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A PRODUCTION RATE-CONSERVED APPROACH TO LEVELING RESOURCES IN LINEAR SCHEDULES

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Abstract

Few attempts have targeted leveling resources in linear schedules by mainly changing production rates. However, this led, in some instances, to a decrease in productivity. Therefore, the paper presents a two-phase model that: (1) generates the linear schedule and calculates start and end dates and available free float days for each activity, and (2) performs resource leveling according to a newly-designed parameter called "average deviation of data points from their mean". The output is a leveled production rate-conserved linear schedule, which clearly highlights the study's contribution in providing a resource leveling tool for linear schedules that preserves the production rates.

Introduction and Related Work

The efficient and timely completion of construction projects, within the constraints of budget and schedule, relies fundamentally on meticulous planning and precise scheduling. More specifically, linear scheduling, known as the Line-of-Balance (LOB) method, stands out for its effectiveness in handling projects with repetitive tasks, such as pipelines, high-rise buildings, and residential housing developments (Gouda et al., 2017). This scheduling methodology distinguishes itself by emphasizing on the synchronization between project locations and sequential activities, thereby ensuring a continuous and seamless workflow (Su and Lucko, 2016). Unlike traditional network scheduling techniques (Harris, 1973), such as the Critical Path Method (CPM), which often struggle with the particulars involved in scaling repetitive projects due to their complexity and the extensive number of units and activities, linear scheduling offers a streamlined approach favorable to managing such projects (El-Rayes, 1997, Harris and Ioannou, 1998, Dhanasekar, 2000, Kang et al., 2001, Arditi et al., 2002, Kenley and Seppänen, 2006, Gouda et al., 2017, Ramani et al., 2022).

On the other hand, resource allocation, an integral component of effective scheduling, necessitates the strategic distribution of essential resources—including labor, equipment, materials, finances, and information—across various tasks to ensure stability in work execution. However, it is considered a complex optimization analysis, especially when it comes to linear or repetitive projects (Zhang et al., 2012). In addition, one of the most pressing challenges in the construction phase is the management of the labor resources in particular, which can fluctuate on a daily basis. These fluctuations can lead to an idle workforce and escalating costs due to the need for frequent hiring and rehiring of workers. They may also adversely affect a contractor's cash flow, thereby highlighting the importance of ensuring continuous liquidity to maintain daily operations. In fact, effective cash flow management is vital to the sustainability and economic viability of construction contractors (Ram and Runeson, 1999, Ezeldin and Ali, 2017). As such, many research efforts have targeted optimizing the allocation of labor resources through resource leveling (El-Rayes and Jun, 2009). However, resource leveling techniques adopted so far in linear scheduling have primarily dealt with adjustments in production rates, which has shown a compromise in productivity (Mattila and Abraham, 1998, El-Rayes and Jun, 2009, Damci et al., 2013, Tang et al., 2014, Dai et al., 2023).

In response to the aforementioned challenges, this study improves upon existing methods and develops a mathematical tool for leveling resources in linear schedules while conserving production rates. The main contribution lies in the tool's potential to simplify the scheduling process of repetitive projects while providing a more stable labor force, reducing unnecessary costs, and promoting smoother project execution.

Research Methodology

This study adopts a Design Science Research (DSR) methodology to address the identified problem of resource leveling in linear scheduling, which is prevalent in project management. The DSR approach is pertinent for the development of innovative solutions to complex problems, following a rigorously defined process. The research is executed in several iterative stages namely: Problem Identification, Solution Development, and Solution Evaluation.

In the initial stage, the need for a systematic approach to leveling resources in linear scheduling is recognized. Linear scheduling, often used in construction and engineering projects, presents unique challenges in allocating resources over time. To address these challenges, the study begins with a comprehensive literature review, coupled with empirical observations from industry practices, in order to establish a foundational understanding of existing methodologies and their shortcomings.

The solution development stage is a two-phase model. The initial phase focuses on creating a linear schedule that ensures a consistent flow of resources. Upon this foundation, free floats and aggregate daily resources are computed. Free floats are buffer periods within the schedule whereby activities can be delayed without affecting other activities and the overall project timeline. The second phase explores strategies for optimizing resource allocation through leveling, with the objective of achieving a more uniform resource utilization over the project's duration. This phase is characterized by a cyclical process of prototyping, whereby iterative designs are created, tested, and refined based on the outcomes.

Finally, the solution evaluation stage involves applying the developed model to a real case study to demonstrate its efficacy in a practical setting. In this case, the model's performance is analyzed through a variety of metrics, such as the smoothness of the resource usage curve and the deviation from the mean. Figure 1 summarizes the research methodology. The next section primarily focuses on the second DSR stage, namely, the two-phase model.

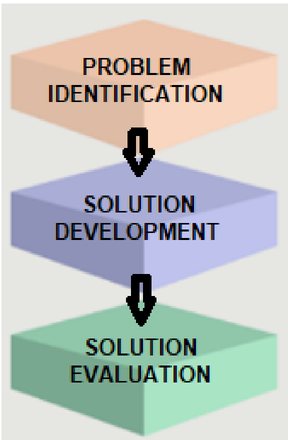

Figure 1: Research Methodology

Two-Phase Model Development

By adopting a combination of theoretical assumptions, mathematical formulations, and leveling techniques, this study aims to provide a comprehensive framework to improve project efficiency, reduce disruptions, and ensure effective resource scheduling and optimization in project management. As aforementioned, the proposed research explores a two-phase approach that first generates an initial linear schedule then performs resource leveling.

Phase 1: Generating an Initial Linear Schedule

This phase focuses on generating an initial schedule that respects the technical constraints, while ensuring a continuous and steady flow of resources to avoid productivity losses caused by the unlearning effect, idle times, and the need to release and then rehire the workforce. It highlights the benefits of a learning curve whereby laborers increase their productivity by repeatedly performing the same task across multiple units. The study adopts several principles to maintain this productivity. Activities are linear and continuous without interruptions, allowing a steady resource consumption. Units are considered as rooms on the same floor, like hotel rooms or office spaces, with activities having a finish-to-start relationship at the unit/room level and a start-to-start or finish-to-finish relationship at the activity level.

The methodology involves using a MATLAB-imported template for mainly calculating start and end dates and daily resource aggregates. This template, inspired by Agrama (2011) and depicted in Figure 2, differentiates among activities based on their durations and relationships (start-to-start or finish-to-finish), while focusing on labor resources. Calculations of start and end dates are made based on the predecessors, relationships, and the comparison of activities' rates. This, in turn, allows for the calculation of the available free float. This float determines the scheduling flexibility of activities and thereby helps in identifying those eligible for leveling in order to optimize the project schedule without affecting the overall project duration.

	A	B	C	D	E
1	number of units	15			
2	number of activities	12			
3					
4	Activity Description				
5	No.	Activity	Duration	Resources	Cost/Day
6	1	A	1	1	40
7	2	B	2	6	140
8	3	C	2	4	100
9	4	D	1	3	80
10	5	E	4	3	80
11	6	F	1	4	100
12	7	G	3	5	120
13	8	H	2	3	80
14	9	I	2	1	40
15	10	J	2	3	80
16	11	K	2	4	100
17	12	L	1	2	60

			Predecessors										
5	No.	Activity	p1	Rp1	p2	Rp2	p3	Rp3	p4	Rp4	p5	Rp5	Multipe Predecessors?
6	1	A	0										NO
7	2	B	1	SS									NO
8	3	C	1	SS									NO
9	4	D	1	SS									NO
10	5	E	2	SS									NO
11	6	F	5	FF									NO
12	7	G	3	SS	5	FF	4	SS	0		0		YES
13	8	H	5	FF									NO
14	9	I	7	FF									NO
15	10	J	9	SS									NO
16	11	K	6	SS	10	SS	0		0		0		YES
17	12	L	11	FF	8	FF	0		0		0		YES

Figure 2: Agrama Sample Template (Agrama 2011)

Phase 2: Performing Resource Leveling

In the second phase, resource leveling is performed to minimize the fluctuations in the generated resource histogram from the first phase. Prior to detailing the leveling procedure, two metrics need to be first defined. The first metric is called the resource improvement coefficient (RIC) proposed by Harris (Harris, 1973). RIC is the ratio of the moment of the current resource histogram to the hypothetical minimum moment histogram; i.e. the histogram which has a perfect uniform resource usage and has the shape of a rectangle. RIC is calculated as follows:

$$RIC = \frac{n\sum y_i^2}{(\sum y_i)^2} \quad (1)$$

Where n is the number of project days and y_i is the resource usage on day i. 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).

Another important metric that needs to be adopted in the leveling procedure is one that quantifies the spread of data points in a histogram and that is the average deviation of data points from their mean ($A.D$). $A.D$ is calculated using equation 2 and is the measure that primarily determines whether to shift the activity or not. The smaller the $A.D$ is, the less the data is spread from the mean, yielding a more favorable and smooth resource histogram.

$$A.D = \frac{\sum|y_i - \bar{y}|}{n} \quad (2)$$

The leveling procedure starts right after the first phase, in other words after generating the linear schedule, computing the available free floats, and calculating the daily resource aggregate for the whole project duration. In this case, the corresponding $A.D$ is computed for the initial generated resource histogram. It is worth mentioning that resource leveling is done for all resources aggregately and not by trade. In other words, 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 positive free floats. However, there is no clear procedure on what order to follow when leveling activities as to reach a smoother resource histogram. Therefore, the permutation of all possible combinations of activities is thoroughly examined and a corresponding $A.D$ value is computed for each combination. In this case, the lower the $A.D$ value is, the smoother the resource histogram is. For instance, assume there are three activities {A,B,C} having positive 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 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 then updated. On the other hand, if the new $A.D$ is greater than the initial value, no changes are made in this case and the next activity in the corresponding combination is then 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 for all other combinations. This results in an array containing $A.D$ values for all possible combinations. The combination corresponding to the smallest $A.D$ value is selected. Finally, RIC is calculated to assess the effectiveness of the leveling procedure. This whole leveling process is summarized in Figure 3.

Case Study: Results & Discussion

The above developed two-phase model was tested on a real case study. The case adopted is the renovation of the Penrose dormitory at the American University of Beirut (AUB), Lebanon. The building consists of 6 floors having the same layout plan as shown in Figure 4. Each floor consists of 16 repetitive rooms. The study was only conducted for one floor as work repetition is witnessed over 16 units. Given an x-y plane, the origin (0,0) is highlighted in red in Figure 4.

Figure 5 displays the CPM network at the unit level and is repeated for each of the 16 rooms. Figure 6 displays the corresponding linear schedule. Figure 7 depicts the initial resource histogram of the project.

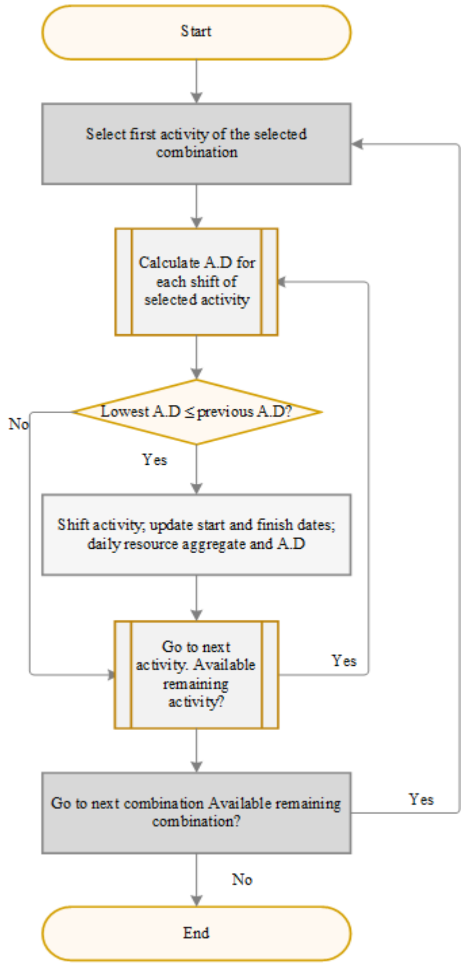

Figure 3: Resource Leveling Process

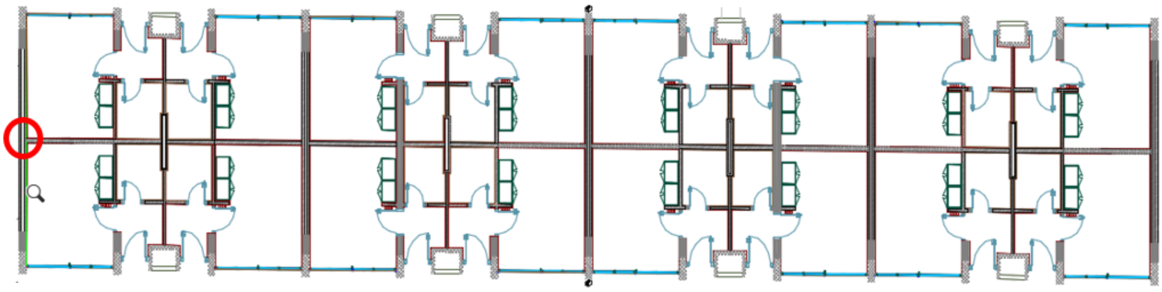

Figure 4: Project Layout

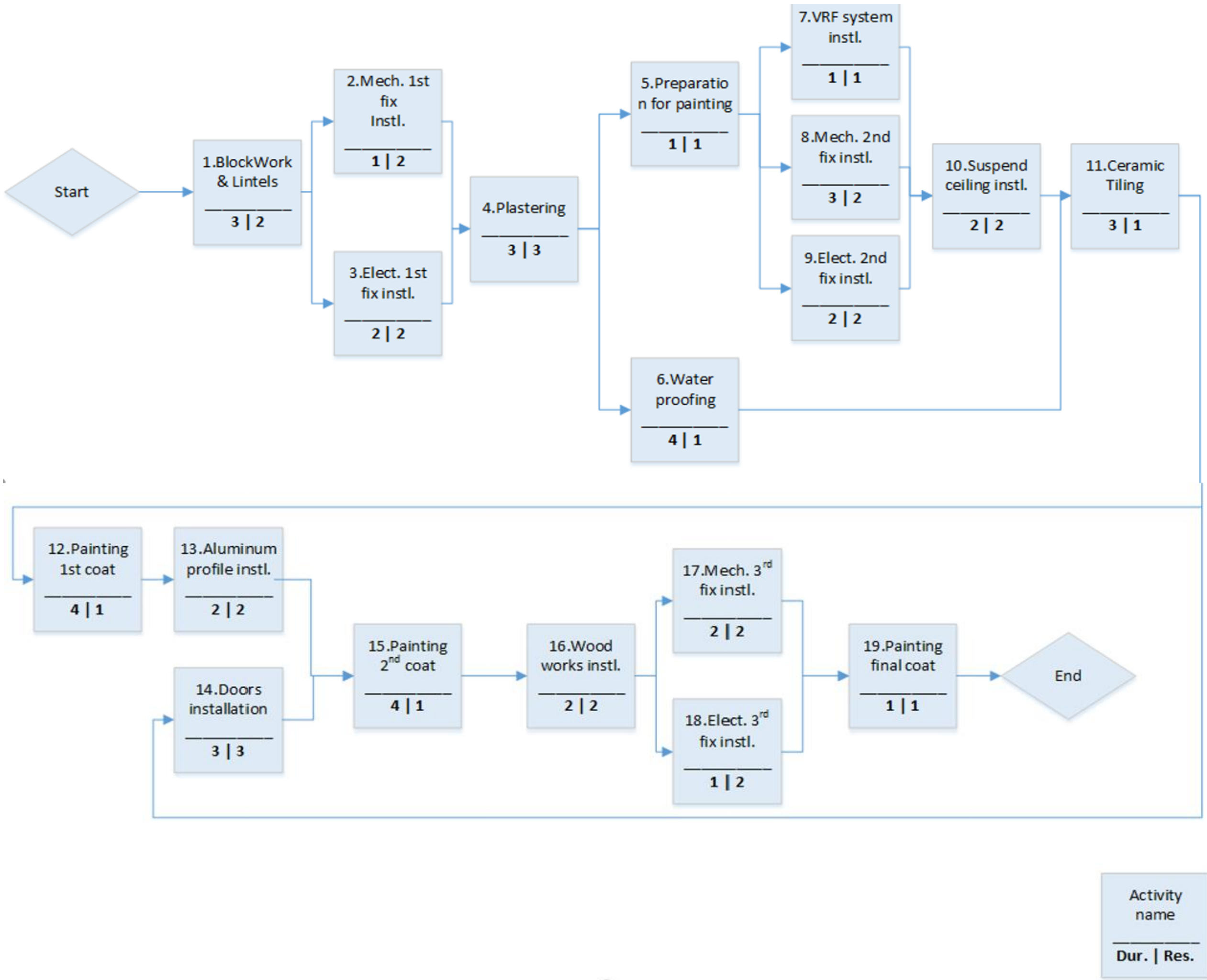

Figure 5: CPM Network at the Unit or Room Level

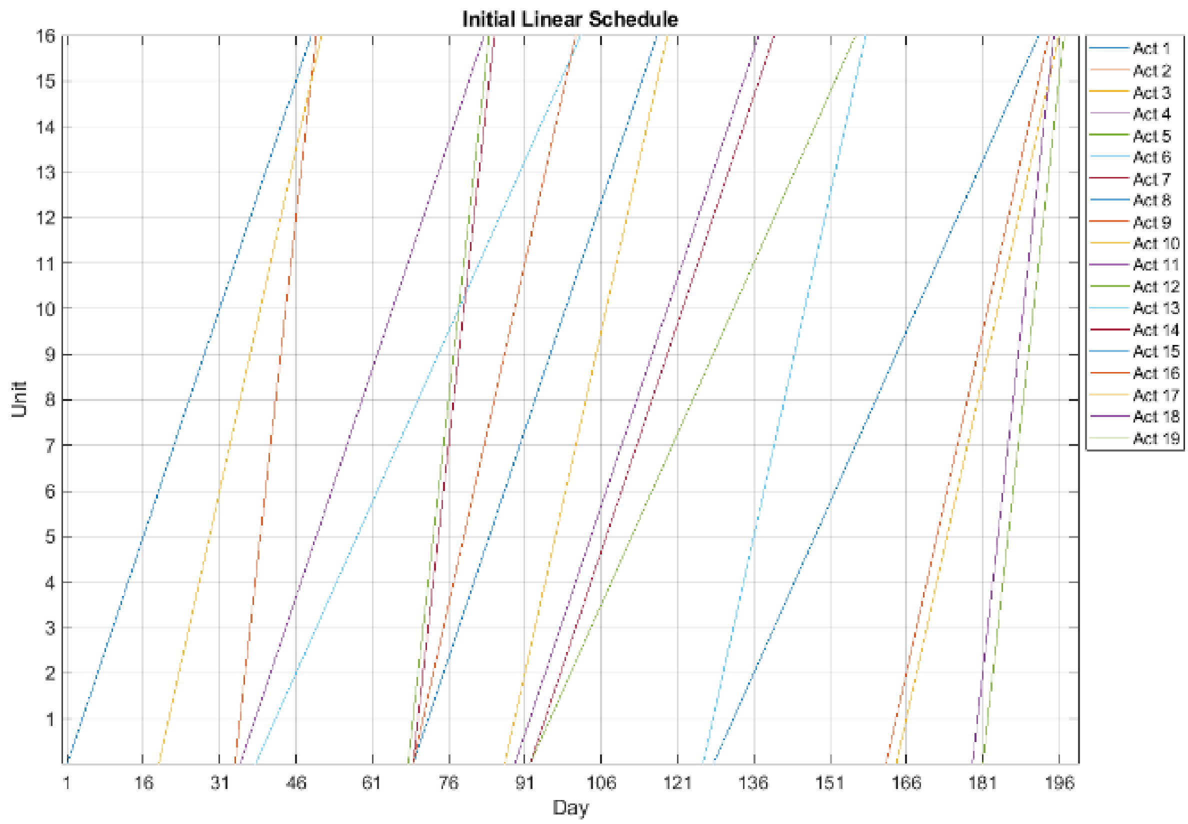

Figure 6: Initial Linear Schedule

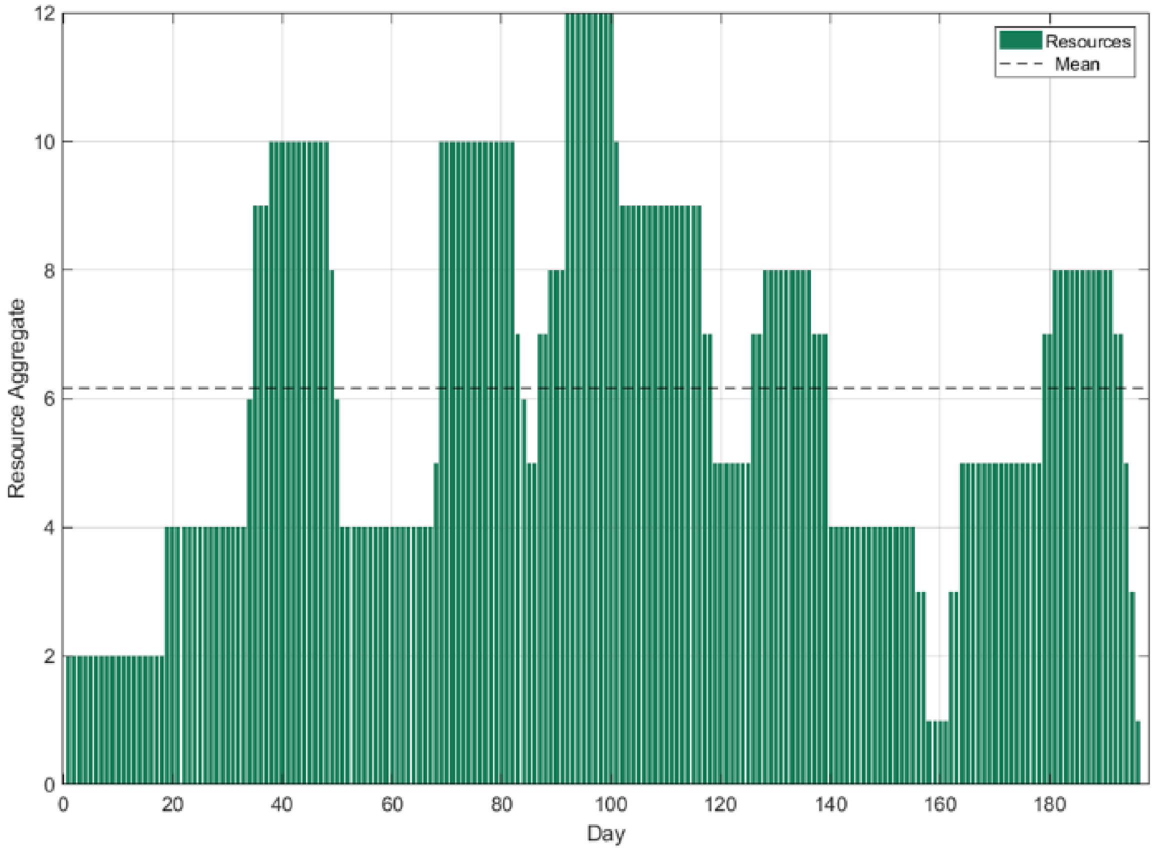

Figure 7: Initial Resource Histogram

As shown in Figure 7, there are a lot of fluctuations (i.e. peaks and valleys) which implies instability in the number of workers on site. After making the necessary calculations in the first phase, the RIC value of the initial resource histogram is computed as 1.23 and the corresponding $A.D$ value is 2.62 using equations 1 and 2 respectively.

Phase 2 is conducted based on the data calculated in Phase 1. Resource leveling is done based on the $A.D$ metric and following the process flowchart depicted in Figure 3. The trial is done to assess the effect of shifting activities on the data spread of the resource histogram. Results revealed that the final and best combination of activities and the order in which they are to be leveled is: {7 (*VRF system instl.*), 3 (*electrical 1st fix*), 14 *(doors installation*), 9 (*electrical 2nd fix*), 18 (*electrical 3rd fix*)} and the corresponding shifts are {2, 9, 25, 14, 1}. Accordingly, the final leveled resource histogram (Figure 8) has an RIC value of 1.148 and an $A.D$ value of 1.965.

It is notable that all resources moved closer to the average resource consumption after leveling (Figure 9), which depicts the daily aggregate resource consumption curves before and after leveling based on the $A.D$ metric. In addition, the maximum resource consumption has decreased from 12 to 9 and the minimum one has increased from 1 to 4 resources per day. Hence, the fluctuations in the daily resource cost decreased as shown in Figure 10, thereby yielding an RIC value of 1.148 instead of the original 1.23. On the other hand, the maximum daily cost decreased from \$380 to \$300 and the minimum daily cost 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 consumption due to leveling affects around 45% of project days. In other words, the alleviation of fluctuations due to leveling spans across 90 days out of 197 project days.

Table 1 summarizes the results generated from applying the two-phase model. The study demonstrates that the strategic use of free float days allows for a more flexible and efficient approach to managing project timelines and resources. In this case, 10 days out of the initial 16 float days were used on average. While using only around 63% of float days, there was a 25% improvement in $A.D$ and 25% reduction in cost. The 25% improvement in $A.D$ signifies a more uniform distribution of resources across the project timeline. This outcome suggests that by employing free float days effectively, the variability in resource allocation can be potentially reduced. In practical terms, this means resources were utilized more consistently, thereby avoiding periods of underutilization or overutilization. Furthermore, a lower average deviation is indicative of improved efficiency in resource management, leading to a more predictable and stable project execution. Similarly, the 25% cost reduction resulted from optimizing the project schedule and using free float days to absorb delays or expedite certain activities without incurring additional expenses. This cost efficiency indicates that projects can not only be delivered faster but also at a lower cost, thereby enhancing the overall return on investment for project stakeholders.

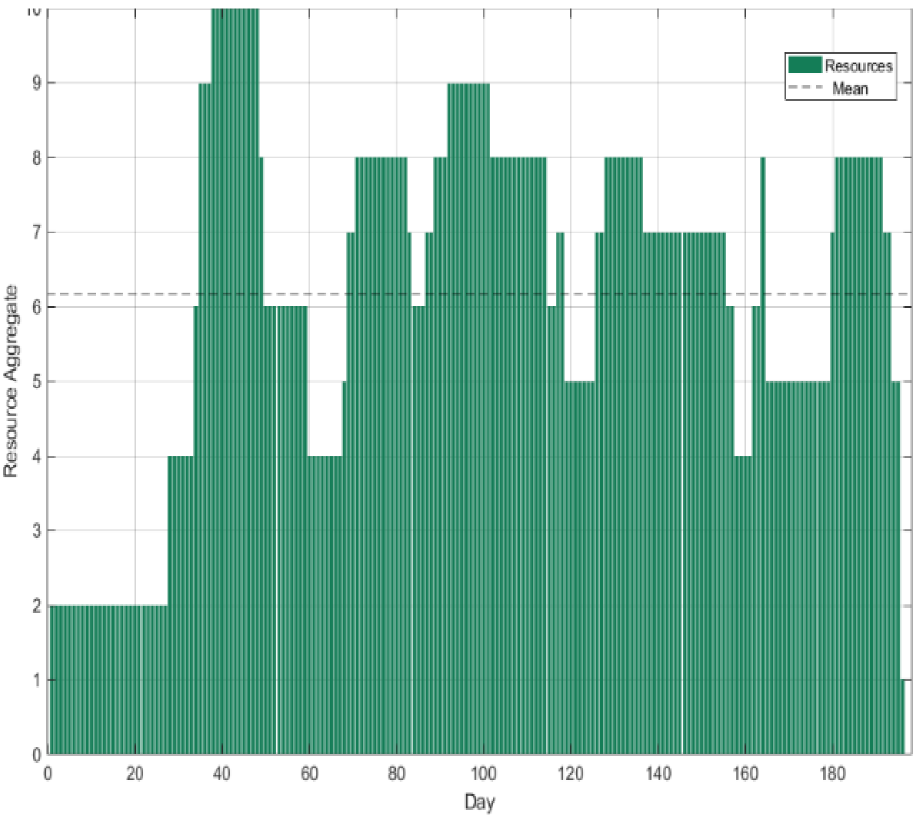

Figure 8: Leveled Resource Histogram

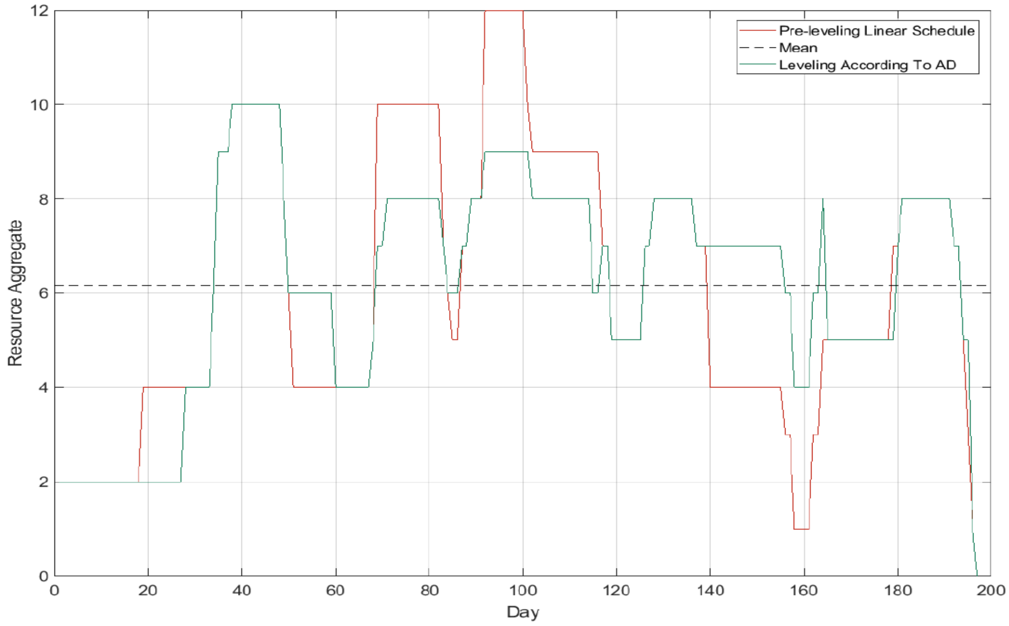

Figure 9: Comparison of Daily Resource Consumption between Pre-Leveling and Leveling based on A. D

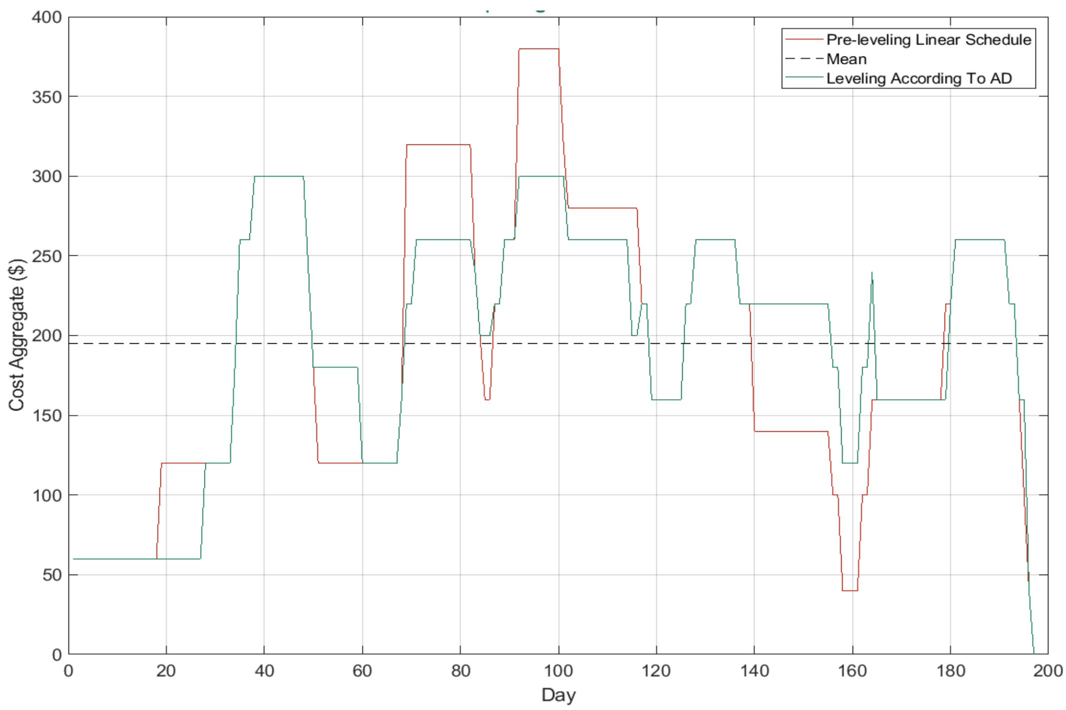

Figure 10: Comparison of Daily Resource Cost between Pre-Leveling and Leveling based on A. D

Table 1:Summary of Results

% Usage of free Float Days	% Improvement in *A. D*	% Improvement in Cost
63	25	25

Based on the above results, it is worth noting that the proposed tool when compared to available commercial ones (e.g. TILOS, DynaRoad, Turbo-Chart, etc.) explicitly maintains production rate continuity while avoiding productivity losses from rate changes. In contrast, the commercial tools either prioritize crew optimization or lack integrated resource leveling algorithms. In addition, the proposed tool introduces a mathematical optimization approach using the average deviation (A.D.) and Resource Improvement Coefficient (RIC) to quantitatively reduce resource fluctuations. It explores all permutations of activity shifts within float windows, an exhaustive technique not found in commercial tools which typically use heuristic or visual-leveling methods.

Conclusion and Future Work

In conclusion, this research fills a critical gap in the existing literature by developing and implementing a robust two-phase mathematical model to generate a leveled linear schedule while conserving production rates. As such, this study focuses on advancing the methodologies used for optimizing resource leveling in particular of linear construction schedules. This, in turn, significantly enhances the efficiency and cost-effectiveness of resource allocation when managing construction projects of repetitive nature.

While the proposed approach has achieved promising results, it exhibits some limitations and further examination is needed to enhance its performance. Future research will look at integrating the proposed model with a variety of project management tools. Such integration could streamline construction project management, thereby fostering a more dynamic and responsive approach to resource leveling. Further research is needed as well to assess the model's applicability across different types of projects, which, in turn, could strengthen its applicability, relevance, generalizability, and impact on the field.

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