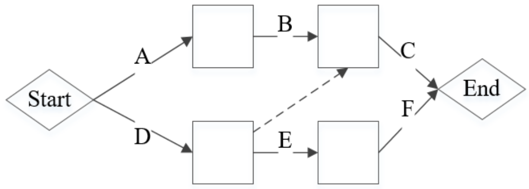


Figure 3 Activity-on-Arrow

However, with the construction projects becoming larger and more complex, the CPM alone proved shortcomings in scheduling repetitive projects. For one thing, imagine having one CPM network with only10 activities/floor repeated over 15 floors. The CPM will consist of 150 activity with numerous lines (links) interconnecting the tasks. The network becomes over-crowded and it would be very hard to visually assess the status of the project and this may create communication problems among the entities involved in managing the project. Figure 4 displays a CPM network consisting of only 5 activities and yet the links are tangled over each other and it is hard to determine what activities each link is connecting when moving from one unit to another. The second shortcoming of CPM is its inability in ensuring continuous flow of resources. Indeed, CPM is foremost intended to optimize the duration of projects rather than addressing special constraints of resources in repetitive projects such as ensuring smooth crew transition from unit to another with no idle time or conflict for equipment and workers (Arditi et al., 2002). Interrupted workflow may impose additional costs and results in hiring and firing and procurement problems (Harris & Ioannou, 1998). Also, the CPM is incapable of locating probable congestion as CPM doesn't deal with locations. CPM doesn't show which activities are ongoing in the same place during the same time. Therefore, repetitive projects require a special scheduling technique such as linear scheduling known also as the line-of-balance (LOB) method.

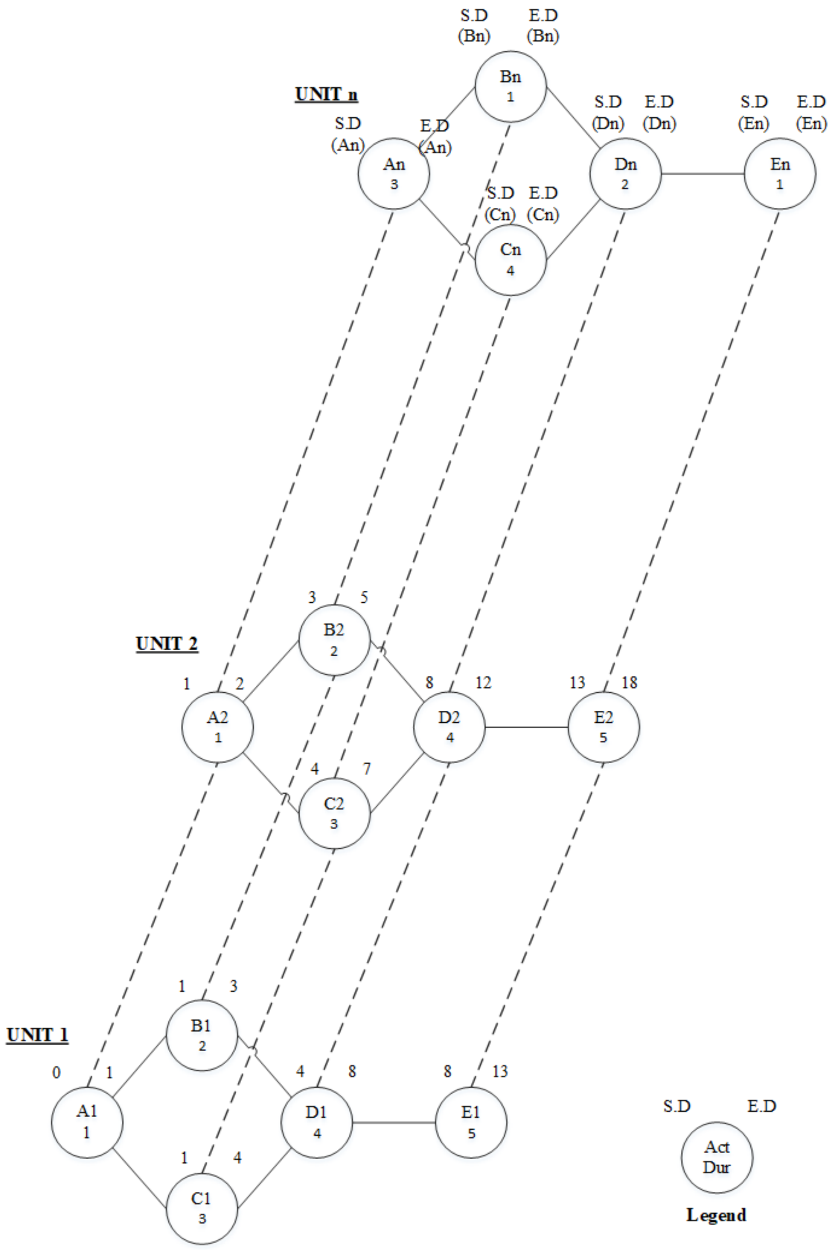


Figure 4 CPM in Repetitive Projects (Harris & Ioannou, 1998)

2.1.3 Program Evaluation and Review Technique (PERT)

During the 1950s, the U.S navy was suffering from overrun in budget and delay in schedule in almost half of the Polaris missile system project. The teams involved in the project started a joint research to develop a planning tool for the Polaris project that would help predict the completion date of a project while incorporating uncertainty. By 1958, the tool became ready to use under the name of the Program Evaluation and Review Technique (PERT). PERT is a probabilistic/stochastic scheduling method that is used when there is high uncertainty in the estimated durations of the individual activities. It uses the usual logic network to get the finish date of the project but it associates each activity with three durations which set up its potential range. These durations which are the optimistic, most likely and pessimistic durations are used to calculate, for each activity, the standard deviation, variance and mean weighted value called the expected duration. An expected duration of the project is calculated by summing all expected durations of activities on the studied path. Finally, the probability of an event occurring at a certain time is calculated using normal distribution formulas (Saleh,2010). Although this method projects a more realistic schedule, it requires a lot of time and effort and might lead to underestimation of duration (Lepadatu, 2010).

2.1.4 Linear Scheduling

The linear scheduling or line-of-balance (LOB) is a powerful planning and scheduling technique that is used to schedule repetitive projects. In general, location-based scheduling and planning systems focus on the connection between the location and the work activities to be executed, while ensuring workflow continuity. This method is used in the literature under the following appellations:

- Line-of-balance
- Disturbance scheduling
- Repetitive scheduling method
- Linear scheduling
- Linear balance charts
- Flow-line
- Vertical production method
- Time vs. distance diagrams (T-D charts)
- Time space scheduling method
- Harmonograms
- Time-location matrix model
- Multiple repetitive construction process
- Horizontal & vertical scheduling
- Velocity diagrams
- Horizontal & vertical logic scheduling for multistory projects

It is a production scheduling technique that was initially established for planning and scheduling manufacturing activities in industrial projects. The method is specifically developed to manage repetitive projects by improving production performance (Kenley & Seppänen, 2006). However, it found application in construction for projects that are of repetitive nature. There are two types of repetitive projects in construction. The first type is the horizontal linear project meaning that the activities repeat horizontally across the length of the project such as highways, tunnels, pavement and pipelines projects, where the units could be assumed to be linear meters. For this type, the LOB schedule consists of units on the x-axis and the time on the y-axis. The second type is the vertical repetitive project such as high-rise buildings where the same activities (e.g. fixing steel and formwork and concreting activities for slabs and columns) repeat from floor to floor. For this type, the time is shown on the x-axis while the location is shown on the y-axis and the floors are taken as units. It is done this way to facilitate the correlation between the graph and the actual crew movement.

El-Rayess (1997) proposed an algorithm for optimizing repetitive projects' scheduling. The model is developed in three stages and it aims at minimizing the project duration. In the first stage, the schedule is generated in compliance with precedence relationships and crew availability constraints. In the second stage, an interruption algorithm is developed to determine a set of potential interruptions in crew formation that might lead to a decrease in project duration. In the third stage, optimizing the schedule is done by selecting the optimal interruptions and crew formation.

Harris & Ioannou (1998) presented the repetitive scheduling method RSM which ensures a continuous flow of resources. The control point is a new concept adopted to draw the sequential production lines that might converge or diverge. To ensure continuous resource employment, two consecutive production lines' control point is positioned near the first unit when the lines diverge (i.e. when the production rate of the successive activity is smaller than that of the preceding activity) and near the last unit when the units converge (i.e. when the production rate of the successive activity is greater than that of the preceding activity).

Dhanasekar (2000) suggested a simulation model to identify the optimal size of resources for a repetitive housing project. The study aims at determining the optimum crew size that results in a decreased project duration and increased resource utilization simultaneously. Congestion is accounted for by implementing time lags in each cluster during the simulation process.

Arditi et al. (2002) highlighted several issues associated with LOB that can be addressed in order to generate a computerized system to be used by construction managers. For one thing, LOB scheduling system can be enhanced by performing project acceleration, leading to potential decrease in project total cost. It can be further enhanced by addressing nonlinear and discrete activities that may occur in repetitive projects and usually not accounted for. Some alternatives are proposed, including producing individual path LOB diagrams and switching between bar charts and LOB that might help in pinpointing certain problems.

Location based management is a new system that is meant to cut back risk, decrease cost of production, enhance construction site harmony and reduce uncertainty in outcomes. (Kenley & Seppänen, 2006). One of the projects that caused a twist in construction industry is the Empire State Building, in which linear scheduling method is adopted. The construction of the Empire State Building has been thoroughly discussed since its establishment. The innovations used while building the structure were merely astonishing. The milestones achieved by the project include accomplishing 102 story-building from scratch designs to operating the facility in only 18 months, at a rate of one floor per day. Also, the project was completed under budget and scored high on safety records. Following are few of the innovations used:

- Location-based planning: calculating the quantities for the corresponding locations (zones and floors) and using flowline.
- Location-based control: after placing quantities in their corresponding locations, they were monitored on daily basis and the crews were inspected to make certain they were working in the right place three times a day.
- Reducing cycle time by learning from manufacturing: while maintaining aligned and continuous production, production was executed like an assembly line (Kenley & Seppänen, 2006).

Hegazy & Kamarah (2008) proposed a scheduling technique for high-rise buildings that aims at optimizing project cost while respecting duration and resource constraints. Each activity can be assigned one of three alternative methods of construction, ranging from slow and cheap to fast and expensive. One strategy is proposed to reduce project duration, which is the interruption in performing an activity trapped between two activities that are slower than it. The interruption is done by starting the activity earlier on the first floors, which makes it possible for the successor activity to start also earlier. This strategy comes at the expense of workflow continuity. However, losing continuity may be negligible when it comes to a large number of floors if applied minimally.

Duffy et al. (2012) proposed a linear scheduling program which incorporates historical data to better forecast schedules for pipeline projects that might involve variations in production rates. The program lets the scheduler forecast and visualize changes in production rates whenever they will occur along any location in the project. Historical data have been collected and analyzed to determine the effects of production variables such as weather and topography on construction production rates.

One of the fundamentals for establishing linear schedules is to ensure continuous flow of resources to avoid costs incurred from interruptions. Therefore, Zou et al. (2016) presented a mixed integer linear program that schedules repetitive projects considering multiple crews for individual activities, with the aim of minimizing the total cost while respecting project deadline. This is done by allocating for each activity a set of crews that flows from one unit to another without interruptions, reducing thereby costs incurred from idle workforce. Altuwaim & El-Rayes (2018) developed a model that simultaneously optimize project duration, interruptions of all crews and cost of these interruptions. Yassine et al. (2014) presented a method to align production lines for location-based management systems by implementing takt time concept, which guarantees continuous flow of resources while reducing waste. Priven et al. (2014) proposed the lean workflow index (LWI) as a polynomial function that measures smoothness and continuity of flow lines in a linear schedule. Another metric to measure quality of production workflow is the one proposed by Sacks et al. (2017) which is the construction flow index (CFI).

Gouda et al. (2017) proposed a hybrid approach to schedule linear projects by allocating multi-tasking skilled crews to perform various activities continuously from one unit to another. The method is tested through a case study and it showed a decrease in the overall number of crews used in the project by permitting multitasking crews assignment.

Kang et al. (2018) developed a scheduling model that takes care of arranging the horizontal and vertical repetitive work areas in order to decrease the interruptions in work periods. Some mathematical formulas are used to determine the number of repetitive areas that should be done by each crew to ensure continuity in works for all crews.

This scheduling technique has been thoroughly targeted in research studies, but very few are the studies that associate resource leveling to it. The next section presents the literature relevant to resource leveling generally and in linear scheduling.

2.2 Resource Leveling

The most adopted method for resource leveling is the one established by Harris (1973). It is called the minimum moment algorithm which is based on the theory that the moment of a histogram whose elements are arranged over fixed intervals is minimum when the histogram has the shape of a rectangle over the whole set. The method aims at minimizing the moment of the histogram by smoothing the peaks and valleys.

Mattila & Abraham (1998) used integer linear programming to level resources in linear scheduling based on the concept of rate float. Rate float is defined as the amount of potential change in production rate of the non-critical segment of an activity before it becomes critical. The objective function used aims at minimizing the absolute deviation of resources from a desired resource usage.

El-Rayes & Jun (2009) presented an optimization resource leveling model for construction projects that is based on two innovative metrics called release and rehire (RRH) and resource idle days (RID) metrics. The optimization model is arranged in three main modules. In the first module, the initial schedule is generated and the free float and total float days of ach activity are determined. In the second module, a genetic algorithm is used to look up for a group of optimal schedules whose resource utilization's efficiency is maximized. In the third module, resource leveling is done by making use of the non-critical activities' available float days.

Damici et al. (2013) proposed a model for leveling resources in Linear scheduling without impacting productivity negatively. The model is optimized using genetic algorithm and based on the principle of "natural rhythm." Natural rhythm of an activity is the maximum productivity rate for this activity when performed by an optimum crew size. Any crew smaller or larger than the optimum crew will result in lower productivity. However, multiple optimum size crews can be used at once to increase productivity. A function for minimizing deviation between activity resources and average resource requirement is defined and well formulated to comply with precedence and duration constraints. Leveling is done by changing the productivity rates of activities. A case study for a pipeline project with one resource (worker) considered is established to validate the model. The model results in a smoother resource histogram.

Tang et al. (2014) presented two-stage scheduling model for leveling resources in linear schedules. In the first stage, the linear schedule is generated by satisfying the set of constraints that consists of precedence relationships, time buffer between activities and project duration. In the second stage, the schedule is further optimized by leveling resources. The controlling activity path (CAP) is determined and segments of activities that are not on CAP are subject to leveling by changing productivity rate to minimize the deviation in daily aggregate resource usage. The change in production rate is done according to the rate float which is the potential change in production rate of a non-controlling activity before it turns into a critical one as discussed earlier. However, Georgy (2008) eliminated the limitation of controlling activity path and considered the whole activity.

Atan & Eren (2018) proposed a method to calculate the minimum project duration that results in the best resource histogram. The method is based on mixed-integer linear and quadratic models. The metric used is release and rehire RRH which is measure of the resource amount that needs to be released tentatively during periods of low demand and rehired later during peak periods.

Tang et al. (2018) handle the problem of leveling resources in LOB through applying the concept of natural rhythm. The objective function used targets minimizing the absolute difference between the daily and the average resource usage for each resource type. Optimization is done by assigning multiple crews for each activity in a way that productivity is maximized i.e. there are no idle times for the crew when moving from one unit to another.

Another purpose for leveling resources in construction projects is to control the cash flows. Construction projects must be continuously financed to ensure sufficient supply of materials, laborers and equipment. Poor financial management might render owners or contractors incapable of financing the project. Therefore, Samer-Ezeldin & Ali (2017) proposed a financial model that aims at analyzing and optimizing cash-flows of contracting companies. The objective function here aims at maximizing the cash flow's Net Present Value (NPV) through assigning time lags to each activity and selecting the set of lags that generate a schedule with maximum NPV.

Hence, resource leveling has, by some means, been applied to linear scheduling. However, no research study is found to relate congestion of workspaces to resource leveling. Accordingly, the following section presents literature pertinent to congestion of workspaces generally and in repetitive project.

2.3 Congestion of Workspaces

Thabet & Beliveau (1994) proposed a scheduling technique for repetitive projects such as multistory buildings that accounts for space requirements of manpower, equipment and material of activities. Activities are categorized into those that don't share workspaces with other activities and those that do. Whenever activities belonging to the latter category coincide in the same working zone at the same time, the productivity of the crews is decreased according to a graph.

Akinci et al. (2002) developed a program that automatically generates the needed workspaces for each activity by specifying the dimensions of the corresponding workspace and its position relative to a reference object on the floor. For example, the window itself is the reference object examined when generating the workspace for windows installation activity.

Guo (2002) presented a study that accounts for space availability based on time and schedule in order to minimize time-space conflicts. It is done by integrating CAD (computer aided design) with MS time schedule to dynamically locate the conflicts. Space demands are classified into labor, equipment, material and temporary facility spaces. Resolving the conflicts is done through rescheduling and prioritizing space for critical activities over non-critical ones.

Congestion occurs when the durations of multiple activities overlap while the activities happen in the same place. Interference between gangs is ranked 4th by carpenters and bricklayers and 2nd out of 11 by steel fixers as a severe productivity problem that causes lost hours and decrease in productivity (Kaming et al., 1997). Overcrowding of workspaces is ranked 7th out of 13 factors affecting productivity in the construction industry in Australia, with a relative importance index of 0.514 (Hughes & Thrope, 2014). Simulation results show a drop in productivity of individual agents due to congestion and show that congestion is higher towards the end of the project when less tasks are remaining to complete (Watkins et al., 2007). Workspaces can be represented by simple shapes like cylinders, cuboids, prisms, spheres, pyramids, cones and polyhedral (Semenov et al., 2014).

Moon et al. (2014) proposed a genetic algorithm (GA) optimization system that is able of generating schedules with minimized workspace conflicts. A parameter called impact factor which is based on the workspace interference adjacency and schedule overlap ratio is analyzed. Simulation of various schedules is done to select the schedule with the minimum time-space overlap.

Semenov et al. (2014) amended the Resource Constrained Project Scheduling Problem (RCPSP) by accounting for workspace congestion and workflow continuity disturbance. A scheduling system that minimizes project duration while satisfying precedence relationships within resource utilization limits, reduces congestion and ensures continuous workflow is established. Congestion is quantified by the interference between the workspaces of different crews during the overlap period.

Roofigari-Esfahan & Razavi (2015) proposed an approach through which potential congestion areas in horizontal linear schedules are determined. These areas result from deviations in optimal production rates of consecutive activities. Optimizing the potential congestion schedules lies in narrowing down the possible production rates that an activity can take on during the project. This approach is further detailed where Roofigari-Esfahan & Razavi (2016) seeks to optimize repetitive projects duration whilst reducing their potential congestion through uncertainty-aware optimization framework. This is done by factoring spatio-temporal constraints into linear schedules and through a fuzzy inference system (FIS) that models the procedure of human reasoning by fuzzy if-then rules. Considering the potential congestion in scheduling and planning helps develop a more realistic schedule. Two case studies are developed to show the added advantages of the suggested method. It is concluded that this method is a powerful tool for managers to better schedule and plan repetitive projects, and that cost factor can be integrated in the model to prohibit cost overruns. However, this method is applicable only to horizontal repetitive linear projects such as pipelines and highways.

Mirzaei et al. (2018) developed a four-dimensional building information modeling (4D-BIM) system to detect dynamic time-space conflict and assess their effect on the performance of the project. Time-space conflicts are detected based on the crew movement in their assigned spaces during various time intervals. This is done by linking the schedule data to the 3D model data. The ratio between the available workspace per laborer and the minimum workspace required for a laborer is used as a measure for congestion. The relationship between workspace decrease and productivity decrease is taken to be linear.

Tao et al. (2018) proposed a non-dominated sorting genetic algorithm II (NSGAII) to solve the problem of scheduling repetitive projects while considering location and congestion. The developed model allows efficient use of resources and improved productivity in a safer working environment. The focus is on project completion time, congestion level and cost. The model is validated through a case study of refurbishing a 3-story hotel project. Each story of the building consists of several similar rooms whose refurbishing requires the exact activities to be repeated from one room to another. The results show that a reduction in duration of project results in increase in either the project total cost or congestion level.

CHAPTER 3

RESEARCH MOTIVATION AND OBJECTIVES

3.1 Problem statement and motivation

The Line of Balance technique is a resource-based scheduling system that facilitates handling repetitive projects. Unfortunately, it executes resource allocation but doesn’t perform resource leveling (Damci et al., 2013). Based on the aforementioned literature, few attempts were made to level resources in linear schedules mostly by changing production rates (i.e. slopes of linear lines). This, however, has led in some instances to a decrease in productivity (Roofigari-Esfahan & Razavi, 2016). Moreover, none of the existing leveling techniques accounts for congestion after leveling, since changing the range of days occupied by certain activities might create spatial conflicts. Although linear schedules are meant to link locations to project days, they don’t really represent accurate locations. For instance, one linear schedule may state that activity A occupies unit 1 during day 1 but doesn’t demonstrate the exact location of A in unit 1 which might be a huge storeroom.

Therefore, the proposed study presents a new leveling procedure for linear schedules that doesn’t alter the production rates of activities but rather makes use of activities’ available float days to refine the resource and cost histograms. However, in this case, changing the start dates of activities when leveling implies that the resources are vacated from specific days and they occupy other ones, which might generate a conflict with resources of already existing activities. In brief, adjusting the cash-flows during planning at the expense of increasing congestion levels throughout construction might affect productivities of the laborers in a negative way. This might impose additional costs on the project resulting from delays in certain activities and might lead again to disturbance in cashflows and budget. As such, the proposed leveling procedure accounts as well for congestion of workspaces following performing resource leveling by amending the existing linear schedules to accurately represent locations.

3.2 Research Objectives

The overall objective of this study lies in providing repetitive project schedulers with a tool for leveling human resources cost without altering production rates and while accounting for workspace congestion. The tool aims at smoothing the variations in laborers installments and their corresponding costs. The interim research objectives are as follows:

1. Develop a tool that performs resource leveling for linear schedules by making use of available activity floats.

This objective consists of developing a resource leveling tool that diminishes the peaks and valleys in a resource histogram through exploiting available float days.

2. Develop a tool that diminishes fluctuations in contractor's payments for laborers.

Correspondingly, the first objective will help in achieving the second one which is aimed at stabilizing the fluctuations in cost of laborers.

3. Develop a 3-dimensional work schedule to locate conflict areas by amending the typical linear schedule.

As for the third objective, it consists of amending the existing linear schedule to accurately represent locations and accordingly detect conflict areas.

3.3 Research Questions

In consideration of the stated objectives, this research will add to the existing literature by answering the following research questions:

1. How can resources and costs be leveled in linear schedules while preserving production rates?
2. What is a good mechanism to accurately represent locations in linear schedules?
3. How can a linear schedule be used to locate conflicts among workspaces and accordingly quantify congestion?

CHAPTER 4

PROPOSED MODEL

The first step in the methodology adopted for conducting this study consists of building a conceptual model based on the acquired knowledge. This model which aims at clarifying the process of generating an initial schedule and performing resource leveling while accounting for congestion is segmented into two major phases. In the first phase, the initial schedule is generated through calculating the start and end dates, free floats and daily resource aggregates. In the second stage, the generated linear schedule is further optimized through performing resource leveling in three scenarios. In the first scenario, resource leveling is done to reduce the fluctuations in the resource histogram. In the second scenario, resource leveling is done to optimize congestion level. Finally, resource leveling is done to enhance the resource histogram and reduce congestion at the same time. Measuring the disturbance in a resource histogram is done according to a parameter called $A.D$ that is explained in section 4.2.1. As for congestion, it is assessed based on the intersection/overlap among workspaces. Each activity is assigned a rectangular workspace whose coordinates are determined with reference to an origin point. The usual linear schedule is amended into a 3D one which plots on each day the 2D workspaces of the activities taking place.

Next, the developed conceptual model is programmed as a computational model in MATLAB which stands for matrix laboratory. MATLAB is a multi-paradigm numerical computing environment and programming platform designed especially for scientists and engineers (MathWorks, 2005). The reason for implementing the model in this environment is that it makes generating an algorithm easier through the built-in functions and computing capabilities, since the suggested model requires extensive computing of multiple parameters. Figure 5 summarizes the methodology followed to conduct the study.

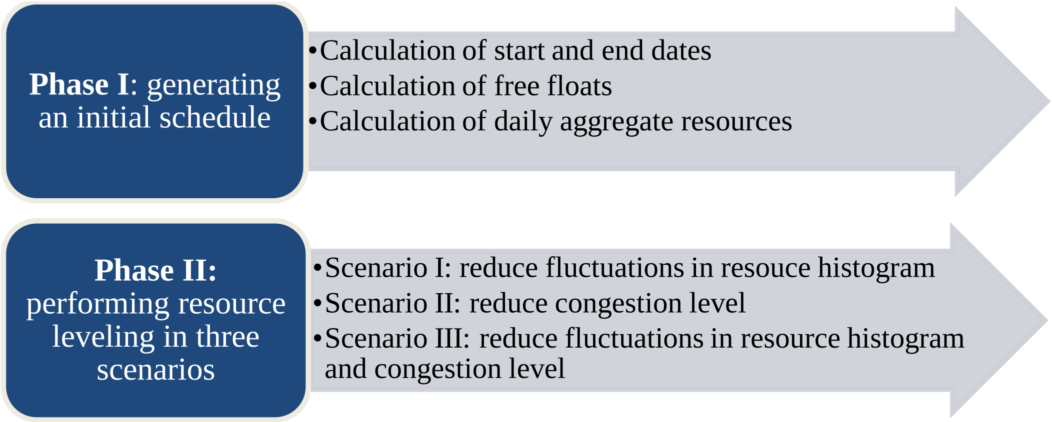


Figure 5 Methodology

4.1 Generating an Initial Schedule

This model aims at providing a continuous and steady flow of resources as interruptions result in a loss of productivity due to the un-learning effect, idle times and release and rehire of workforce. When a crew executes the same activity repeatedly over many units, the laborers develop a learning curve that enhances their productivity (Lee et al., 2015). Due to interruptions, un-learning effects occur and negatively affect productivity. Therefore, the following assumptions are adopted throughout the study:

1- Activities are completely linear, i.e. there is no change in production rates of activities across units.

2- Activities are continuous, i.e. there is no interruption in the work of a crew when moving from one unit to another. This implies a uniform resource histogram for each activity separately due to continuity and constancy in resource consumption of each activity.

3- Multiple unrelated activities can happen in the same unit but the congestion level is still to be assessed.

4- The units in this study are considered as rooms located on the same floor such as hotel rooms or building offices.

5- The relationship among the activities is taken as finish to start (FS) at the unit level, i.e. once the activity is finished in a room, its successor can start in the corresponding room. This thereby implies that activities have a start-to-start (SS) relationship at the floor level. In this case, the successor activity doesn’t wait for its predecessor to be executed across all units to start, but rather starts in the same room after the completion of its predecessor there.

6- Only human resources are considered for simplicity, however the workspace associated for each activity takes into consideration the space needed for materials.

In order to perform the calculations of start and end dates and daily resource aggregates, a template, which should be filled by the user as shown in Figure 6, is imported into MATLAB. The spreadsheet features are inspired from Agrama (2011). Columns to be filled by the user are the ones colored in grey, as for the light-blue ones they are automatically filled based on the inserted data. After the user inserts the number, name, duration, resources, cost per day and predecessors of each activity, an Rp term which could be signified by either SS or FF is automatically determined. If the unit duration of an activity is greater than its predecessor’s unit duration, the control point between the two activities is positioned near the first unit and the controlling relationship (Rp) is signified by start-to-start (SS) term (Ammar, 2010).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	number of units	15														
2	number of activities	12														
3																
4	Activity Description					Predecessors										
5	No.	Activity	Duration	Resources	Cost/Day	p1	Rp1	p2	Rp2	p3	Rp3	p4	Rp4	p5	Rp5	Multipe Predecessors?
6	1	A	1	1	40	0										NO
7	2	B	2	6	140	1	SS									NO
8	3	C	2	4	100	1	SS									NO
9	4	D	1	3	80	1	SS									NO
10	5	E	4	3	80	2	SS									NO
11	6	F	1	4	100	5	FF									NO
12	7	G	3	5	120	3	SS	5	FF	4	SS	0		0		YES
13	8	H	2	3	80	5	FF									NO
14	9	I	2	1	40	7	FF									NO
15	10	J	2	3	80	9	SS									NO
16	11	K	2	4	100	6	SS	10	SS	0		0		0		YES
17	12	L	1	2	60	11	FF	8	FF	0		0		0		YES

Figure 6 Template

On the other hand, if the unit duration of an activity is less than its predecessor's unit duration, the control point between the two activities is positioned near the last unit and the Rp is signified by finish-to-finish (FF) term (Ammar, 2010). The last column determines whether the activity has multiple predecessors or not.

The calculations of start and end dates for each activity follows the next procedure. The predecessor for each activity is first examined. If an activity i possesses no predecessor as shown in Equation 1, its start and end dates ($S.D$ and $E.D$ respectively) are calculated using Equation 2 and Equation 3, where $TtlDur(i)$ is the total activity duration for all units.

$$P(i) = 0 \quad (1)$$

$$S.D(i) = 1, \quad (2)$$

$$E.D(i) = S.D(i) + TtlDur(i)\ , \quad (3)$$

For an activity that is found to have only one predecessor, the rate of the activity is compared to the rate of its predecessor. If its Rp is SS as shown in Figure 7, the activity can start in the first unit just after its predecessor is finished in the same unit. The activity' start and end dates are calculated using Equation 4 and Equation 5.

$$S.D(i) = S.D\big(P(i)\big) + D(P(i)) \tag{4}$$

$$E.D(i) = S.D(i) + TtlDur(i) \tag{5}$$

$D(P(i))$ is the unit duration of the predecessor activity.

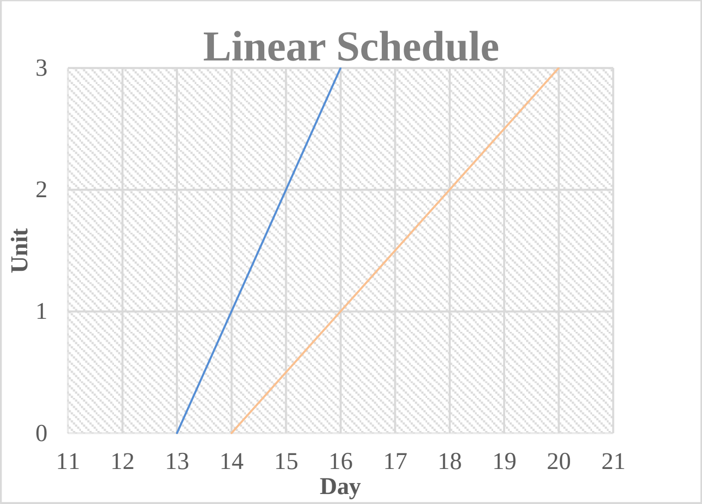


Figure 7 Calculating S.D when Rp=SS

If the activity rate is greater than its predecessor's rate (Rp is FF) as shown in Figure 8, the activity can't start until adequate lead time has passed to avoid a conflict in the logical constraints. In this case, the end time of the activity is first calculated based on the end time of its predecessor in the last unit. The activity' end and start dates are calculated using Equation 6 and Equation 7:

$$E.D(i) = E.D(P(i)) + D(i) \tag{6}$$

$$S.D(i) = E.D(i) - TtlDur(i) \tag{7}$$

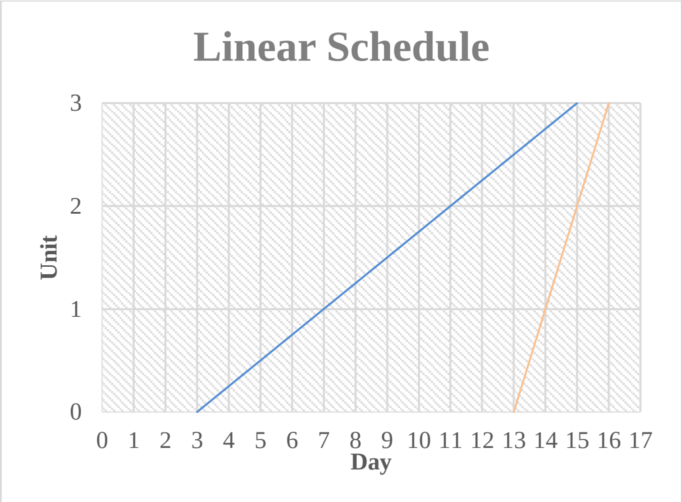


Figure 8 Calculating S.D when Rp=FF

Finally, for an activity that is found to have multiple predecessors, its start date must be calculated such that its linear line doesn't intersect with any of its predecessors' lines. To do so, the rate of the activity is compared to the rate of each of its predecessors and accordingly potential start dates are calculated. The maximum potential start date is taken as the activity's start date.

Knowing the precedence relationships between the activities and the start and end dates of each activity, one can determine the corresponding available free float. The free float of an activity is defined as the amount of time an activity can be delayed without delaying the successor activity. The activities eligible for leveling are the ones that have positive free float, since shifting the ones with no float affects the overall project duration. If the activity (i) has a greater production rate than its successor (s) and $U.D(i)$ is the unit duration of the activity as shown in Figure 9, float $F(i)$ is computed based on Equations 8 and 9. $M_S(i)$ is the maximum start day that an activity i can take without delaying its successor activity s.

$$M_S(i) = S.D(s) - U.D(i) \quad (8)$$

$$F(i) = M_S(i) - S.D(i) \quad (9)$$

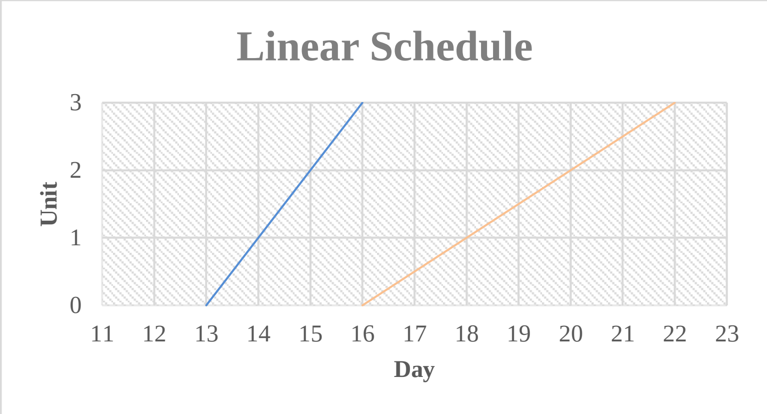


Figure 9 Calculating Float when Rp=SS

If the activity to level (i) has a slower production rate than its successor (s) and $U.D(s)$ is the unit duration of the successor as shown in Figure 10, the float $F(i)$ of that activity is then computed based on Equations 10 and 11. $M_E(i)$ is the maximum end day of the activity i that won't cause delay in the successor activity s.

$$M_E(i) = E.D(s) - U.D(s) \quad (10)$$

$$F(i) = M_E(i) - E.D(i) \quad (11)$$

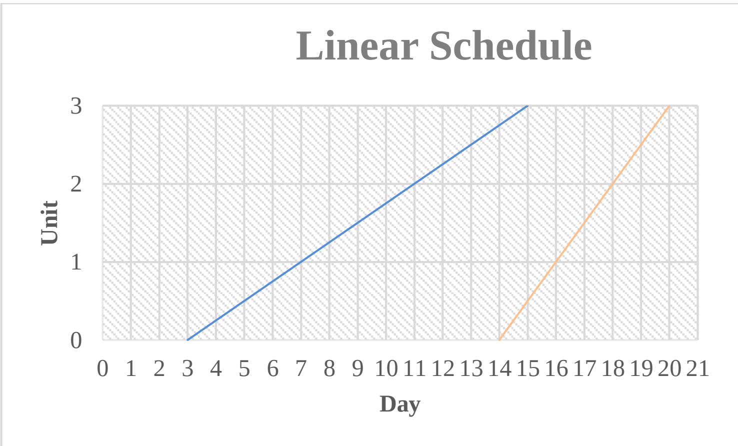


Figure 10 Calculating Float when Rp=FF

Last, if an activity has multiple successors, the rate of the activity is compared to the rates of all its corresponding successors and possible maximum start or end days are calculated like aforementioned. All possible shifts are calculated and the minimum shift is selected as free float of the activity. This minimum shift satisfies the precedence relationship between the activity and all its successors since it doesn't move the activity to start on a day that might create later conflicts in the logical constraints between the activity and any of its successors.

4.2 Resource Leveling Scenarios

4.2.1 Scenario One

The flowchart below (Figure 11) summarizes the leveling procedure for this scenario. One measure that can quantify the spread of data points in a histogram is the average deviation of data points from their mean ($A.D$). $A.D$ is calculated using Equation 13, where y_i is the resource usage on day i of the project, $\bar{y}$ is the average resource usage across all days and *n* is the number of project days. It is the metric adopted in this study to proceed with the leveling procedure and to determine whether to shift the activity or not. The smaller the $A.D$ is, the less the data spread is from the mean, yielding a more favorable resource histogram.

$$A.D = \frac{\sum |y_i - \bar{y}|}{n} \qquad (12)$$

To measure the effectiveness of a leveling procedure, Harris (1973) proposed a factor called the resource improvement coefficient (RIC). RIC is the ratio of the moment of the current resource histogram to the hypothetical minimum moment histogram, i.e. the histogram which has perfectly uniform resource usage and has the shape of a rectangle. RIC is calculated as follows:

$$RIC = \frac{n \sum y_i^2}{(\sum y_i)^2} \tag{13}$$

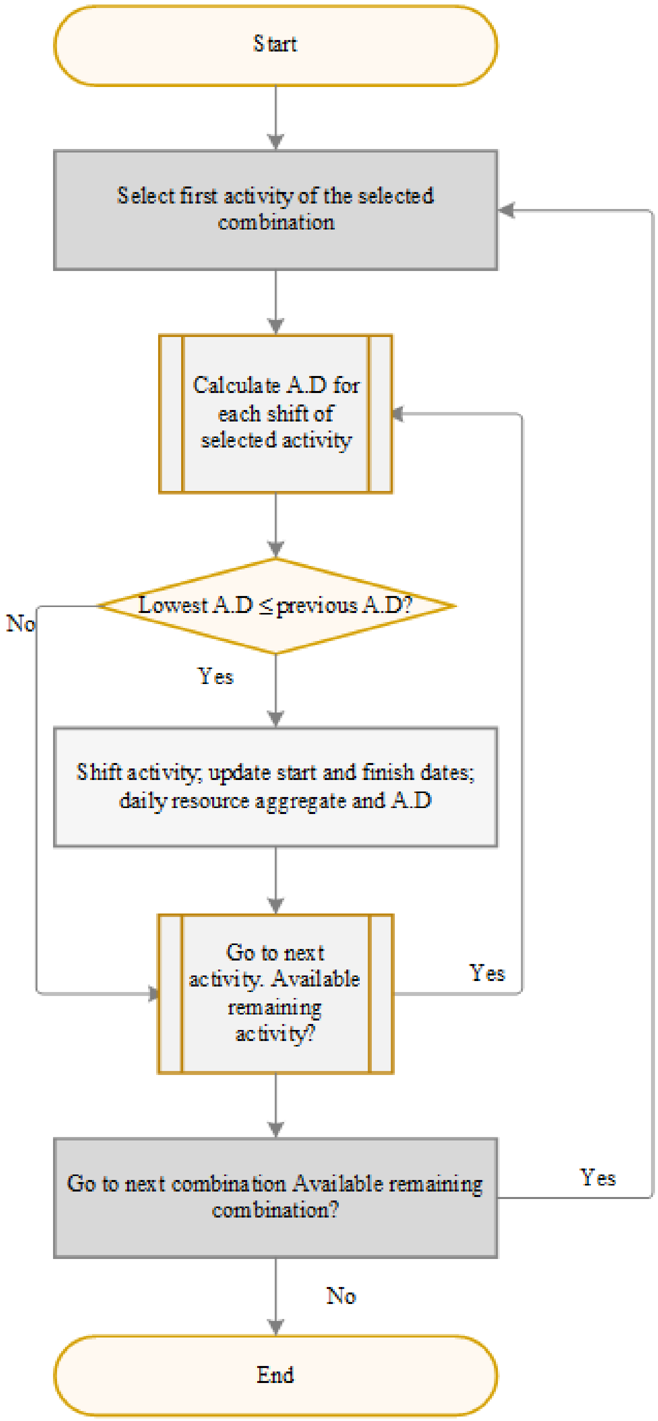


Figure 11 Flowchart of Leveling according to ***A.D***

Ideally speaking, RIC must be 1. The closer the RIC value is to 1, the closer the shape of the histogram is to a rectangle. The decrease in the sum of squares of the daily resource usage is a measurement of the improvement in the histogram (Harris, 1973).

Hiyassat (2001) suggested a criterion which can be adopted to reduce the number of calculations used in the traditional leveling approach. The criterion used for selecting activities to level is the value of the $R \times S$ term, where R is the resource rate and S is the free float of the activity. However, this might not be the optimal order of leveling that would lead to the smoothest resource histogram. Therefore, another concept is adopted throughout this study to level activities, which is discussed next. The procedure adopted to level the activities is explained below, starting with float calculations of each activity.

After determining start and end dates, available free float, resource consumption and precedence relationships of each activity, the leveling procedure can begin. The linear schedule is established based on these data and the daily resource aggregate is calculated for the whole project duration. Accordingly, the corresponding $A.D$ is calculated for the initial resource histogram. Resource leveling is done for all resources aggregately and not by trade, i.e. the focus is on the histogram representing daily aggregate resource consumption across all trades. As previously mentioned, the activities eligible for leveling are the ones having free float. However, it is not known what order of leveling these activities leads to the smoothest resource histogram. Therefore, the permutation of all possible combinations of activities is determined.. For instance, assume there are three activities {A,B,C} having free floats. The permutation of their possible combinations is {A,B,C}, {A,C,B}, {B,A,C}, {B,C,A}, {C,A,B} and {C,B,A}. Next, the first activity in the first combination is selected. The $A.D$ for each shift of this specific activity is then calculated and the shift with the lowest $A.D$ value is chosen. If the corresponding $A.D$ is lower than or equal to the initial $A.D$, the activity is shifted by the corresponding amount and the start and finish times, remaining float of the activity and the daily resource aggregate are updated. If $A.D$ is greater than the initial value, no changes are made and the next activity in the corresponding combination is selected. After examining the last activity in the specified combination, the $A.D$ value for the corresponding resource histogram is stored and the procedure is repeated all over for all the combinations. This results in an array containing $A.D$ values for all the combinations. The combination corresponding to the smallest $A.D$ value is selected, since a lower $A.D$ value designates a smoother resource histogram. Finally, RIC is calculated to assess the effectiveness of the leveling procedure.

The reason for choosing free float instead of total float to perform resource leveling is to eliminate the risk of delaying the project since total floats directly affect the project duration. On the other hand, messing with the free floats of activities might delay the activities' successors without necessarily affecting the total duration.

4.2.2 Scenario Two

In order to assess the effect of shifting activities on the project congestion level, a second scenario is conducted in which leveling is done according to the congestion level (f) only and with no consideration to $A.D$ levels. The same procedure followed in scenario 1 is adopted except for the congestion level parameter (f), which is needed to decide on the shifting of the activity. The flowchart for this case is summarized in Figure 12. The model searches for shifts that result in minimized congestion level.

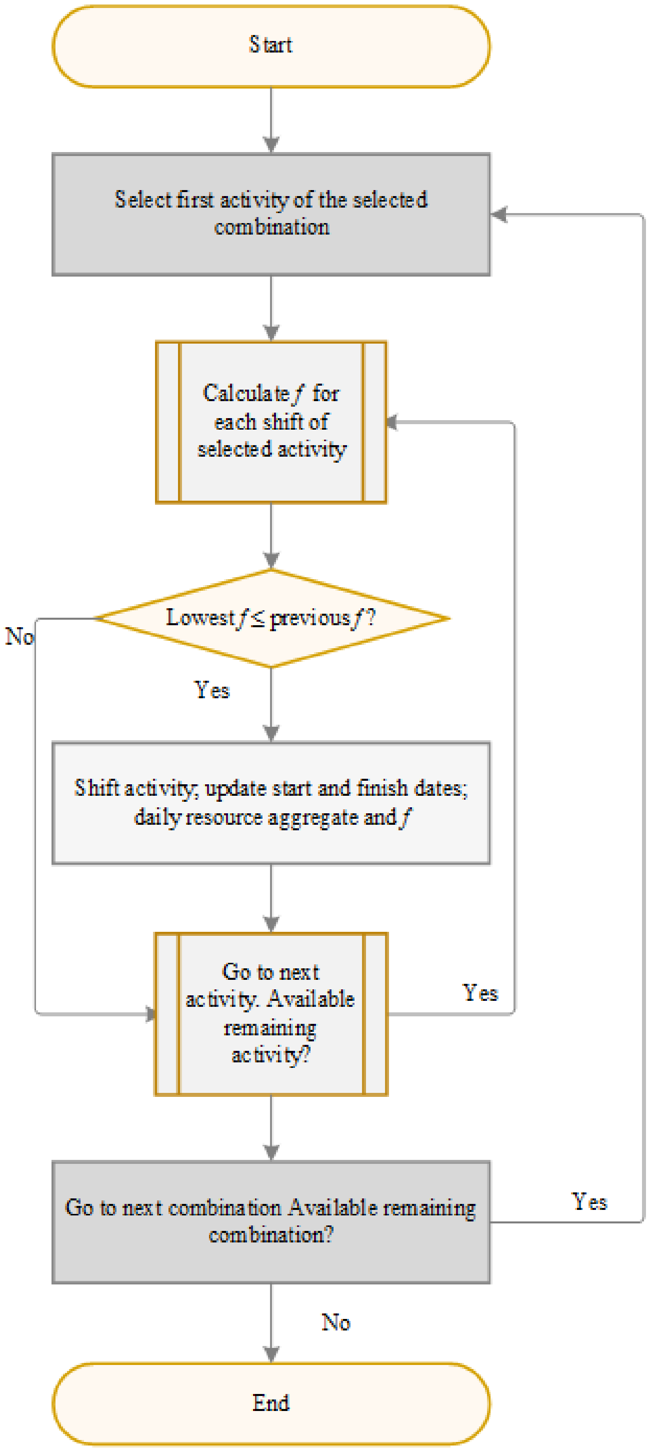


*Figure 12 Flowchart of Leveling according to **f***

Workspace congestion should be avoided because of the negative effects it has on productivity and project quality (Tao et al., 2018). Figure 13, adopted from Semenov et al. (2014), summarizes competition between crews for workspace and possible congestion. There are four activities A_1, A_2, A_3 and A_4. The lower part of the figure highlights the active workspaces based on the bar chart above it. For example, during $\Delta d_{2,3}$, which is the overlap in duration between activities A_2 and A_3, W_2 and W_3 , which represent the workspaces for activities A_2 and A_3 , are active and highlighted in bold, but they are distant and pose no conflict. However, during $\Delta d_{2,4}$, there is an overlap in workspace creating congestion during this specific time.

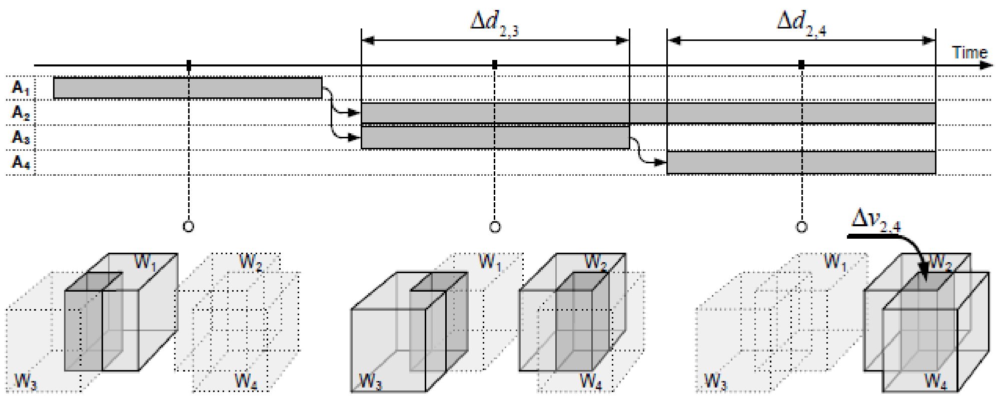


Figure 13 Workspace Competition (Semenov et al., 2014)

In this research, congestion calculations are based on the method of Tao et al. (2018). To do so, the average resource density for activity i (ρ_i) is first calculated based on Equation 14:

$$\rho_i = \frac{R_i \times v_k}{v(\omega_i)} \tag{14}$$

Where R_i is number of resources used for activity i, v_k the space volume occupied by one unit resource k and $v(\omega_i)$ is the volume of space ω allocated to activity i. Basically, this term calculates the ratio of the space required by a specific activity to the space allocated to it. Second, the interference of workspaces between any pair of activities i and i' is calculated based on the equation below

$$I_i = \sum (\rho_{i'} \times \upsilon(\omega_i \cap \omega_{i'}) \times \Delta d_{(i,i')} \tag{15}$$

Where $\rho_{i'}$ is the resource density of activity i', $\upsilon(\omega_i \cap \omega_{i'})$ is the intersection in workspaces between activities i and i' and $\Delta d_{(i,i')}$ is the overlap in durations between the two activities. Finally, the congestion level f is computed as follows:

$$f = \frac{\sum I_i}{n} \tag{16}$$

Where n is the number of activities. To simplify the matter, consider the following example. Suppose we have three activities with the characteristics shown in Table 1. Table 2 represents the overlap in durations and workspaces of these activities.

Table 1 Characteristics of Activities

Activity	Number of Resources	Volume of Workspace (m^3)	Duration (days)
1	4	450	6
2	3	270	5
3	3	180	3

Table 2 Overlap in Durations and Workspaces

Activities	1 & 2	1 & 3	2 & 3
Overlap in duration (days)	2	3	1
Overlap in workspace (m^3)	120	90	0

Assume that the volume of operation space of each human is 7 m^3. According to the equations above, the resource density, interference for each activity, and overall congestion level are calculated as follows:

$$\rho_1 = \frac{4 \times 7}{450} = 0.062$$

$$I_1 = 0.078 \times 120 \times 2 + 0.117 \times 90 \times 3 = 50.31$$

$$\rho_2 = \frac{3 \times 7}{270} = 0.078$$

$$I_2 = 0.062 \times 120 \times 2 + 0.117 \times 1 \times 0 = 14.88$$

$$\rho_3 = \frac{3 \times 7}{180} = 0.117$$

$$I_3 = 0.062 \times 90 \times 3 + 0.078 \times 1 \times 0 = 16.74$$

$$f = \frac{50.31 + 14.88 + 16.74}{3} = 27.31$$

By visually inspecting the linear schedule, one can directly assess what unit each activity is occupying on a specific day. However, determining the locations for all activities on all days of the project duration can be a tedious task especially if the project involves numerous tasks and units. Therefore, it is easier to use an equation that directly calculates the unit number for an activity on any day based on the activity's unit duration. Therefore, this study suggests a method to determine the unit that any activity is occupying on any day of the project. The method consists of three equations. Equation 17 is used to calculate the possible location of an activity on a specific day. Equation 18 and Equation 19 are used to specify the exact unit the activity is occupying on that day.

$$L(i)_X = \frac{X - S.D(i)}{U.D(i)} \tag{17}$$

$$if\ R = 0 \rightarrow U(i)_X = L(i)_X + 1 \tag{18}$$

$$if\ R \neq 0, \rightarrow U(i)_X = \lceil L(i)_X \rceil \tag{19}$$

$L(i)_X$ is the location of activity i on day X, R is the remainder of Equation 17, $U(i)$ is the unit that activity i is occupying on day X. The operator ⌈ ⌉ applies the ceiling function, which gives the smallest integer that is greater than $L(i)_X$ (Weisstein, 2002).

As previously mentioned, the overlap in activities' workspaces occur only when there is overlap in the durations of these activities. To determine whether there is an overlap in the activities' durations, the conditions stated in Figure 14 retrieved from Kassem et al. (2015) are adopted throughout this study. However, the second condition in the first case of Figure 14 is changed from Activity 2 SD < Activity 2 FD to Activity 2 SD > Activity 1 SD. These conditions allow to check for durations overlap and to calculate the duration of this overlap as displayed in Table 3.

Table 3 Overlap Duration

Case	Overlap Duration
i	FD1-SD2
ii	FD1-SD2 or FD1-SD1
iii	FD1-SD1
iv	FD2-SD1
v	FD2-SD2
vi	FD2-SD1 or FD1-SD1

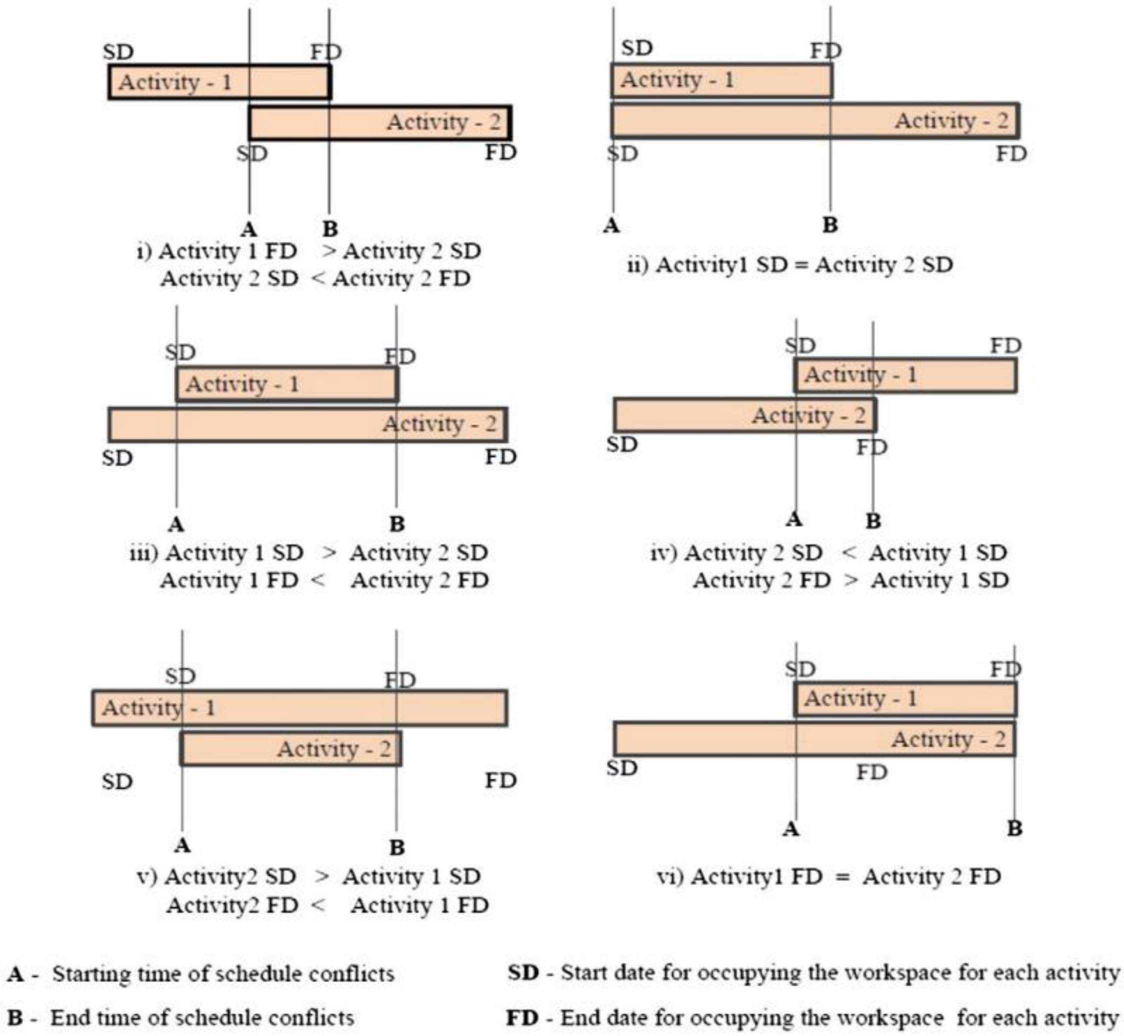


Figure 14 Schedule Overlap Conditions (Kassem et al., 2015)

In order to calculate congestion, the locations of each two activities happening simultaneously are compared. If two activities are happening on the same day in the same unit, their workspaces are further analyzed. In this case, the coordinates of the two workspaces are checked for intersection. If the conditions in Equation 20 and Equation 21 are satisfied, then there is no overlap in workspaces A and B of the two activities.

$$X_{\max(A)} > X_{\min(B)} \;\&\; X_{\min(A)} < X_{\max(B)} \qquad (20)$$

$$Y_{\max(A)} > Y_{\min(B)} \;\&\; Y_{\min(A)} < Y_{\max(B)} \qquad (21)$$

If these conditions are not satisfied, then there is overlap in the workspaces of activities as shown in Figure 15. The calculation of this overlap area is based on the method by Mirzaei et al. (2018) using Equation 22 and Equation 23:

$$X_{AB} = \left|Min\{X_{max(A)}, X_{max(B)}\} - Max\{X_{min(A)}, X_{min(B)}\}\right| \tag{22}$$

$$Y_{AB} = \left|Min\{Y_{max(A)}, Y_{max(B)}\} - Max\{Y_{min(A)}, Y_{min(B)}\}\right| \tag{23}$$

Where A and B are workspaces for two different crews as shown in Figure 15.

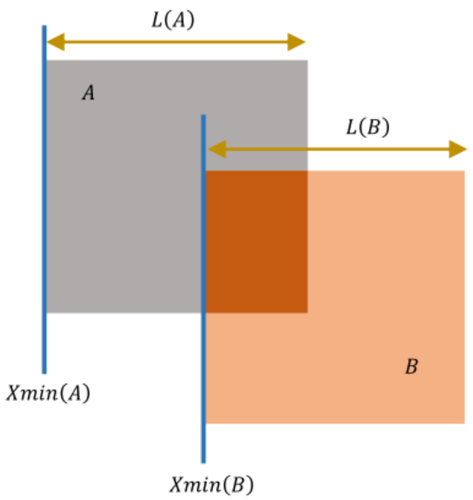


Figure 15 Overlap Area Dimensions (Mirzaei et al., 2018)

In order to make use of the linear schedule in quantifying congestion, it is amended into a 3-dimensional graph by adding one more axis as shown in Figure 16. This schedule consists of five activities repeated over four units, with locations depicted by x and y coordinates, and the time reflected through the z coordinate. For example, the red staircase curve plots vertically the time spent at the center of gravity of each unit as well as the flow of resources between units (i.e. horizontal parts of the curve). The red box represents the workspace for the red activity in the specific unit on the specific day.

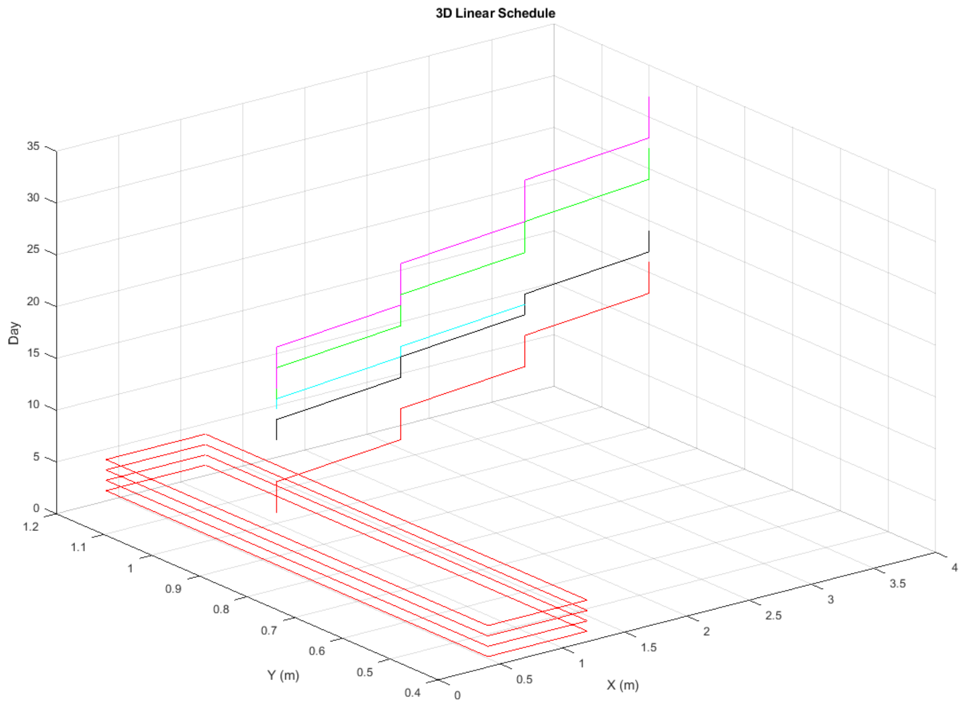


Figure 16 Amended Linear Schedule

The same concept applies to all other activities happening in different units. However, for simplicity purposes, only concurrent and overlapping workspaces are plotted on the 3-dimensionl schedule to assess congestion. Integrating the plotted conflicting areas within the previously explained congestion formulas helps in calculating the overall congestion level. All workspaces are considered to have the same height and assumed to include space needed for equipment used by crew performing the tasks.

4.2.3 Scenario Three

Finally, accounting for both measures is tested in this section. The reasoning goes as summarized in the flowchart in Figure 17.

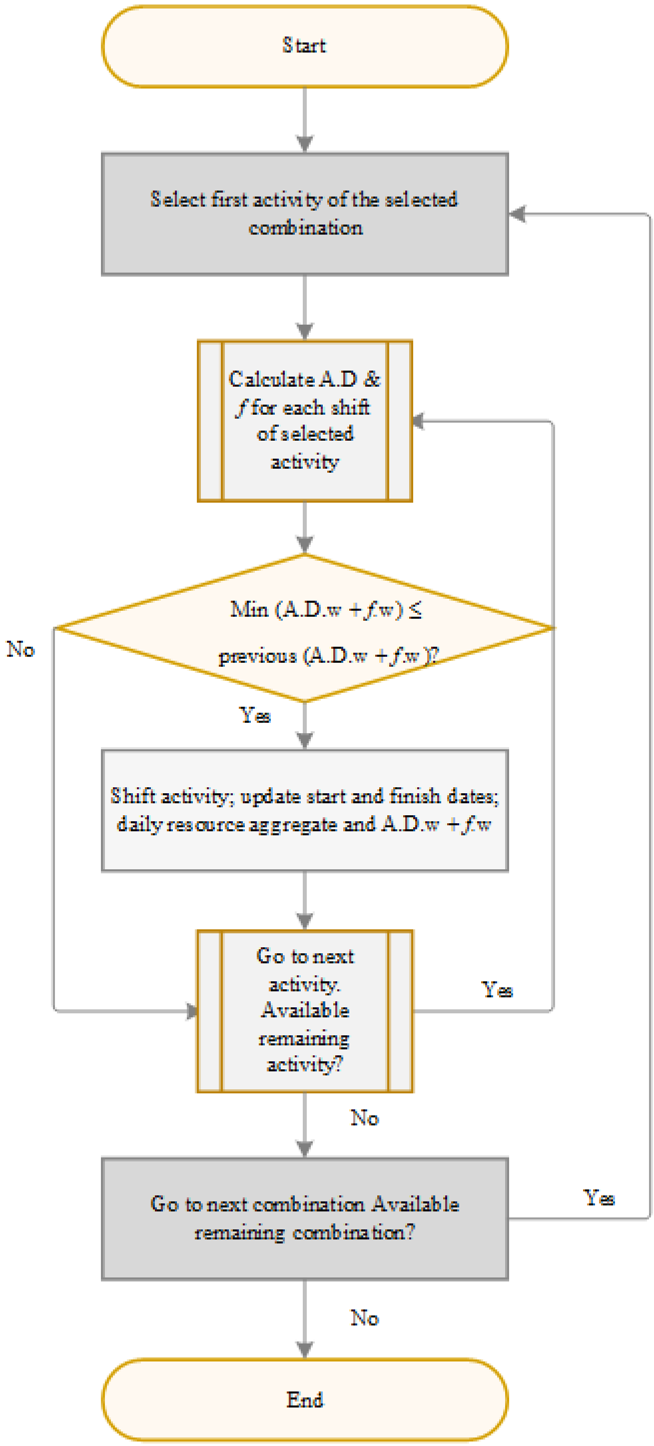


Figure 17 Flowchart of Leveling according to $\boldsymbol{A.D}$ *&* $\boldsymbol{f}$

Each parameter is assigned a weight factor that is user-defined. $A.D.w$ is the weighted $A.D$ i.e. it is $A.D \times w_1$ where w_1 is the weight factor assigned by the user to $A.D$. Also,

$f.w$ is $f \times w_2$ where w_2 is the weight factor assigned to f. The $A.D$ and f values for each shift of the activity are first calculated and each one is multiplied by its corresponding weight factor. The two products are summed and the lowest sum is selected. If this lowest sum is less than or equal to the previous sum, the shift is performed and all the dates, daily resource aggregate/cost, $A.D$ and f values are updated. If it is greater than the previous sum, no changes are made, and the next combination is selected.

Finally, all the above steps of the model are undertaken within a graphical user interface (GUI) that allows the users to easily manage any schedule.

4.3 Graphical User Interface (GUI)

A Graphical User Interface (GUI) (Figure 18) is developed to allow the users to easily interact with the model without having to deal with the code text lines. The user has to select two files that are appended to the program. The files are the template containing all information about the activities as the one shown in Figure 6 and the template containing the coordinates of each activity in each unit. Once the files are selected, the program can start.

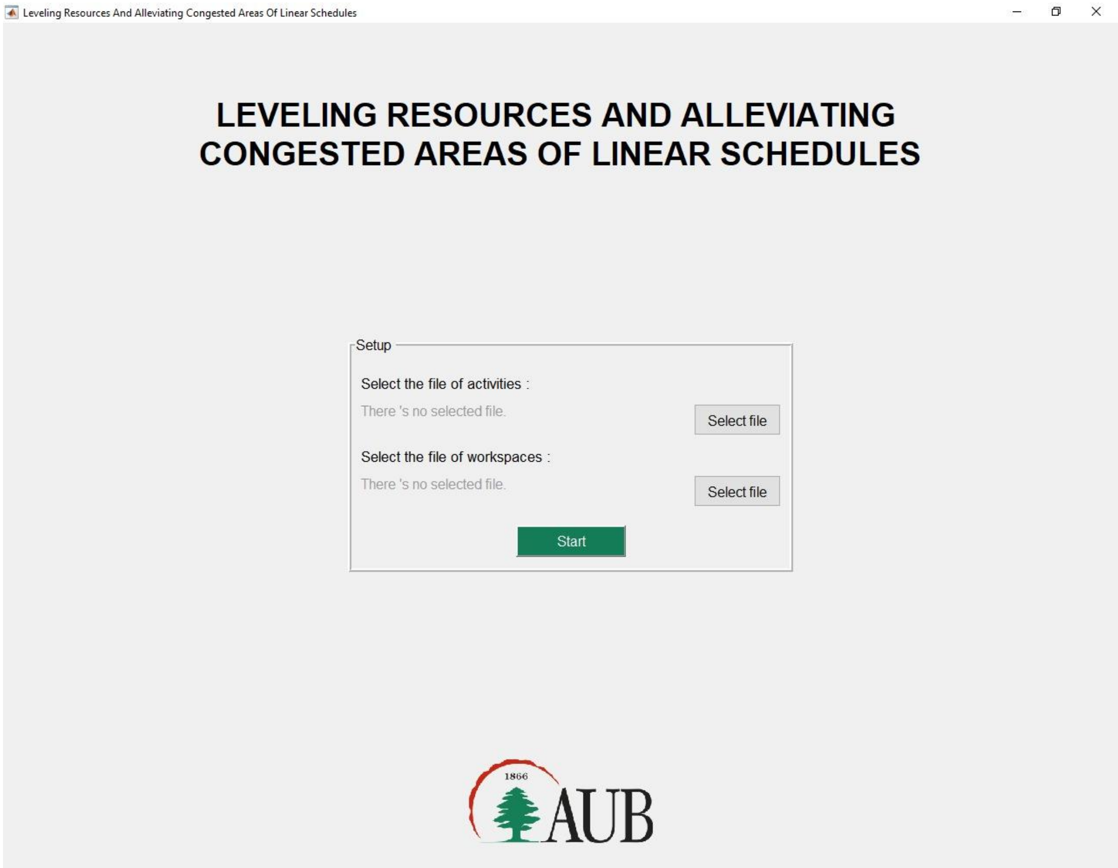


Figure 18 GUI 1: Introductory GUI

Next, another GUI opens based on the selected files and it consists of four parts as shown in Figure 19. In order to assess the effect of each parameter on the overall schedule and on each other, the model is tested in five phases. In the first phase, an initial schedule is generated by calculating the start and end dates of all the activities while satisfying the precedence relationships. This is carried out in the section titled "Pre-leveling Linear Schedule" of the latter GUI. In the second phase, leveling of resources is performed according to $A.D$ and while keeping an eye on congestion levels. The second section of the GUI titled "Leveling: AD" addresses this scenario. In the third phase, leveling of resources is performed according to congestion level and while observing $A.D$ values. This is addressed in the third section of the GUI titled "Leveling: Congestion Level".

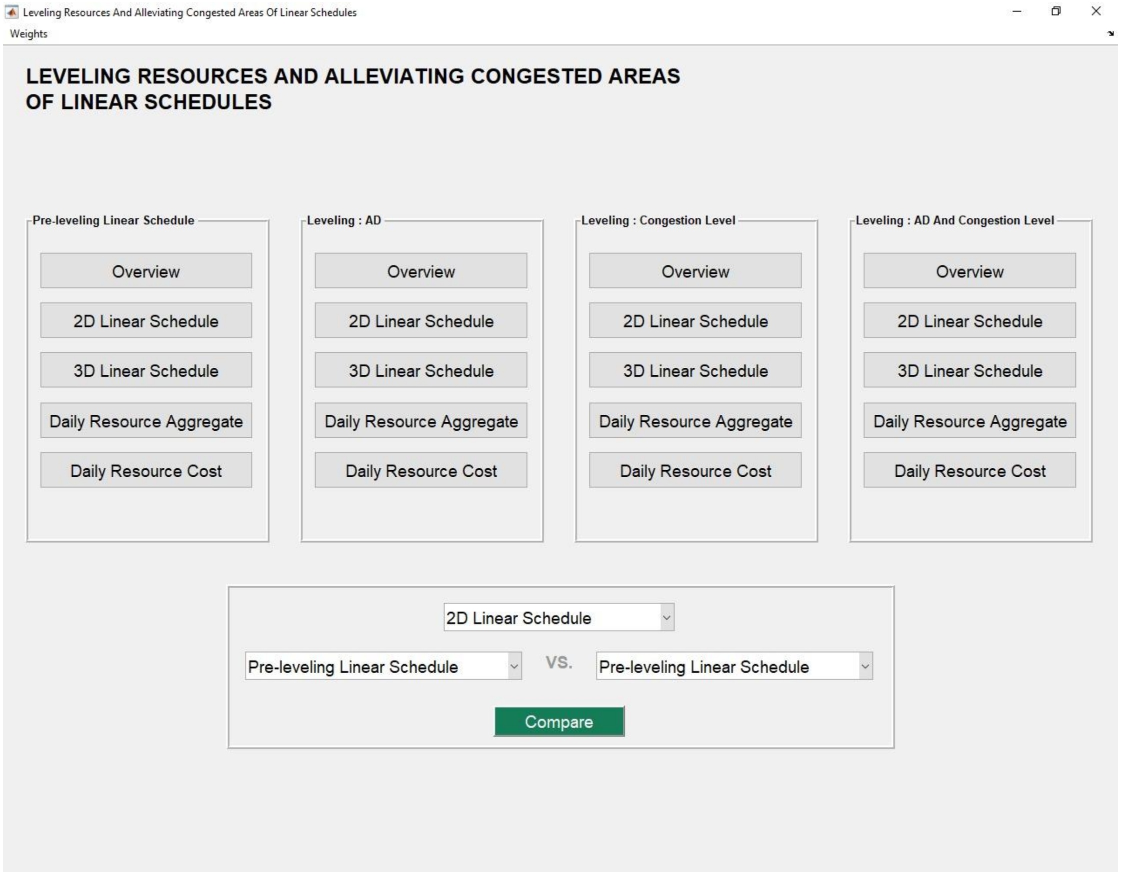


Figure 19 GUI 2: Resource Leveling GUI

In the fourth phase, resource leveling is done according to both $A.D$ and congestion levels. The section titled "Leveling: $A.D$ & Congestion Level" tackles this part. The last part of the GUI allows comparison among any two scenarios as shown in the bottom of Figure 19. The options included in the upper drop-down menu of the comparison window are "2D Linear Schedule", "3D Linear Schedule", "Daily Resource Aggregate" and "Daily Cost Aggregate" as shown in Figure 20. The options included in both lower drop down menus include any of the previously mentioned four sections.

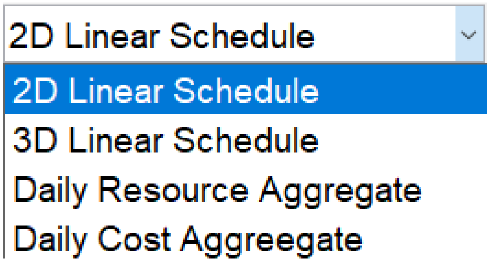
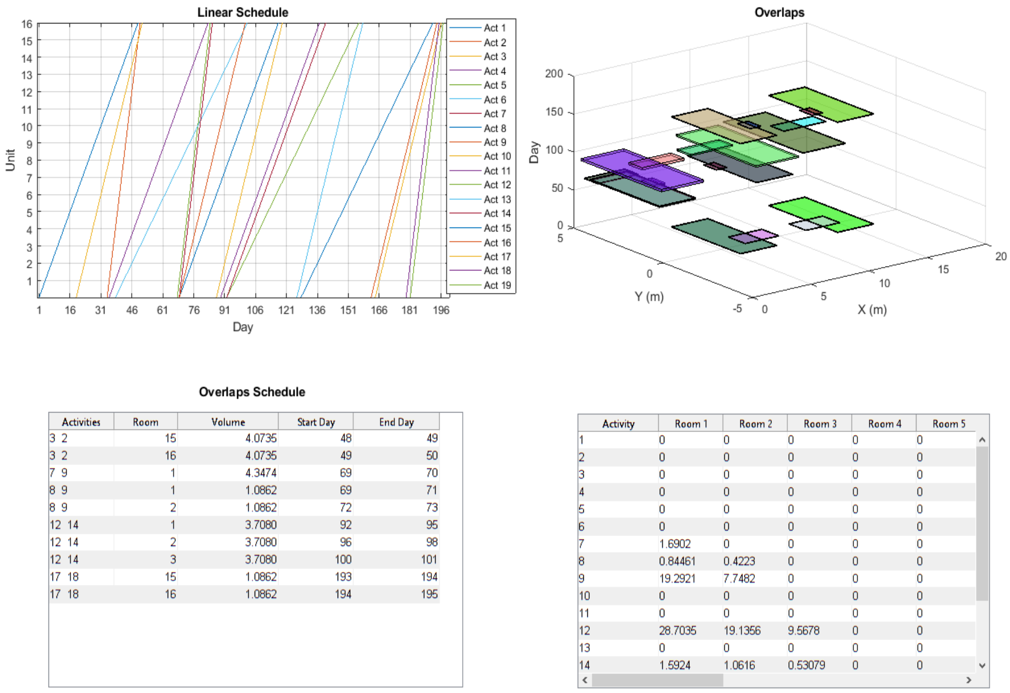


Figure 20 Upper Drop-down Menu of Comparison Window

Each section of the first four above mentioned sections is further composed of five parts. The first part generates an overview GUI displaying the usual 2D linear schedule, the 3D linear schedule showing conflicts among workspaces, a table clarifying conflicting activities along with the volume, duration and room number of conflicts and a table showing the interference value of intersecting activities as displayed in Figure 21. The volume and duration of conflicts are necessary for calculating the interference and consequently the congestion level.



Activities	Room	Volume	Start Day	End Day
3 2	15	4.0735	48	49
3 2	16	4.0735	49	50
7 9	1	4.3474	69	70
8 9	1	1.0862	69	71
8 9	2	1.0862	72	73
12 14	1	3.7080	92	95
12 14	2	3.7080	96	98
12 14	3	3.7080	100	101
17 18	15	1.0862	193	194
17 18	16	1.0862	194	195

Activity	Room 1	Room 2	Room 3	Room 4	Room 5
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	1.6902	0	0	0	0
8	0.84461	0.4223	0	0	0
9	19.2921	7.7482	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	28.7035	19.1356	9.5678	0	0
13	0	0	0	0	0
14	1.5924	1.0616	0.53079	0	0

Figure 21 GUI 2: Overview Option

In the Overlaps Schedule of Figure 21, double clicking on any value in the Volume column generates an individual graph showing the workspaces of the corresponding intersecting activities aside as displayed in Figure 22. The height of the cube represents the duration of the overlap.

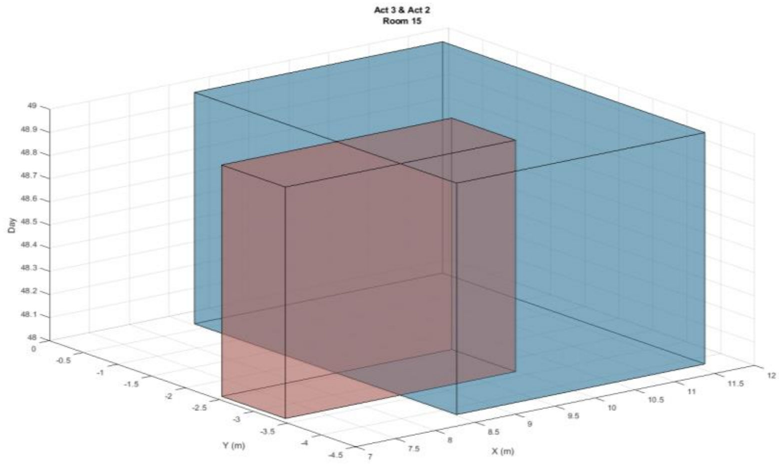


Figure 22 Individual Overlap Graph

CHAPTER 5

CASE STUDY AND EXPERIMENTAL SCENARIOS

The case adopted is the renovation of the Penrose dormitory at the American University of Beirut (AUB). The building consists of 6 floors with the floor plan shown in Figure 23. Each floor consists of 16 repetitive rooms. The study is conducted for one typical floor and the rooms are considered units. The point circled in red is taken as the origin having (0,0) coordinates. Figure 24 displays the CPM network at the unit level.

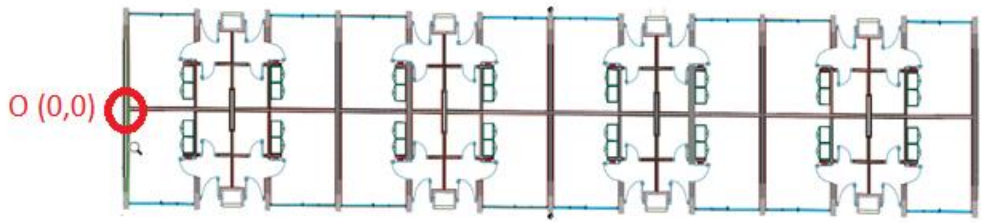


Figure 23 Project Layout

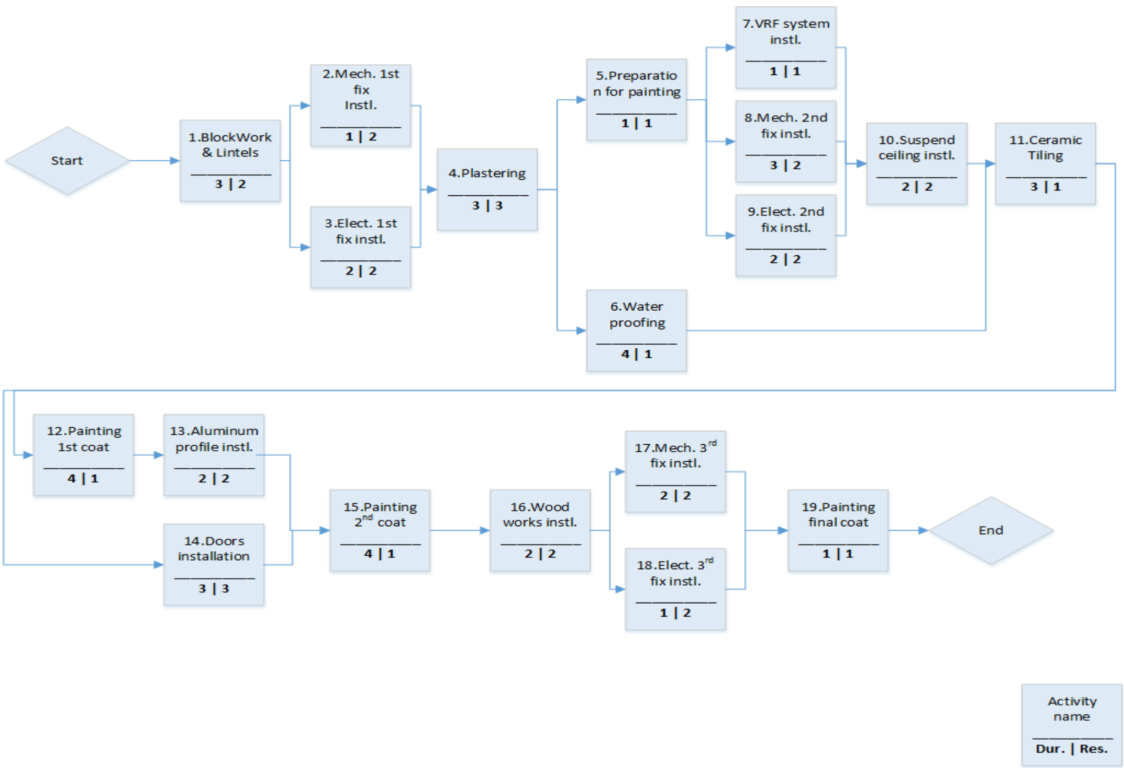


Figure 24 CPM Network

Table 4 shows the finishing activities that take place in each room along with the unit duration, resource consumption and cost per day for each activity. As aforementioned, each activity is assigned a rectangular workspace whose coordinates are extracted from a digital CAD drawing given the specified origin location. It was assumed that the workspaces include, in addition to the activity space, a space allocated for necessary equipment needed to perform the activity. For simplicity purposes, all the workspaces are assumed to have a height of 3 m. The nature of linear projects makes it easy to get the coordinates of the activity in all units because of the symmetry in the layout.

Table 4 Activities Description

Activity Description				
ID	Activity	Duration	Human Resources	$/Day
1	Blockwork & Lintels	3	2	60
2	Mech. 1st fix instl.	1	2	60
3	Elect. 1st fix instl.	2	2	60
4	Plastering	3	3	80
5	Preparation for painting	1	1	40
6	Water proofing	4	1	40
7	VRF system instl.	1	1	40
8	Mech. 2nd fix instl.	3	2	60
9	Elect. 2nd fix instl.	2	2	60
10	Suspend ceiling instl.	2	2	60
11	Ceramic Tiling	3	1	40
12	Painting 1st coat	4	1	40
13	Aluminum profile instl.	2	2	60
14	Doors installation	3	3	80
15	Painting 2nd coat	4	1	40
16	Wood works instl.	2	2	60
17	Mech. 3rd fix instl.	2	2	60
18	Elect. 3rd fix instl.	1	2	60
19	Painting final coat	1	1	40

5.1 Linear Schedule Generation

After importing the network details, the model first generates an initial schedule based on Equations 1 through 11. Table 5 shows the start and end dates as well as the free float days of each activity. The project duration is 197 days. It is important to note that this duration is fixed as a constraint and no one leveling scenario will result in an increase in project duration.

Table 5 Initial Schedule Days

ID(i)	S.D(i)	E.D(i)	F(i)
1	1	49	0
2	34	50	0
3	19	51	14
4	35	83	0
5	68	84	0
6	38	102	0
7	69	85	17
8	69	117	0
9	69	101	16
10	87	119	0

ID(i)	S.D(i)	E.D(i)	F(i)
11	89	137	0
12	92	156	0
13	126	158	0
14	92	140	33
15	128	192	0
16	162	194	0
17	164	196	0
18	179	195	1
19	181	197	0
-	-	-	-

Figure 25 displays the initial linear schedule. As mentioned before, activities that are independent are allowed to occur in the same unit. Therefore, it is acceptable to have intersecting lines in the linear schedule.

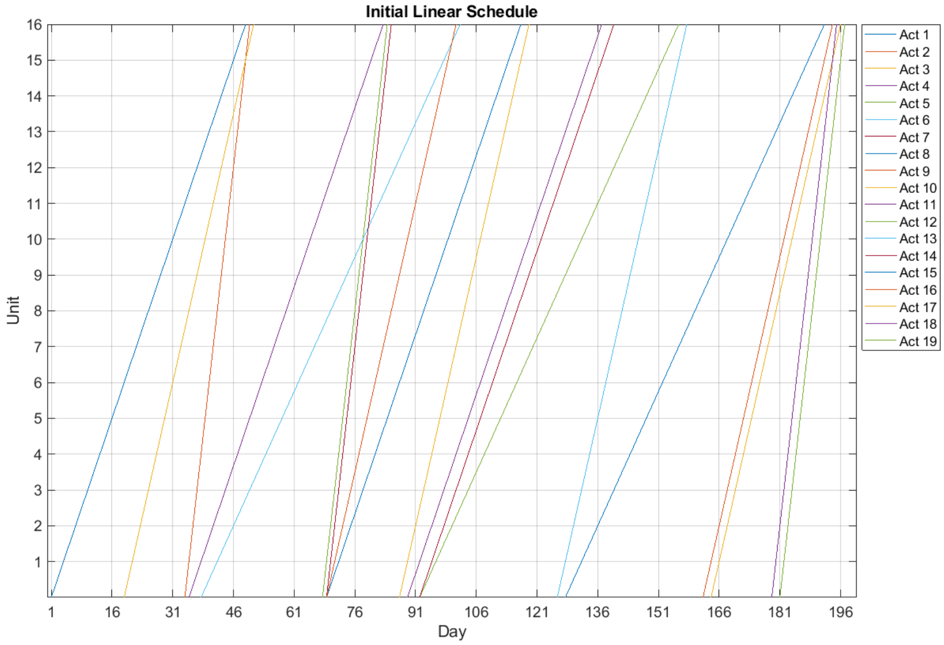


Figure 25 Initial Linear Schedule

The intersecting activities in the initial schedule are mechanical with *electrical 1st fix installation* (room 15), *electrical 2nd fix installation* with *VRF system installation* (room 1) and with *mechanical 2nd fix installation* (rooms 1 and 2), painting 1st coat with *doors installation* (rooms 1, 2 and 3), *mechanical* with *electrical 3rd fix installation* (rooms 15 and 16). Their workspaces are shown on the 3D linear schedule (Figure 26).

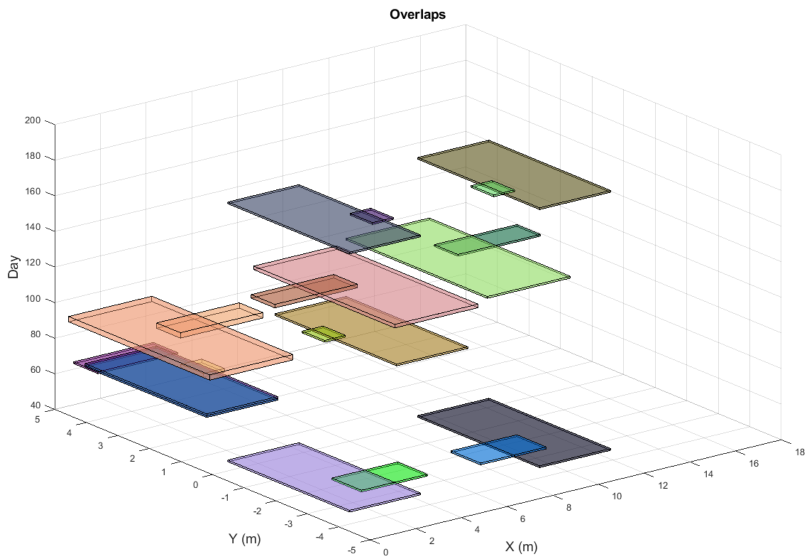


Figure 26 Initial 3D Linear Schedule

Knowing the activities that are happening on each day, the daily resources are counted and the initial resource histogram profile is generated, as shown in Figure 27. It has an $A.D$ value of 2.622, the initial I is around 125 resulting in a congestion level of 6.533 , and its RIC value is:

$$RIC = \frac{197 \times 9224}{1216^2} = 1.23$$

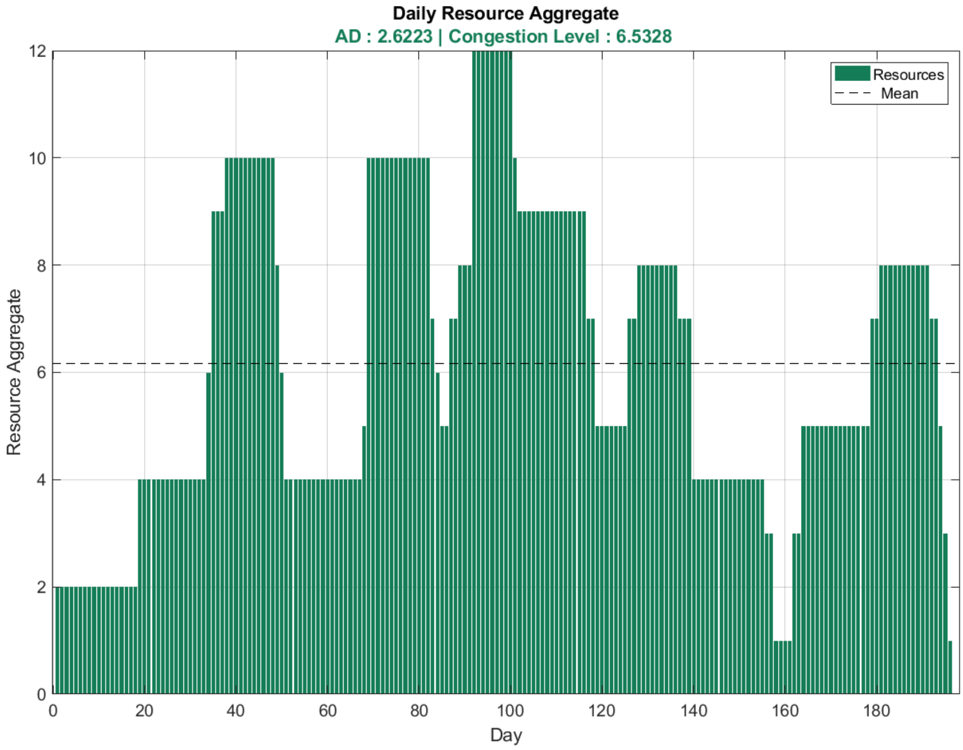


Figure 27 Initial Resource Histogram

Based on the calculated dates and the precedence relationships among the activities, free floats for all activities are then determined. The activities having positive float days are *electrical 1st fix installation* with 14 float days, *VRF system installation* with 17 float days, *electrical 2nd fix installation* with 16 float days, *doors installation* with 33 float days, and *electrical 3rd fix installation* with 1 float day.

5.2 Scenario 1: Leveling According to $A.D$

5.2.1 Scenario 1: Results

In the first scenario, leveling of resources is done according to $A.D$ and without taking congestion levels into account. This is done to assess the effect of shifting activities on the data spread of the resource histogram. The procedure followed is the one shown in Figure 11. The final combination of the activities to level is *VRF system installation*(7), *electrical 1st fix installation*(3), *doors installation* (14), *electrical 2nd fix installation*(9), electrical 3rd fix *installation*(18) and the corresponding shifts are {2, 9, 25, 14, 1}. The intersecting activities are *mechanical* with *electrical 1st fix installation* (rooms 6 and 7), *electrical* with *mechanical 2nd fix installation* (rooms 13, 14, 15 and 16) and *electrical* with *mechanical 3rd fix installation* (room 17) leading to an interference value of 75. The final resource histogram reached (Figure 28) has an $A.D$ value of 1.965 and congestion level of 5.313. The RIC value for this leveled resource histogram is:

$$RIC = \frac{197 \times 8614}{1216^2} = 1.148$$

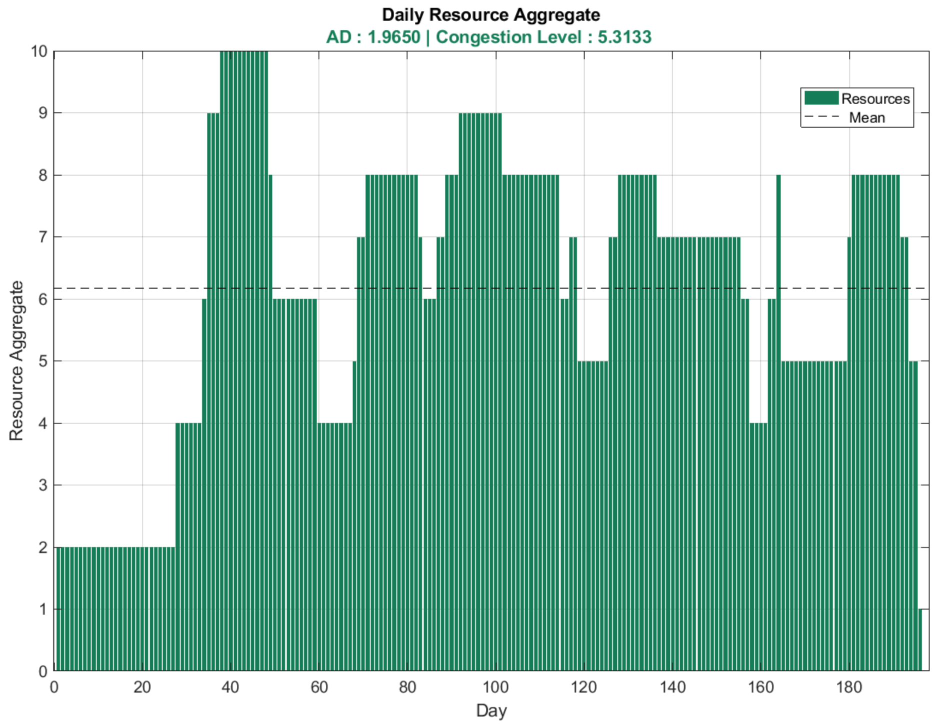


Figure 28 Leveled Resource Histogram: According to $\boldsymbol{A.D}$

Although the congestion level is not controlled in this case, it is observed in order to assess the effect of leveling according to $A.D$ on f. Figure 29 displays the overlaps in workspaces after leveling.

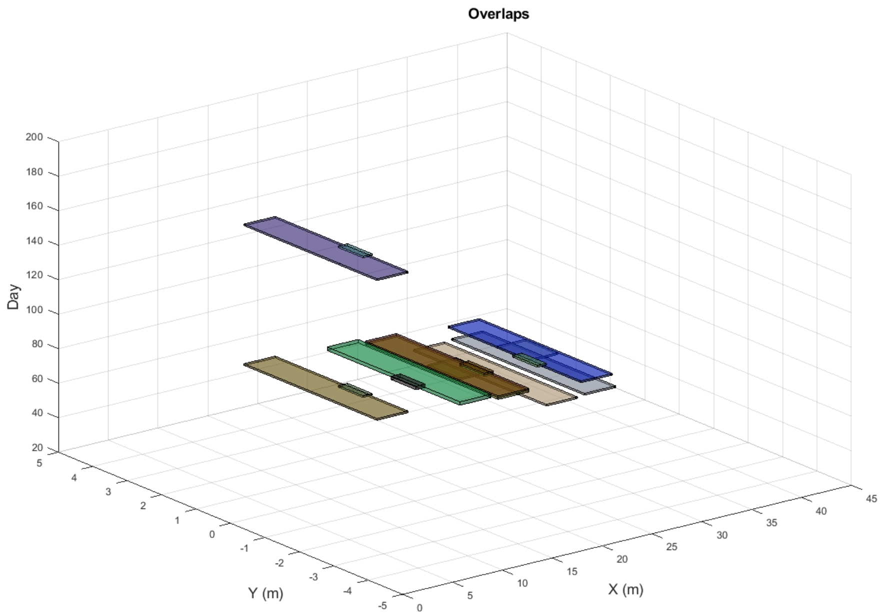


Figure 29 Leveled 3D Linear Schedule: According to $\boldsymbol{A.D}$

5.2.2 Scenario 1: Analysis

It is notable that all resources moved closer to the average resource consumption after leveling, as shown in Figure 30 which depicts the daily aggregate resource consumption curves of pre-leveling and after leveling according to $A.D$. In addition, the maximum resource consumption has decreased from 12 to 9 and the minimum has increased from 1 to 4 resources per day. Accordingly, the fluctuations in the daily resource cost decreased as shown in Figure 31 yielding $anRIC$ value of 1.148 instead of the original 1.230. The maximum daily cost decreased from 380$ to 300$ and the minimum increased from 40$ to 120$. The leveling conducted caused somehow a stabilization in the daily cost of resources. It is important to note that the change in daily resource consumptions due to leveling affects around 45% of project days. In other words, the enhancement in fluctuations spans over 90 days out of 197 project days.

Although minimizing congestion is not targeted in this case, changing the start dates of certain activities lead to a reduction in the number of overlapping activities, relieving thereby congested areas. Figure 32 plots the overlapping workspaces before and after leveling.

The initial float days have an average of 16 days; however, the used float days have an average of 10 days. Using only around 63% of float days, the schedule scored 25% improvement in the resource histogram and cost fluctuations and 19% decrease in congestion. The schedule has been improved without consuming all available free float day, avoiding thereby potential delays. Additional flexibility is provided by total float.

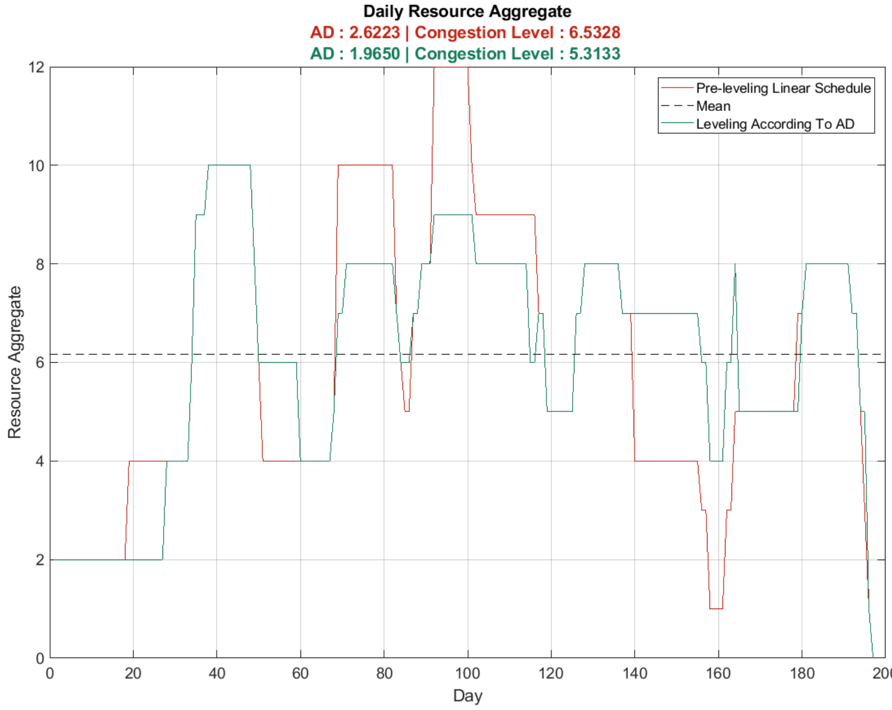


Figure 30 Comparison of Daily Resource Consumption between Pre-Leveling and Leveling according to $\boldsymbol{A.D}$

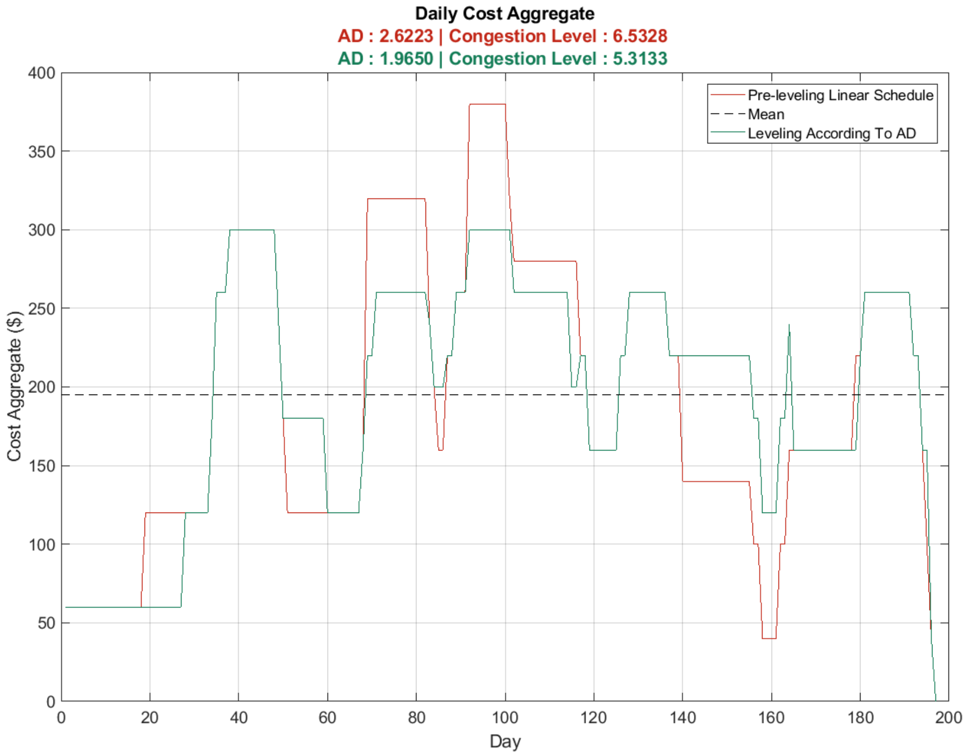


Figure 31 Comparison of Daily Resource Cost between Pre-Leveling and Leveling according to $\boldsymbol{A.D}$

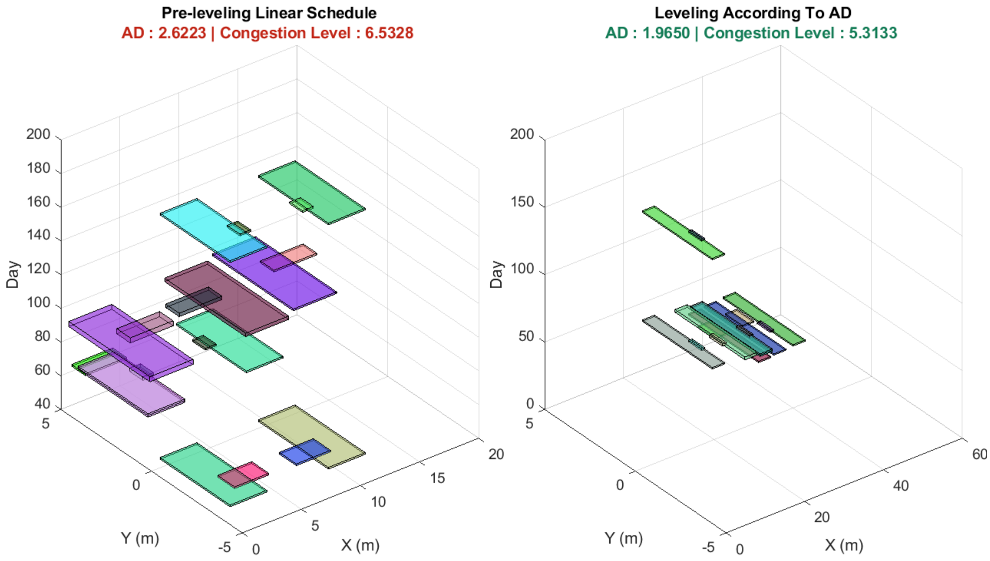


Figure 32 Comparison of Workspaces between Pre-Leveling and Leveling according to $\boldsymbol{A.D}$

5.3 Scenario 2: Leveling According to the Congestion Level

5.3.1 Scenario 2: Results

The best combination of activity leveling orders is *VRF system installation*(7), *electrical 2nd fix installation*(9), *doors installation*(14), *electrical 1st fix installation*(3), and *electrical 3rd fix installation*(18) with corresponding shifts of {3, 0, 19, 14, 0}. The intersecting activities are *mechanical* with *electrical 1st fix installation* (rooms 1 and 2), *mechanical* with *electrical 2nd fix installation* (rooms 1 and 2), *VRF system installation* with *electrical 2nd fix installation* (rooms 3 and 4) and mechanical with *electrical 3rd fix installation* (rooms 15 and 16) yielding an interference value of 73. The resource histogram obtained for this case (Figure 33) has and $A.D$ value of 2.173, congestion level of 4.313, and an RIC value of 1.184 as computed below:

$$RIC = \frac{197 \times 8890}{1216^2} = 1.184$$

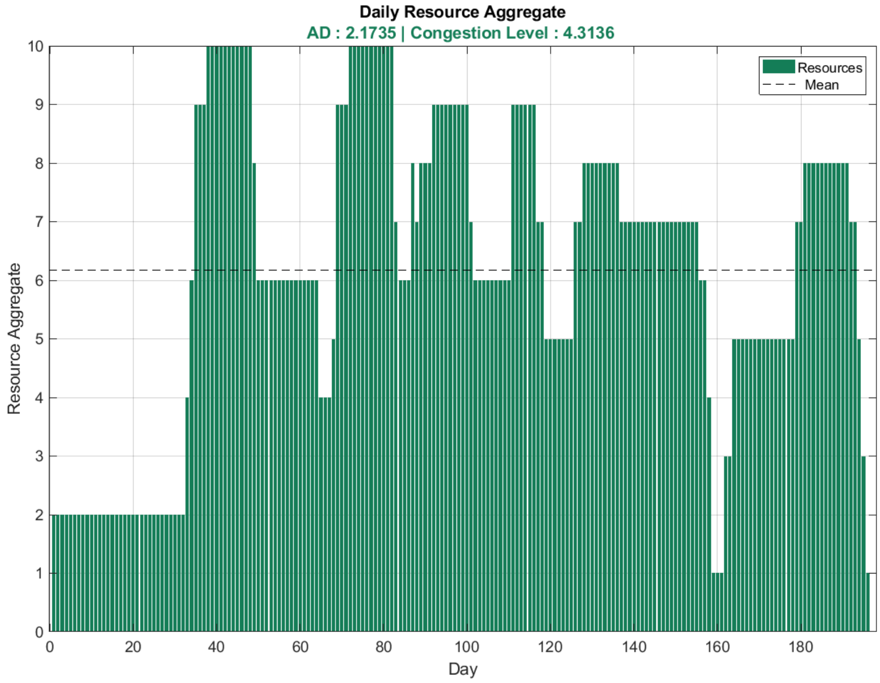


Figure 33 Leveled Resource Histogram: According to ***f***

Figure 34 shows the overlap in workspaces for leveling according to f levels.

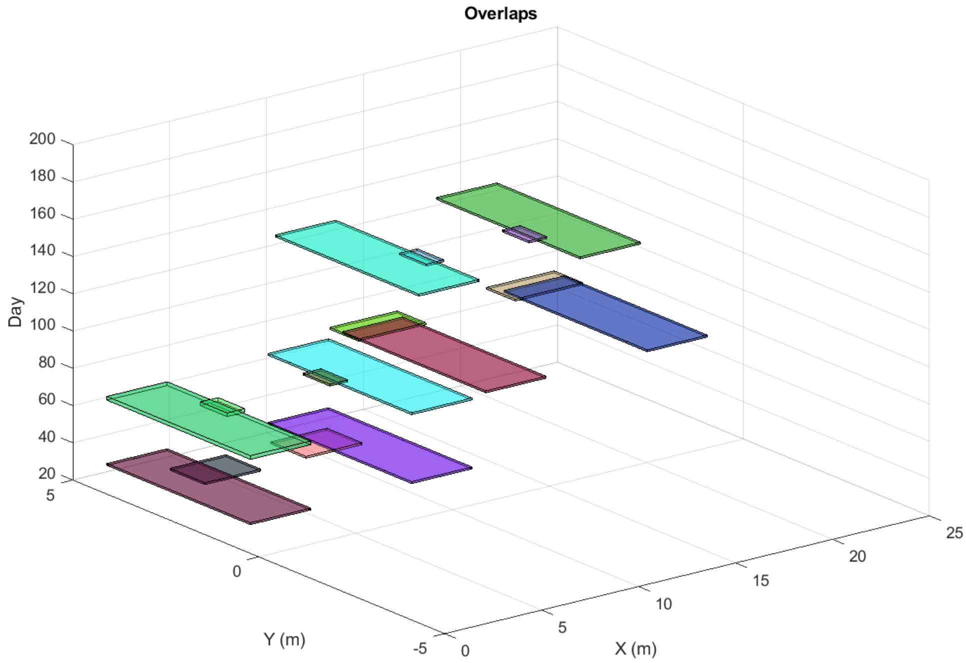


Figure 34 Leveled 3D Linear Schedule: According to ***f***

5.3.2 Scenario 2: Analysis

The result of changing the start dates of certain activities to optimize congestion is reflected in Figure 37. The congestion level has decreased along with $A.D$, although minimizing $A.D$ is not targeted in this case. The number of intersecting activities and the magnitude of overlapping workspaces decreased as shown in Figure 37. Some researchers, like Kenley & Seppänen (2006) in Location-based Scheduling, prohibit unrelated activities to occur in the same unit. In other words, unrelated activities' linear lines are prevented to intersect, which might lead to a longer project duration. In this study, the program allows activities to occur in the same unit but while monitoring the location of each activity. In case the scheduler decided it is impractical to have certain activities take place in the same unit, they can adjust the generated schedule accordingly. The program, in this scenario, searches for shifts that lead to minimized conflicts in workspaces with no concern given to the fluctuations in daily aggregate resource and cost consumption. This explains, for instance, the large gap just before day 160 in Figure 35, where the daily resource usage dropped from 7 to 1.

Figure 35 shows that all daily resources moved closer to the average resource consumption with the maximum dropping from 12 to 9 resources. Consequently, the RIC value dropped to 1.184. Figure 36 shows that leveling in this case caused the inconsistencies in the daily cost of resources to decrease, pulling down the maximum cost from 380$ to 300$.

The used float days have an average of 7 days. Using only around 44% of float days, the schedule achieved 17% improvement in resource histogram and cost fluctuations and 34% decrease in congestion. The enhancement in fluctuations of daily resource consumption and cost due to leveling impacted around 38% of project days. Less than half of available free float days are used to amend the schedule.

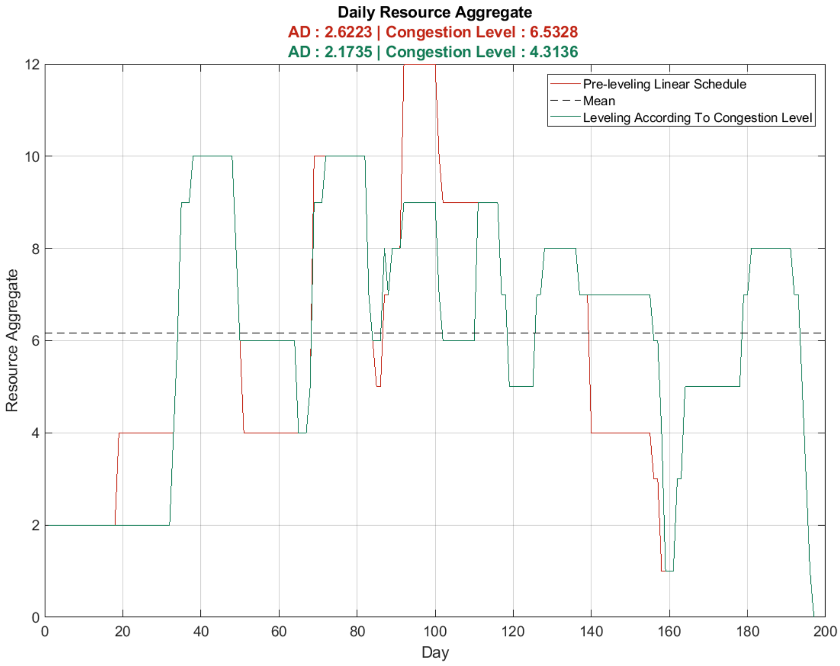


*Figure 35 Comparison of Daily Resource Consumption between Pre-Leveling and Leveling according to **f***

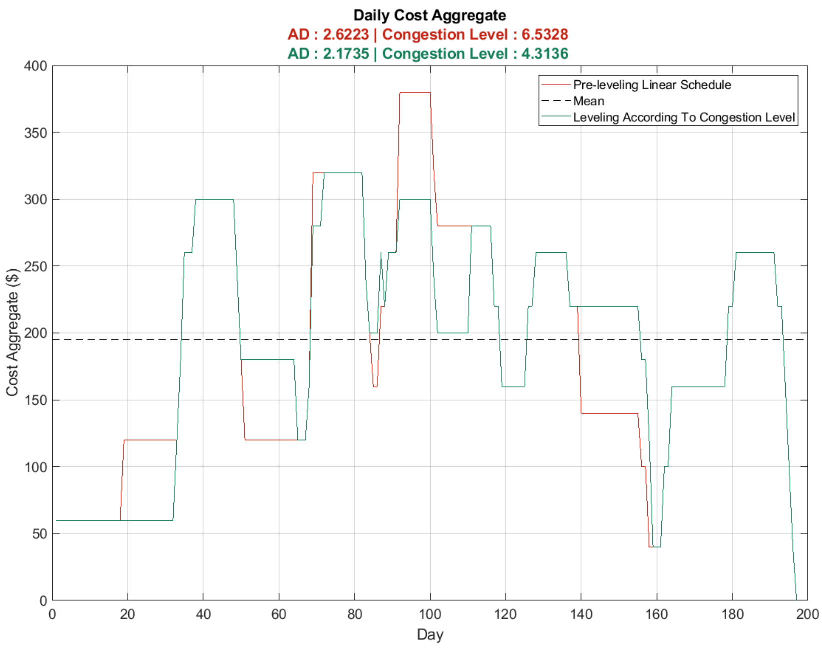


*Figure 36 Comparison of Daily Resource Cost between Pre-Leveling and Leveling according to **f***

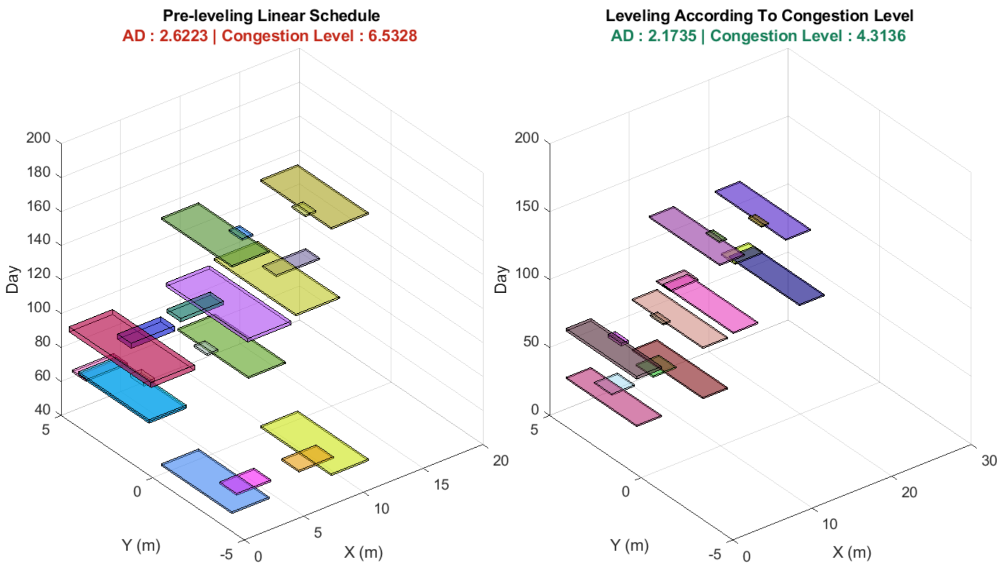


Figure 37 Comparison of Workspaces between Pre-Leveling and Leveling according to $\boldsymbol{f}$

5.4 Scenario 3: Leveling According to $\boldsymbol{A.D}$ and Congestion Level

5.4.1 Scenario 3: Results

As mentioned previously, in this case each parameter should be assigned a weight factor. A trial is conducted with both weights being 0.5. The chosen combination of resource leveling orders is *VRF system installation*(7), 3 *electrical 1st fix installation*(3), *electrical 2nd fix installation*(9), *doors installation*(14), *electrical 3rd fix*(18) with corresponding shifts of $\{3, 9, 0, 25, 0\}$. The intersecting activities are *mechanical* with *electrical 1st fix installation* (rooms 1 and 2), *mechanical* with *electrical 2nd fix installation* (rooms 1 and 2), *VRF system installation* with *electrical 2nd fix installation* (rooms 3 and 4) and *mechanical* with *electrical 3rd fix installation* (rooms 15 and 16). Interference value is around 70. Figure 38 shows the daily resource histogram which has an $A.D$ value of 2 and an f level of 4.313. This RIC for this leveling procedure is:

$$RIC = \frac{197 \times 8758}{1216^2} = 1.167$$

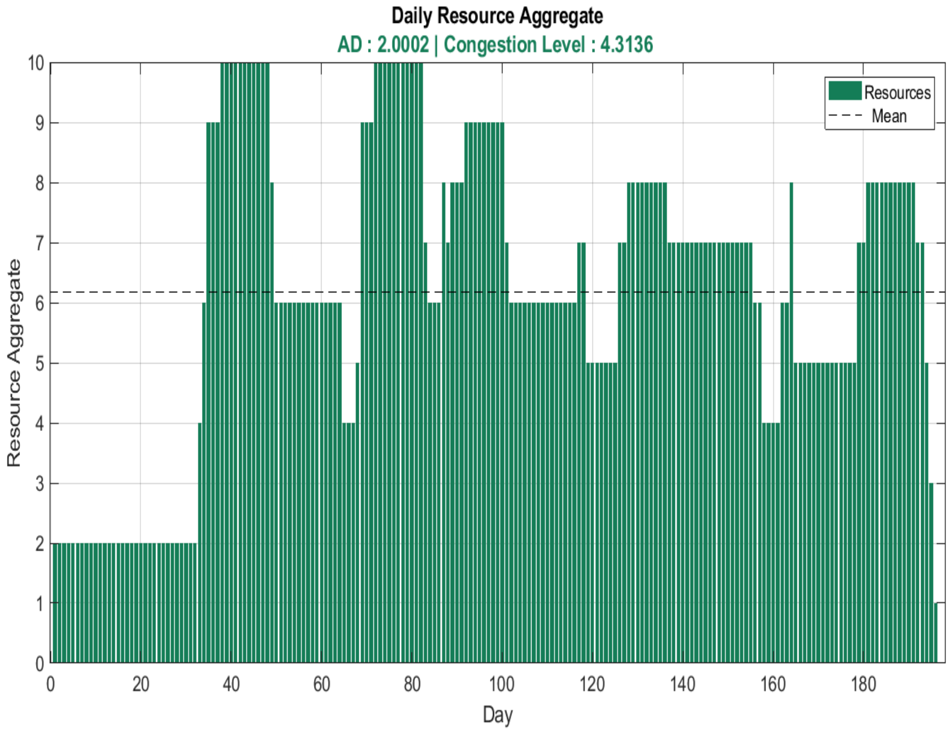


Figure 38 Leveled Resource Histogram: According to $\boldsymbol{A.D}$ *&* $\boldsymbol{f}$

Figure 39 displays the remaining conflicting workspaces after leveling according to both parameters.

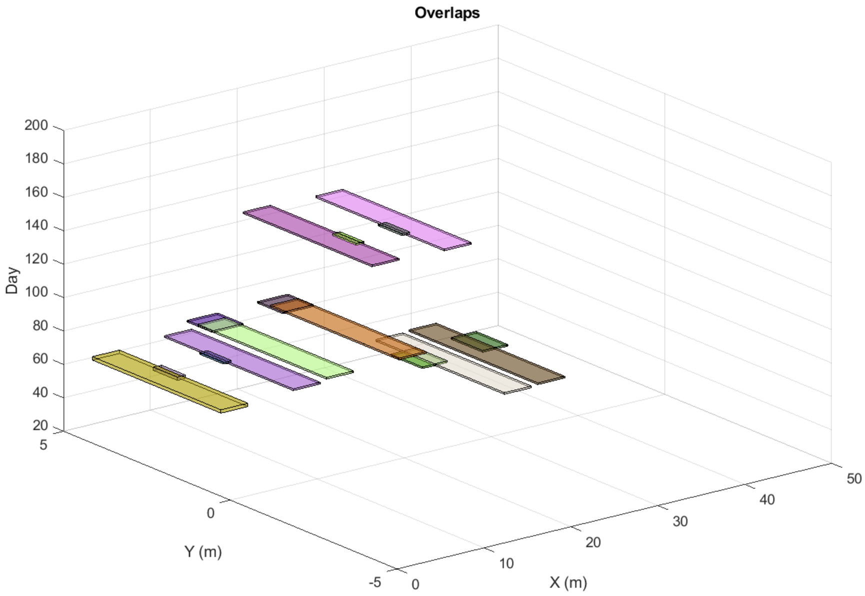


Figure 39 Leveled 3D Linear Schedule: According to $\boldsymbol{A.D}$ *&* $\boldsymbol{f}$

5.4.2 Scenario 3: Results

Enhancing the fluctuations in resource consumption and corresponding cash flow while considering workspace congestion resulted in a more stabilized resource consumption profile and decreased congestion level as displayed in Figure 40. Figure 42 shows that the number and size of conflicting activities have decreased. The average deviation of daily resource aggregates from their mean dropped to 2 and congestion level dropped to 4.3, given that a weight of 0.5 is assigned to both factors. The maximum daily resource usage dropped from 12 to 9 and the minimum increased from 1 to 4, and all other resources got closer to the average yielding a RIC value of 1.167. The enhancement influenced around 50% of project days. Accordingly, the maximum cost dropped from 380$ to 300$ and the minimum increased from 40$ to 120$, but all costs moved closer to the average cost which is around 190$ as shown in Figure 41. This improvement in resource histogram is less than the improvement attained by leveling according to $A.D$ only which resulted in an $A.D$ value of 1.965. However, it is greater than the improvement obtained by leveling according to f only that yielded an $A.D$ value of 2.173. The results are logical since we are searching for optimal shifts that balance between $A.D$ and f. As for congestion level, it shrank from 6.533 to 5.313 in the first scenario and to 4.314 in the other two scenarios.

The used float days have an average of 7 days. Using only around 46% of float days, the schedule scored an improvement of 24% in resource consumption profile and 34% decrease in congestion. This way, the schedule is enhanced on many levels without putting it at risk of delay since less than half of the available free float days are used. For one thing, the disruptions in daily resource consumption is reduced avoiding thereby extensive hiring and firing. Also, the fluctuation in the contractor's cash-flows is reduced allowing them to better finance the project. Finally, multiple unrelated activities occurred in the same unit without creating extensive congestion, decreasing overall project duration and avoiding negative effects on productivity.

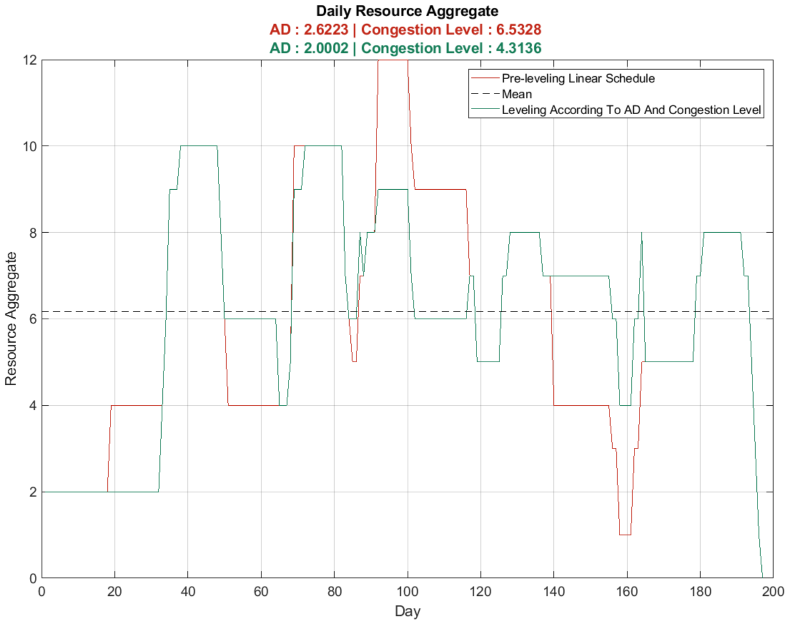


Figure 40 Comparison of Daily Resource Consumption between Pre-Leveling and Leveling according to $\boldsymbol{A.D}$ *&* $\boldsymbol{f}$

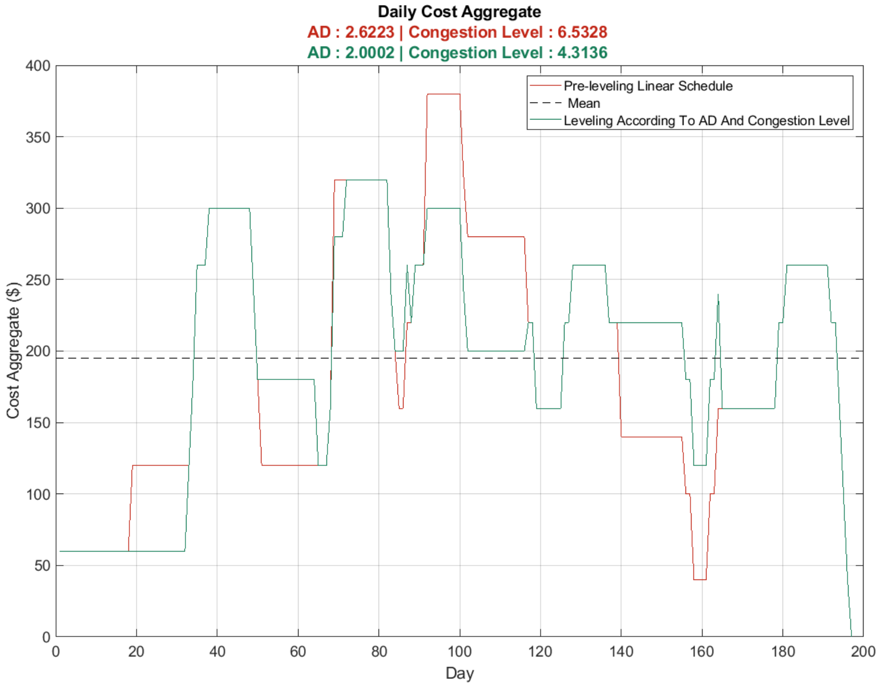


Figure 41 Comparison of Daily Resource Cost between Pre-Leveling and Leveling according to $\boldsymbol{A.D}$ & $\boldsymbol{f}$

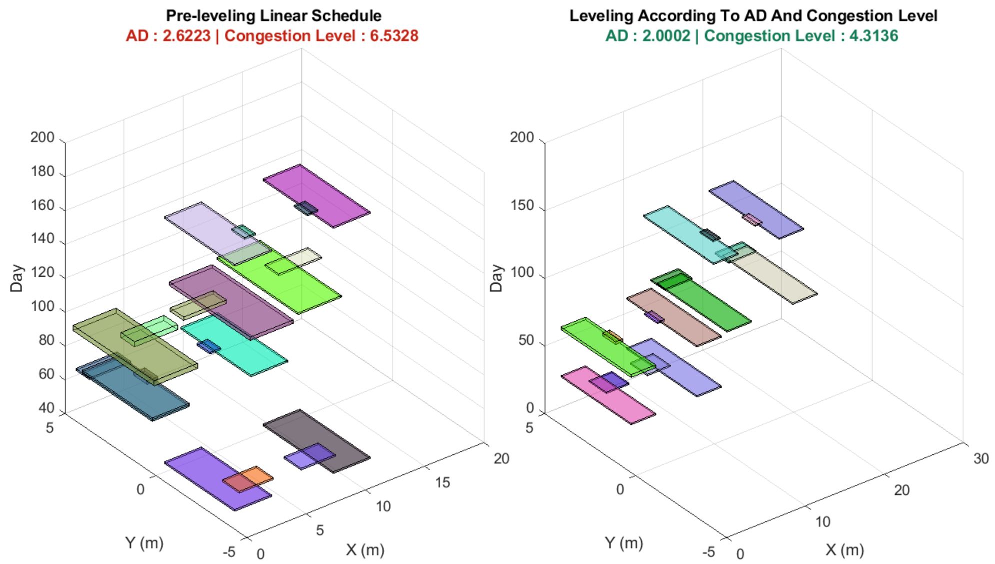


Figure 42 Comparison of Workspaces between Pre-Leveling and Leveling according to $\boldsymbol{A.D}$ & $\boldsymbol{f}$

5.5 Summary of Results

In a nutshell, the results from each case are summarized in Table 6. All RIC values are now closer to 1, implying that this leveling procedure is effective. Effectiveness of a leveling procedure lies in diminishing the peaks and valleys in the daily resource histogram which is reflected tin all the above post-leveling resource histograms. The maximum improvement in resource consumption and cost flow is attained in the first scenario, where the focus is on deviation of daily resources from their average with no regard to congestion which seemed to also record decrease. The maximum improvement in congestion is reached in the other two scenarios. Also, in all scenarios, a portion of the available free float days is used, eliminating the risk of increasing project duration. There is also a part of the total float that is not used which provides additional flexibility.

Table 6 Summary of Results

Case	**% Usage of Free Float**	**% Improvement in $A.D$**	**% Improvement in f**	**% Improvement in Cost**	**RIC**
Leveling acc. to $A.D$	63	25	19	25	1.148
Leveling acc. to f	44	17	34	17	1.184
Leveling acc. to $A.D$ & f	46	24	34	24	1.167

It can be inferred that resource leveling and congestion levels are positively correlated. Amending the resource histogram in this case study has always been associated with decrease in congestion. Consuming float days is one way to ameliorate the time schedule regarding disturbance in resource usage and cost; however, it doesn’t help in decreasing project duration. Other ways to decrease duration could be hiring multiple crews to work in parallel or hiring multi-skilled workers who can perform various tasks.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The presented study aimed at developing a new resource leveling technique for linear schedules and at amending the existing linear scheduling to more accurately represent locations. This has been achieved by designing a comprehensive algorithm that allows the user to easily manage any schedule. A graphical user interface (GUI) is developed to make the algorithm easier to use and it offers many options. The GUI allows the user to generate various schedules according to project requirements. The scheduler can compare the results from various scenarios and weigh the options to make a decision.

A new parameter is adopted to perform resource leveling on linear schedules which is the average deviation of data points from their mean $A.D$. The reason for adopting this parameter is that it measures the peaks and valleys (i.e. the disturbance) in a resource histogram. The model is tested on a real case-study project through three scenarios. The three scenarios are 1st) leveling according to $A.D$, 2nd) leveling according to f, 3rd) leveling according to $A.D$ & f. For each scenario, the GUI offers to display an overview showing the two-dimensional linear schedule, the three-dimensional linear schedule illustrating the conflicting workspaces, a table stating the ID's of overlapping workspaces along with the location, duration and volume of overlaps and a table displaying the interference value for each overlap. Additionally, it offers to display the resource histogram, the cost histogram and a comparison between these histograms and the schedules of any two scenarios. The purpose for conducting various scenarios is to assess the effect of each parameter on the other and on the overall schedule. As a first note, both $A.D$ and f levels have decreased in all scenarios. However, the improvement in resource histogram and cost profile is higher in the first scenario (25%) than in the second (17%) and third (24%) ones. The improvement in workspace congestion is higher in the second scenario (34%) than in the first scenario (19%) but is equal to that in third scenario (34%). These results are attained using only 63%, 44% and 46% of free float respectively in the three scenarios. RIC value decreased in all scenarios however the lower value is attained in the first scenario (1.148) resulting in an almost rectangular resource histogram. Thus, the proposed leveling procedure proved to be an effective one, especially that not all available free float days are used, which eliminated the risk of delaying the project. Also, consuming a part of the float days still doesn't put the project at risk of delay because of the additional flexibility provided by the total float. Leveling by examining the average deviation of daily aggregate resource usage from their overall mean while preserving production rates results in a smoother resource histogram. Thereby, this reduces the above-mentioned costs and improves contractor's cash-flows. Also, assigning workspaces for all activities and checking for conflicts in these workspaces leads to a less congested schedule, decreasing negative effects of congestion on workers' productivity.

6.2 Conclusion

Planning and scheduling are substantial prerequisites to the success of any construction project. Various scheduling techniques are available for different types of projects. Linear scheduling is a scheduling technique used for repetitive projects such as multi-story buildings and pipelines. The effective project management of linear schedules including resource allocation and leveling, and space management contributes substantially to the success of the project. Resource leveling helps decrease the cost of the project resulting from release and rehire of laborers and idle resource times (Atan & Eren, 2018). It also leads to a better distribution of contractor's payments for laborers. Space management plays a crucial role in providing uncongested workspaces, avoiding herewith decrease in labor productivity.

It has been observed that changing the start dates of certain activities according to a well-studied procedure relieve the project from congested workspaces and unstable resource consumption. This study adds to the literature by presenting a new leveling procedure for linear schedules that preserves production rates and checks for overloading in linear schedules. Additionally, it contributes to modification of the regular linear schedule into a 3-dimensional schedule that accurately represents locations. It is up to the scheduler to decide whether to have an uncongested workspace, leveled resource usage or a middle ground solution among both, depending on project requirements.

It is also worthy to note the following. As mentioned earlier, different types of projects require different scheduling techniques. For instance, linear scheduling is the most efficient way to schedule repetitive projects. However, this doesn't eliminate the need for CPM as a basis for generating linear schedules. Indeed, linear scheduling would be best utilized as a complement for CPM (Chrzanowski & Johnston, 1986). In brief, different types of scheduling methods could be employed simultaneously to handle and manage construction projects.

6.3 Limitations & Recommendations for Future Research

Although the objectives of this study have been attained, existing limitations could be addressed and suggested recommendations could be embraced to further enhance the outcomes of future research. The limitations of the proposed model consist of the following. First, only line-type activities are considered. Other activities could be of box or bar types. Second, activities that have varying production rates across the units are not considered. Third, only finish-to-start relationships are considered. Fourth, only human resources are considered; a more accurate model would address additionally other resources such as materials and equipment. Fifth, although a rectangular distribution of resources across project duration is the most convenient distribution to stabilize cash flows, however, real resource usage might take another distribution such as triangular. The reason for such a distribution is that most of the activities might occur near mid of the project, making resource usage peak at this time. Future research could address these limitations.

The model generates an initial schedule that satisfies resource, time and logical constraints. However, it doesn't account for waste in time buffer. Therefore, it is recommended for future studies to adopt lean principles in generating an initial schedule which could be done through producing to TAKT time. Also, considering the learning effect projects a more realistic schedule, since the time required by the workers to perform the same activity will decrease as the time increases.

Finally, it is worth stating that scheduling and arrangement of space in construction are fundamental to project management because of the direct influence they have on machine running, security, resource deployment, power distribution, construction progress and cost (Ma et al., 2005). Proper management of resources redeem the project from poor resource utilization, potential delays and cost overruns.

APPENDIX

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