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METAHEURISTIC MULTI-OBJECTIVE OPTIMIZATION APPROACH FOR REPETITIVE CONSTRUCTION PROJECT SCHEDULING

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ABSTRACT

The optimization of schedules for repetitive projects is a crucial phase in establishing an effective project timeline concerning both duration and cost. This study presents an innovative metaheuristic multi-objective optimization model tailored for repetitive projects. Distinguished by its original features, this model empowers schedulers to identify an optimal schedule that concurrently minimizes project duration, total cost, and interruption time. It encompasses various constraints and factors, including learning and forgetting effects, inter-activity soft logic, limited work interruption allowances, multiple crew formations, multiple construction methods per activity, while retaining all Critical Path Method (CPM) scheduling capabilities. The effectiveness of this new approach was validated through application to two case studies, demonstrating its capability to deliver optimal schedules for repetitive projects with heightened accuracy in minimizing project duration, cost, and interruption. Furthermore, the integration of learning effects, soft logic, and work interruption allowances within the optimization process substantially reduced project duration and cost, thereby yielding more precise and dependable optimal solutions.

Keywords: *Learning effect, Optimization, Project planning, Repetitive project, Soft logic*

TEKRARLI İNŞAAT PROJESİ ÇİZELGELEMESİ İÇİN METASEZGİSEL ÇOK AMAÇLI OPTİMİZASYON YAKLAŞIMI

ÖZET

Tekrarlı projeler için çizelgeleme, hem süre hem de maliyet açısından etkili bir proje programı oluşturmada çok önemli bir aşamadır. Bu çalışma, tekrarlı işlemleri bulunan projelere uyarlanmış yenilikçi bir metasezgisel çok amaçlı optimizasyon modeli sunmaktadır. Model, planlayıcılara proje süresini, toplam maliyeti ve kesinti süresini aynı anda en aza indiren optimal çizelgeyi belirleme olanağı veren orijinal özellikleriyle öne çıkmaktadır. Model, Kritik Yol Yöntemi (CPM) planlama yeteneklerini korurken, öğrenme ve unutma etkileri, etkinlikler arası yumuşak mantık, iş kesintileri, birden fazla ekip oluşumu, her faaliyet için birden fazla inşaat yöntem seçimi dahil olmak üzere çeşitli kısıtlamaları ve faktörleri kapsamaktadır. Bu yaklaşımın etkinliği, tekrarlı projeler için proje süresini, maliyetini ve kesintiyi en aza indirerek daha yüksek doğrulukla en uygun programları sunma yeteneğini gösteren iki örnek olay incelemesine uygulanarak doğrulanmaktadır. Ayrıca, öğrenme etkilerinin, yazılım mantığının ve iş kesintisi ödeneklerinin optimizasyon sürecine entegrasyonu, proje süresini ve maliyetini önemli ölçüde azaltmakta ve böylece daha kesin ve güvenilir optimum çözümler elde edilmektedir.

Anahtar Kelimeler: *Öğrenme etkisi, Optimizasyon, Proje planlama, Tekrarlı proje, Yumuşak mantık*

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1. Introduction

The repetitive construction projects entail numerous similar units, each requiring completion of a predefined set of activities. Achieving a comprehensive schedule for repetitive projects, therefore, demands meticulous planning and management of all resources. The crews must complete work in one unit before moving on to the next, necessitating the project scheduler to ensure continuity of work for all resources involved. Maintaining work continuity for crews can reduce idle time and costs, while enhancing productivity and boosting morale among laborers [1].

Two main categories of project scheduling methods exist. The first one is called time-driven and the second type is resource-driven [2]. However, time-driven methods, like the Critical Path Method (CPM), do not account for the work continuity constraint, making them unsuitable for scheduling repetitive projects [3]. This resulted in the development of resource-driven techniques, including the linear scheduling method [4], the Line of Balance (LOB) [5], and other approaches that adapt any of the aforementioned methods. In addition, many methods adopting the Gantt method, Linear Scheduling Method (LSM) and Program Evaluation and Review Technique (PERT) are actively used in the engineering practice; however, the applicability of these techniques varies according to the type and size of the project [6]. On the other hand, resource-based systems guarantee that each team works without any interruptions to minimize downtime, making them appropriate for scheduling repetitive undertakings. The resource-driven methods have proven effective in scheduling repetitive projects, but certain limitations must be addressed for optimal, practical outcomes [7].

The strict adherence to work continuity constraints between repetitive activities may result in longer project durations and higher indirect costs [8]. However, some argue that permitting interruptions during specific tasks when organizing recurrent projects may lead to reduced project timelines [1]. When scheduling and optimizing the project, it is important to consider the forgetting effect resultant from interruptions. The interruptions should be kept to a minimum to prevent idle time and mitigate costs.

Integrating the learning effect into scheduling repetitive projects is believed to result in better accuracy when forecasting project duration, cost, and labor requirements. However, the previous optimization models for repetitive projects did not consider this effect, leading to less reliable and usable optimum solutions for project planners. In addition, it is essential to evaluate various logical sequence alternatives for resolving the time-cost trade-off quandary in repetitive projects [9].

In construction, the order of activities can be categorized into two distinct types: 1) hard logic, which is mandatory and unalterable and 2) soft logic, which presents various potential sequences of activities and allows for the selection of the optimal one [10]. Optimal selection of soft logic for repetitive activities can lead to reduced overall project duration and cost [2]. Soft logic exists in repetitive projects in two forms: firstly, soft logic between units and their interrelations, which has already been studied in the literature [9]; secondly, soft logic within activities themselves in the same unit, which has not been considered in previous optimization models.

Pivotal for effective project management is the accurate identification and incorporation of both forms of soft logic into project planning and execution. There is clearly a crucial necessity for a novel optimization model that surpasses these limitations and generates practical optimal solutions suitable for the construction industry.

The most significant aspect that distinguishes the current study from previous researches is that the developed method has provided convenience and flexibility to the decision-maker considerably. Many variables, each of which must be solved separately, are addressed in an integrated manner through the proposed method. The development of this new model fills a gap in the literature because it combines elements such as learning and forgetting effects, flexible relationships between activities, and the ability to incorporate work interruptions, various crew configurations, and multiple construction methods for each task.

This research introduces a heuristic multi-objective optimization model that addresses all the constraints and factors involved, including the learning and forgetting effects, maintaining soft logic between activities, limiting work interruptions to minimize project duration and reduce crews' idle time, multiple crew formations, multiple construction methods for each activity, and retaining all CPM scheduling capabilities. The proposed model can concurrently reduce the project duration, total cost, and work disruption. This paper presents two case studies; the first validates the model, while the second illustrates its complete capabilities.

2. Literature Review

Optimization studies can be categorized by either their objectives or their methods. The key optimization objectives include minimizing project duration, cost, idle time, resource fluctuations and maximizing profit and net present value [11]. To accomplish these goals, several optimization approaches have been developed, which can be classified as: 1) Mathematical methods, including linear, dynamic, and constraint programming, have been employed in previous researches: [2, 12, and 13]. 2) Heuristic methods have also been utilized [8]. 3) Meta-heuristic methods, such as genetic, particle swarm, and ant colony algorithms, have shown promising results in this field [14, 15]. These techniques can be applied deterministically, or with the use of stochastic models by incorporating simulation techniques, like fuzzy set theory, in order to tackle scheduling uncertainties [16].

Reda [17] presented a linear programming model, which implemented activity time-cost curves to minimize direct costs while maintaining a consistent production rate, in order to optimize the duration of activities. Moselhi and El-Rayes [18] as well as Senouci and Eldin [19] have formulated dynamic programming models to determine the optimal crew size for each activity in order to reduce the project cost. Hegazy and Wassef [20] along with Elbeltagi et al. [21] have applied Genetic Algorithm (GA) techniques to establish the ideal combination of construction methods, crew numbers and interruption durations of activities to decrease the entire project cost.

El-Rayes and Moselhi [22] developed a dynamic programming model, while Hyari and El-Rayes [23] utilized a GA model to minimize project duration and interruption time for each crew. Both models accommodated work interruptions and identified the optimal crew formation, enabling the achievement of minimum project duration. Ipsilandis [24] proposed a linear programming model that considers idle time of resources to minimize overall project duration.

Liu and Wang [25] combined single and multiple-skilled crews through a constraint-programming model to boost productivity and work quality while reducing project duration. Zou et al. [8] proposed a heuristic model that prioritizes work continuity while minimizing the number of crews and allowing for work interruptions to meet a given deadline.

Multi-objective models have been introduced to optimize more than one objective. El-Rayes [26], Moselhi and Hassanein [12] have proposed object-oriented models that incorporate dynamic programming formulas to minimize project duration or cost by finding the best crew formation. Zhang et al. [27] minimized both duration and cost by using a heuristic permutation tree-based model, while Senouci and Al-Derham [28] utilised a GA model to consider various construction methods. Long and Ohsato [29] used a GA model that enables interruptions while optimising duration and cost. GA models developed by Hyari et al. [30] and Eid et al. [31] yield a set of Pareto optimal solutions by taking into account delay damage and early completion incentives.

Heravi and Moridi [15] put forward a particle swarm model to reduce project time and cost by taking into account resource availability and the cost of idle resources. García-Nieves et al. [13] suggested a linear programming model that minimizes project duration or cost while allowing multiple modes of execution. Zou and Zhang [2] proposed a constraint-programming model to minimize project costs within a specified deadline by considering the soft logic of the same activity in different units.

Kaveh et al. [32] presents an innovative algorithm for addressing many-objective trade-offs in construction scheduling, aiming to select the ultimate solution from a set of non-dominated solutions according to the priorities set by the project team. Bettemir and Yücel [33] suggests that construction options can be created by allocating various crew sizes for task execution, with job efficiency being evaluated based on the crew size. The construction duration of each activity is calculated taking into account the necessary workmanship, crew size, and job efficiency, thereby automating the generation of crashing alternatives.

Stochastic models were utilized to incorporate uncertainty into the schedule. For instance, Bakry et al. [34] and Salama and Moselhi [35] created models that optimize project duration and cost while accounting for uncertainties associated with work quantities, resources availability, productivities, and costs. Other studies aimed at optimizing different objectives. For instance, Huang and Halpin [36] optimized the project's overall construction rate by using a graphic linear programming model. Srisuwanrat and Ioannou [37] maximized profits while considering probabilistic durations by using GA model. Huang and Sun [11] maximized the net present value with the help of GA model. Bragadin and Kahkonen [38] minimized idle time for resources using a heuristic algorithm. Notably, previous optimization models failed to utilize learning and forgetting effects, despite their potential to reduce significantly project duration and cost, both during the construction phase and in preparing bid plans.

Hassan et al. [39] devised an innovative multi-objective stochastic scheduling optimization framework suitable for both sequential and non-sequential repetitive construction endeavors. This model can effectively pinpoint optimal crew configurations and deployment dates for each task, aiming to minimize both project duration and cost. Additionally, few studies considered the soft logic between different units. Zou and Rong [40] considers the soft logic relations among sub-activities and explores methods to enhance the objective while adhering to the constraints posed by resource availability.

In recent years, while the subject of scheduling in construction projects has been investigated, the studies have particularly focused on delay analysis. Researchers on that topic have conducted numerous studies, which is one of the primary areas of scientific study due to the effects of delays on time and cost in construction projects [41]. Çevikbaş and Işık provides a benchmarking tool to evaluate the merits of delay analysis methods to the practitioners [42]. Also a new delay analysis method is proposed that overcomes the disadvantages of existing delay analysis methods in order to minimize delay-related problems in construction projects [43].

This study puts forward an innovative multi-objective optimization model that takes into account key constraints and factors that influence the duration and cost of iterative projects, for example, the learning and forgetting effects and the flexible logic between varied activities. The unit remains the same, enabling restricted work disruption, various crew formations, and diverse construction methods for each activity, a limitless number of preceding and succeeding events, and the conventional relationship types. The objective of this approach is to reduce the project length, overall expenditure, and interruption time all at once.

3. Methodology

To improve the optimization of repetitive scheduling, this study proposes a model that takes into account simultaneous constraints and satisfies several multi-objectives at once. The methodology for the research is divided into two stages. Firstly, an in-depth literature review was conducted in order to ascertain the limitations of prior repetitive scheduling optimization models and to identify the key parameters that bear on project scheduling and can create a more realistic schedule. The next phase entails creating a metaheuristic multi-objective optimization model that factors in the aforementioned parameters collectively and allows multiple scheduling choices to define the best solutions, which reduce the project's overall duration, total cost, and total downtime.

The proposed model comprises three principal modules, 1) input module, 2) schedule and cost development module, 3) multi-objective optimization and ranking module. The model was developed employing Excel spreadsheets. The developed model has numerous features, such as:

• For each undertaking, a multitude of team structures can be appointed, with limitations set by the user as major and minor benchmarks.

• Each task can have up to ten distinct construction methods. Each of the construction methods may introduce varying technologies, building materials, machinery, employee crews, and strategies to accomplish the work.

• The duration of activities in each unit is calculated taking into account the learning effect.

• Users are allowed to interrupt any selected activity between units. The duration of interrupted activities will be calculated taking into account the forgetting effect.

• Each activity may have any number of predecessor and successor relationships.

• The relationships between activities can be finish-to-start (FS), finish-to-finish (FF), start-to-start (SS), or start-to-finish (SF) with or without delays.

• The user can repeat activities for all units or a specific range of units.

• The activities can be scheduled in parallel, shifted or optimized modes. The optimized mode can combine parallel and shifted crews to minimize the project duration. In the parallel mode, all crews for the same activity are scheduled to begin at the same time. In the shifted mode, the start of each activity is shifted from the others, with multiple crews not starting the activity at the same time.

• The project cost is determined by accounting for the direct cost, indirect cost, liquidated damages caused by delays, and fees for incentives for early completion.

• The model allows for multi-mode use, optimizing duration, cost, and interruption simultaneously, or single-mode use, optimizing each objective individually.

• This model is suitable for repetitive projects with typical durations, such as housing compounds, roads, and piping projects.

3.1. Input Module

The aim of this module is to gather all necessary data for the development and optimization of project schedule and cost. It is categorized into three major input groups.

The first group is project input which comprising of;

• activity count and unit count,

• project completion deadline,

• liquidated damages per day and maximum liquidated damages,

• daily early completion incentives and maximum early completion incentives,

• daily indirect costs.

The second group is activities' input for schedule development consists of;

• the available construction methods for each activity,

• the initial duration of each activity for each available construction method,

• all of the activity's precedence relationships, which can be one of the following four types: SF, SS, FF, FS.

• the minimum number and maximum number of crews that can be assigned,

• the learning effect for each activity,

• the allowance for interruption,

• the maximum interruption duration if allowed,

• the forgetting duration due to interruption if allowed,

• the soft logic options between activities,

• available construction methods for each activity,

• crews scheduling options (work in parallel, in a shifted arrangement, or in an optimized arrangement), and

• the range of units for each activity to been executed.

The last group is input for cost development of the activities includes;

• the cost of materials per unit for each method,

• the cost of labor per day for each method,

• the cost of equipment per day for each method, and

• the cost of any subcontractors per unit for each method.

The aforementioned input items consist of information about the project to be analysed and the decision maker's preferences. Therefore, the inputs must be provided by the decision maker.

3.2. Schedule and Cost Development Module

The aim of this module is to compute the commencement, conclusion, and direct expenditure of every operation in each unit. It then proceeds to ascertain the overall project length, entire expenditure, and total pause time for every cycle employing heuristic regulations.

The subsequent stages explicate how to conduct the schedule and expenditure estimations:

1. Determine the average rate (R) of any activity *(i)* through Eq. (1),

$$R_i = \frac{c_i}{DI_i - DL_i * (\frac{U}{c_i} - 1)} \tag{1}$$

Where activity *(i)* has c_i crews, an initial duration of DI_i and a learning duration of DL_i, and there are U total units. The average rate combines the traditional activity rate with its learning rate.

2. The starting point *(S)* for an activity *(i)* in unit *(1)* can be determined by following these steps:

• For the initial activity in the first unit, the starting point is presumed to be: $S_{11} = 1$

• If an activity *(i)* has preceding activities, then for each of these preceding activities:

If $R_i < R_{(i-1)}$, then:

for FS relationship: $S_{i1} = F_{(i-1)1} + 1$

for SS relationship: $S_{i1} = S_{(i-1)1}$

for FF relationship: $S_{i1} = F_{(i-1)1} – DI_{(i)} + 1$

for SF relationship: $S_{i1} = S_{(i-1)1} – DI_{(i)}$

If $R_i > R_{(i-1)}$, then:

for FS relationship: $S_{i1} = F_{(i-1)u} – (\Sigma DI_i + \Sigma DL_i) + 1$

for SS relationship: $S_{i1} = S_{(i-1)u} - (\Sigma DI_i + \Sigma DL_i)$

for FF relationship: $S_{i1} = F_{(i-1)u} - (\Sigma DI_i + \Sigma DL_i) - DI_{(i)} + 1$

for SF relationship: $S_{i1} = S_{(i-1)u} - (\Sigma DI_i + \Sigma DL_i) - DI_{(i)}$

Where $F_{(i-1)1}$ represents the finish of the preceding activity of i in unit 1, $F_{(i-1)u}$ depicts the end of the previous activity of i in the final unit U, and ΣDI_i and ΣDL_i indicate the total initial duration and learning duration of activity i respectively. The sums of DI_i and DL_i are contingent on the quantity of units and crews designated to activity i.

3. The initiation and completion of activity *(i)* within unit *(j)* and their respective expenditures are determined according to the illustration presented in Figure 1.

If interruptions are not allowed, the term $DINT_i$, which represents the duration of interruptions for activity i, will be removed from all equations.

The Conflict (CF) value guarantees that there is no overlap or unnecessary delay between two activities within the same unit. The variance can be determined by computing the duration between the start of activity i and the completion of its preceding activities within the same unit.

4. The duration of learning can be calculated using one of the following ways:

• Linear assumption by the user, for example: 5% of the initial duration.

• The linear model, expressed as Eq. (2) and Eq. (3), was developed by Thomas et al. [44].

$$Y_i = Y_1 * (i)^2 \tag{2}$$

$$s = log(LR) / log(2) \tag{3}$$

Where Y_i represents the duration of unit *(i)*, s denotes the learning curve slope calculated by using Eq. (3), Y_1 is the initial duration of the first unit, and LR is the learning rate expressed as a percentage.

5. The total cost of the project is determined using Eq. (4).

$$TC = \sum_{1}^{n} DC_i + IC * DP + LD * DD + IN * DE \tag{4}$$

As given in Eq. (4), where $\sum_1^n \mathrm{DC_i}$ represents the sum of direct costs for all activities, IC denotes the indirect cost per day, DP specifies the project duration, LD represents the late delivery cost per day, and DD is the duration of delay beyond the due date. DP is the project duration, LD is the liquidated damages per day, DD is the delayed duration, IN is the incentive fees per day, and DE is the early completion duration.

6. If interruption is permitted, the subsequent regulations must be adhered to. Interruption is not allowed for the first or last activities since it will not benefit the project schedule. Interruption should only be applied when the current activity has a higher rate than its predecessor and successor activities, as this is the sole situation in which allowing interruption will reduce the overall project duration. For an activity, the interruption duration to be used should be the minimum of the following: the maximum interruption duration set by the user.

The interruption duration for an activity within a unit should be at a minimum to ensure that it follows the previous activity without any positive or negative delay. The duration of interruption resulting in an average rate of the interrupted activity being equivalent to that of the succeeding activity should also be considered.

The initial point *(S)* at which activity *(i)* begins in unit *(1)* is determined by the following formula:

for FS relationship: $S_{i1} = F_{(i-1)u} - (\sum DI_i + \sum DINT_i + \sum DL_i) + 1$

for SS relationship: $S_{i1} = S_{(i-1)u} - (\sum DIi + \sum DINT_i + \sum DL_i)$

for FF relationship: $S_{i1} = F_{(i-1)u} - (\sum DI_i + \sum DINT_i + \sum DL_i) - DI_{(i)} + 1$

for SF relationship: $S_{i1} = S_{(i-1)u} - (\sum DI_i + \sum DINT_i + \sum DL_i) - DI_{(i)}$

The duration of forgetting should be included in the activity duration. Additionally, the average rate of interrupted activity should be recalculated to take into account the interruption duration, as demonstrated in Eq. (5).

$$R_i = \frac{c_i}{DI_i + (DINT_i - DL_i)(\frac{U}{C_i} - 1)} \tag{5}$$

7. If the optimal crew arrangement is chosen, the subsequent steps will be enforced.

• The first activity will be scheduled in parallel mode, then

• If $R_i > R_{(i-1)}$, activity *(i)* will be scheduled in shifted mode

• If $R_i < R_{(i-1)}$, activity *(i)* will be scheduled in parallel mode

Additionally, optimized crew arrangement will minimize the project duration. It produces schedules with less durations and costs without any additional resources.

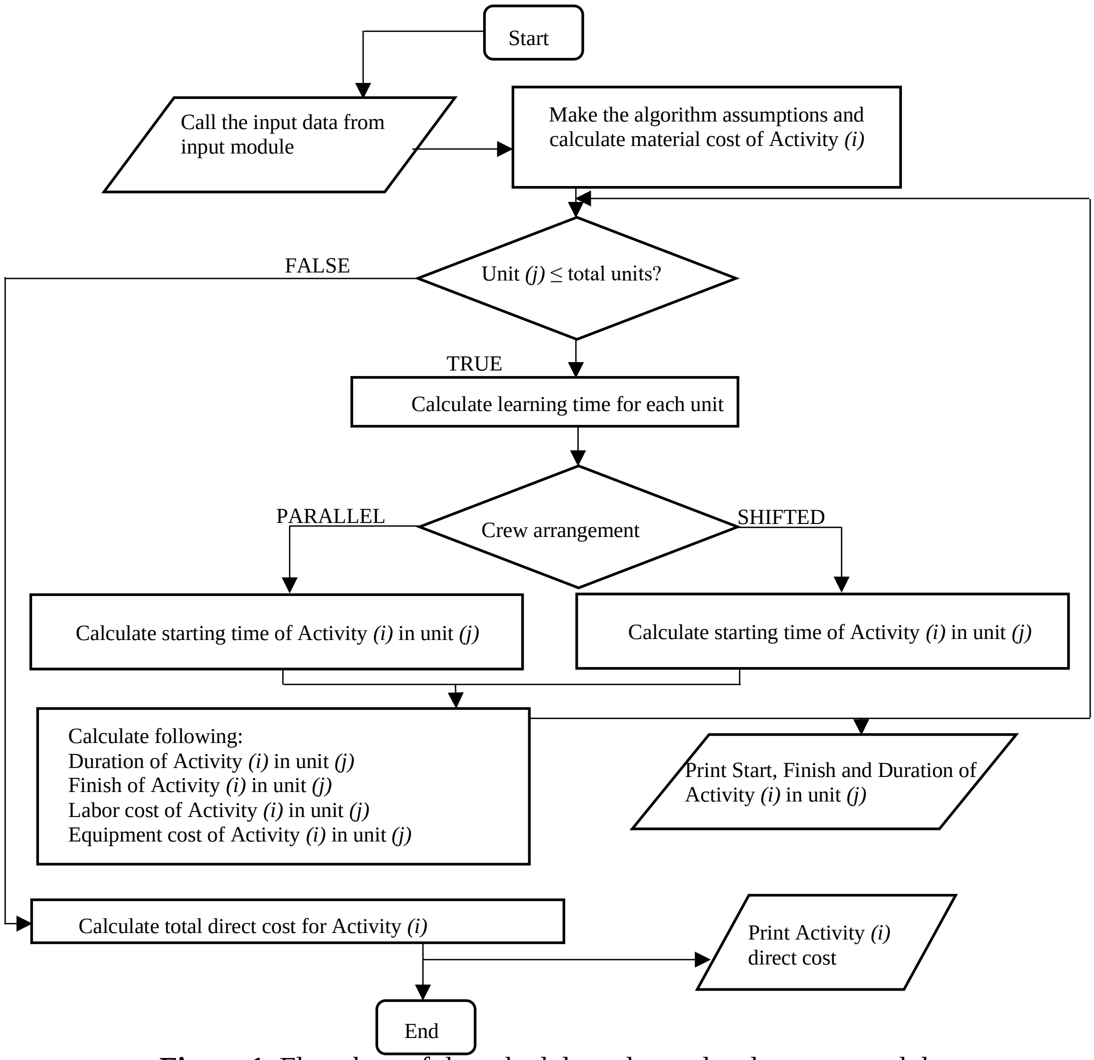

Figure 1. Flowchart of the schedule and cost development module

3.3. Optimization and Ranking Module

The aim of this module is to create a multi-objective optimization system that determines the best combination of crew formations for activities, construction methods, interruption durations, and soft logic to minimize project time, cost, and work interruption simultaneously, employing metaheuristic rules. In multi-objective optimization, no single solution can satisfy all objectives at once. Instead, the focus is on Pareto optimality to generate non-dominated Pareto optimal solutions. However, the proposed model is designed to conduct optimization in the following modes to help the users in making trade-offs between different solutions based on their preferences: single mode for optimizing time of the project, single mode for optimizing total project cost, multi-mode for optimizing the combined impact of duration, cost, and interruption, and multi-mode for identifying Pareto frontiers.

3.4. Decision Variables

The model takes into account various decision variables that impact both project duration and cost. These variables include:

• The number of crews assigned to an activity, which will be constrained within minimum and maximum limits to reflect available resources for each activity. However, increasing the number of crews will raise the activity's cost and diminish learning benefits.

• Construction method, encompassing different technologies, materials, equipment, labor crew configurations, and methods employed to execute the activity.

• Allowance for work interruptions, which can be implemented in specific activities to decrease project duration.

• Soft logic between activities, representing different options for job sequencing logic within the activity sequence.

3.5. Objective Functions

The model is designed to minimize project duration, overall cost, and interruption durations. It integrates several objective functions, which vary depending on the optimization mode, as depicted in Eqs. (6-9).

$$\text{Minimize total project time} = \text{DP} \tag{6}$$

$$\text{Minimize total project cost} = TC = \sum_1^n DC + IC * DP + LD * DD + IN * DE \tag{7}$$

$$\text{Minimize total interruption time} = \sum_1^n DINT \tag{8}$$

The collective influence of duration, cost, and interruption can be assessed through the weighted sum approach [45]. This method transforms the multi-objective optimization challenge into a single objective optimization by consolidating all objectives into a single function, enabling the calculation of the Combined Impact Factor (CIF) as outlined in Eq. 9. To standardize each objective function, project duration, total project cost, and interruption time are divided by predetermined constant values specified by the user. Subsequently, each normalized optimization objective is multiplied by a weighting factor, indicating the relative significance of that particular objective.

$$CIF = \left(W_d * \frac{DP}{DP^*}\right) + \left(W_c * \frac{TC}{TC^*}\right) + \left(W_{dint} * \frac{DINT}{DINT^*}\right) \tag{9}$$

W_d represents the relative weighting factor for duration, W_c stands for the relative weighting factor for cost, and W_{dint} signifies the relative weighting factor for interruption time. $DP*$ denotes the suggested project time by the user (i.e., project deadline), $TC*$ represents the suggested project cost by the user (i.e., preliminary budget), and $DINT*$ indicates the suggested total interruption time by the user.

4. Model Application

This module comprises two primary stages: Initially, it generates potential combinations of decision variables for all activities in each iteration through a permutation tree-based approach, ensuring the attainment of the optimal solution. All feasible iterations are created and cataloged in matrices, utilized in the computations of the schedule and cost development module subsequently. Upon the completion of each iteration, the outcomes, in conjunction with the input data, are stored in a repository provided they meet the user's requirements.

During the scheduling process, interruption duration will be computed, as outlined in Section 3.2, ensuring that the chosen interruption duration positively affects the project schedule. Subsequently, the module organizes all outcomes based on the chosen mode and objectives. In the case of a single mode, the results are ranked in descending order according to the selected objective.

4.1. Case Study 1

To validate the results obtained by the proposed model, the case study presented by Hegazy [46] as used. The project entails constructing a 3-kilometer highway that is divided into 10 sections, each with a length of 300 meters. The project deadline is tight, and the contractor opted to work from both the east and west to prevent resource congestion.

The project incurs a daily indirect cost of \$300, with a liquidated damage set at \$100000/day and an early completion incentive of \$20000/day. Table 1 refers for all necessary data on the relevant project activities.

Table 1. The information for case study

Activity	Location	Section	Pred.	Quantity	Max. no. of crews	Mode 1 Cost (\$)	Mode 1 Dur. (day)	Mode 2 Cost (\$)	Mode 2 Dur. (day)	Mode 3 Cost (\$)	Mode 3 Dur. (day)
1. Excavation	East	1-5	-	2100 m^3	2	21000	3	30000	2	-	-
2. Subbase	East	1-5	1	600 m^2	2	7800	2	-	-	-	-
3. Base	East	1-5	2	6000 m^2	3	72000	10	80000	8	100000	5
4. Binder	East	1-5	3	6000 m^2	1	30000	1.2	-	-	-	-
5. Asphalt	East	1-5	4	3600 m^2	1	14400	1	-	-	-	-
6. Curbs	East	1-5	3	600 m	1	31200	2	38000	1	-	-
7. Lightning	East	1-5	6	7 Poles	2	19245	2	25000	1	-	-
8. Sidewalks	East	1-5	7	300 m	2	10950	2	-	-	-	-
9. Paint	East to West	1-10	8 and 17	300 m	1	198	0.2	-	-	-	-
10-17. Same as 1-8 but at West	West	10-6	Same as Activities 1-8								

4.2. Results and Discussion for Case 1

The problem was solved using the proposed model with the same inputs and options as [46]. Interruption was not allowed, learning effect was not utilized, and scheduling was done in parallel mode.

Table 2 presents the comparison between Hegazy [46] and the proposed model's results for a single objective function to minimize cost. The study determined that both models produced schedules with similar costs and durations. However, the proposed model utilized fewer crews while maintaining the same construction method. Furthermore, the proposed model yielded superior and more precise optimum solutions, particularly when leveraging the learning effect and calculating costs based on daily labor expenses.

Table 2. The comparison of results for Case 1

Point of comparison	**Hegazy [46]**	**The proposed model**
Optimal set of crew combination $c_i = \{c_1, c_2, \ldots, c_n\}$	{2,1,3,1,1,1,2,2,1,2,1,2,1,1,1,1,1}	{2,1,2,1,1,1,1,1,1,2,1,2,1,1,1,1,1}
Total no. of crews	24	21
Optimal set of construction methods combination $cm_i = \{cm_1, cm_2, \ldots, cm_n\}$	{1,1,3,1,1,1,1,1,1,1,1,3,1,1,1,1,1}	{1,1,3,1,1,1,1,1,1,1,1,3,1,1,1,1,1}
Optimal project duration	29.2 days	29.2 days
Optimal project total cost	$2419530	$2419530

Another scenario was analyzed to consider the optimized mode of crew's arrangement instead of scheduling all crews in parallel or in the shifted mode, while maintaining all other options constant. The analysis resulted in a superior solution with a minimum cost of $2359730 and a duration of 26.6 days. When the project duration decreased by 8.90%, the total cost also decreased by 2.47%. Table 3 shows the minimum cost solution obtained.

Table 3. The optimum results for minimum cost with optimized crew arrangement

No	**Set of crew combination $c_i = \{c_1, c_2, \ldots, c_n\}$**	**Set of construction methods combination $cm_i = \{cm_1, cm_2, \ldots, cm_n\}$**	**Selected crew arrangement**	**Project dur. (day)**	**Total cost ($)**
1	{2,1,3,1,1,1,1,1,1,2,1,3,1,1,1,1,1}	{1,1,3,1,1,1,1,1,1,1,1,3,1,1,1,1,1}	{p,p,s,s,s,p,p,p,s,p,p,s,s,s,p,p,p}	26.6	2359730

Each activity will be examined to illustrate the additional benefits and capabilities of the proposed model. Two more scenarios will be explored, using the same options as [46], to generate solutions for (1) minimum duration and (2) minimum combined impact of duration and cost. The results obtained from the proposed model for minimum duration can be found in Table 4, while Table 5 displays the four best solutions for minimum combined impact of both duration and cost.

Table 4. The optimum schedule for minimum duration

No	**Set of crew combination $c_i = \{c_1, c_2, \ldots, c_n\}$**	**Set of construction methods combination $cm_i = \{cm_1, cm_2, \ldots, cm_n\}$**	**Project dur. (day)**	**Total cost ($)**
1	{2,2,3,1,1,1,1,2,1,2,2,3,1,1,1,2,2}	{2,1,3,1,1,2,2,1,1,2,1,3,1,1,2,2,1}	23.2	2497080

Table 5. The optimum schedules for minimum combined impact of both duration and cost

No	Set of crew combination $c_i = \{c_1, c_2, \ldots, c_n\}$	Set of construction methods combination $cm_i = \{cm_1, cm_2, \ldots, cm_n\}$	Project dur. (day)	Total cost ($)	CIF
1	{2,2,3,1,1,1,2,2,1,2,2,3,1,1,1,2,2}	{2,1,3,1,1,2,1,1,1,2,1,3,1,1,2,1,1}	24.2	2462530	96,542%
2	{2,2,3,1,1,1,1,2,1,2,2,3,1,1,1,1,2}	{2,1,3,2,1,1,2,1,1,2,1,3,1,1,2,2,1}	23.2	2497080	97,004%
3	{2,2,2,1,1,1,1,1,1,2,2,2,1,1,1,1,1}	{2,1,3,1,1,1,1,1,1,2,1,3,1,1,1,1,1}	26.2	2440530	97,157%
4	{2,2,3,1,1,1,1,2,1,2,2,3,1,1,1,2,2}	{2,1,3,2,1,1,2,1,1,2,1,3,1,1,2,1,1}	24	2486705	97,199%

The CIF for each solution is calculated using the following data: weighting factors have been assigned to duration, cost, and interruption duration at 20%, 80%, and 0%, respectively. *DP** stands at 30 days, while *TC** is set at $2450000.

4.3. Case Study 2

The second case study presents as an illustrative example, employing various options to highlight the comprehensive capabilities of the proposed model and underscore the significance of diverse parameters in the analysis. This case study centers on a project encompassing the construction of eight villas. The scope of work for each villa involves executing internal finishes, commencing from block works and culminating in final additions. The project is bound by a strict deadline of 65 days. Indirect costs incurred by the project amount to $1000 per day, while liquidated damages are set at $2000 per day, with a maximum cap of $50000. Notably, the project does not offer any early completion incentive fees. Learning duration is estimated at 8% of the original duration for every crew involved in the activities. Additionally, a forgetting duration of 4% from the original duration is assumed for activities interrupted during execution. Table 6 comprehensively outlines all necessary data related to the project's activities, considering two proposed scenarios for soft logic. It is important to note that all relationships between activities are assumed Finish-to-Start (FS) with no lags or leads, providing a standardized framework for analysis and comparison.

Table 6. The information for Case Study 2

Activity	Soft Logic (1)	Soft Logic (2)	Max. no. of crews	Interruption (days)	Construction Method 1			Construction Method 2		
	Pred. Act.	Pred. Act.			Labor Cost($)/ day	Mat. Cost ($)/ unit	Dur. (days)	Labor Cost($)/ day	Mat. Cost ($)/ unit	Dur. (days)
1. Blockworks	-	-	3	-	1875	16000	6	500	16000	5
2. Plastering dots	1	1	2	5	1950	4000	3	-	-	-
3. Electrical conduits	2	2	2	-	1425	7000	5	600	7000	4
4. Plastering fill	3	3	2	-	1950	10000	5	-	-	-
5. Wiring pulling	4	4	2	-	1500	11000	4	500	11000	2
6. Marble flooring	5	7	3	-	1350	12000	6	-	-	-
7. Painting 1st coat	6	5	2	-	1650	8000	5	-	-	-
8. Doors installation	7	6	2	5	1800	9000	2	700	9000	1
9. Painting final coat	8	8	2	-	1650	5000	3	-	-	-
10. Electrical final fix	9	9	2	-	1800	11000	2	-	-	-

4.4. Results and Discussion for Case Study 2

Initially, the case study was approached in a single-mode analysis to discern optimal solutions for individual objective functions. Table 7 presents the optimal crew numbers, construction methods, soft logic, interruption allowances, and resultant durations, costs, and interruption durations for each objective. To calculate the Combined Impact Factor (CIF) and minimize the collective effects of duration, cost, and interruption duration, relative weighting factors were applied: 30% for duration, 65% for cost, and 5% for interruption duration. Key parameters included *DP** (65 days), *TC** ($1250000), and *DINT** (10 days).

Table 7. The optimum results for Case Study 2

#	**Set of crew combination** $c_i = \{c_1, c_2, \ldots, c_n\}$	**Set of construction methods combination** $cm_i = \{cm_1, cm_2, \ldots, cm_n\}$	**Interruption allowance**	**Selected soft logic**	**Proj. dur. (day)**	**Total cost ($)**	**Interruption dur. (day)**	**CIF**
Objective 1: Minimizing duration								
1	{3,2,2,2,2,2,2,2,2,2}	{2,1,2,1,1,1,1,2,1,1}	{0,1,0,0,0, 0,0,1,0,0}	1	53	1310464	8.52	N/A
Objective 2: Minimizing cost								
1	{2,1,1,1,1,1,1,1,1,1}	{1,1,1,1,1,1,1,1,1,1}	{0,0,0,0,0, 0,0,1,0,0}	1	66.64	1226768	4.2	N/A
Objective 3: Minimizing conbined impact of duration, cost and interruption duration								
1	{2,1,1,1,1,2,2,1,2,2}	{2,1,1,1,1,1,1,1,1,1}	{0,0,0,0,0, 0,0,0,0,0}	1	60.04	1255768	0	93.01
2	{3,1,1,1,1,2,2,1,2,2}	{2,1,1,1,1,1,1,1,1,1}	{0,0,0,0,0, 0,0,0,0,0}	1	60.04	1258168	0	93.14
3	{2,1,1,1,1,2,2,1,2,2}	{2,1,2,1,1,1,1,1,1,1}	{0,0,0,0,0, 0,0,0,0,0}	1	59.04	1267392	0	93.15
4	{3,1,1,1,1,2,2,1,2,2}	{1,1,1,1,1,1,1,1,1,1}	{0,0,0,0,0, 0,0,0,0,0}	1	61.04	1250228	0	93.18
5	{3,1,1,1,1,2,2,1,2,2}	{2,1,2,1,1,1,1,1,1,1}	{0,0,0,0,0, 0,0,0,0,0}	1	59.04	1269792	0	93.28

To underscore the significance of integrating learning and forgetting effects in the optimization process, the case study was revisited under identical original conditions but without considering these effects. The results presented in Table 8 mention the substantial impact of integrating learning and forgetting effects. Specifically, incorporating these effects reduced the project duration by 10.16% (from 59 days to 53 days) and lowered project costs by 9.96% (from $1362400 to $1226768). Notably, applying the learning effect led to a smaller number of crews when minimizing project costs, fostering further learning development due to increased repetitions.

Table 8. The optimum results without learning and forgetting effects

#	**Set of crew combination** $c_i = \{c_1, c_2, \ldots, c_n\}$	**Set of construction methods combination** $cm_i = \{cm_1, cm_2, \ldots, cm_n\}$	**Interruption allowance**	**Selected soft logic**	**Proj. dur. (day)**	**Total cost ($)**	**Interruption dur. (day)**	**CIF**
Objective 1: Minimizing duration								
1	{2,2,2,2,1,2,3,2,2,2}	{2,1,1,1,2,1,1,2,1,1}	{0,1,0,0,0, 0,0,1,0,0}	2	59	1362400	12	N/A
Objective 2: Minimizing cost								
1	{3,2,2,2,2,2,3,2,2,2}	{1,1,1,1,1,1,1,1,1,1}	{0,1,0,0,0, 0,0,1,0,0}	2	62	1353800	12	N/A

Furthermore, the study investigated the benefits of allowing work interruption in specific activities during repetitive project optimization. Table 9 displays the outcomes of the analysis conducted under the condition of disallowing work interruption in any activity. Integrating work interruption resulted in 5.02% reduction in project duration (from 55.8 days to 53 days) and 8.93% decrease in project costs (from $1239200 to $1226768). These findings underscore the positive impact of judiciously applying work interruption strategies in enhancing project efficiency and reducing costs.

Table 9. The optimum results without interruption

#	Set of crew combination $c_i = \{c_1, c_2, \ldots, c_n\}$	Set of construction methods combination $cm_i = \{cm_1, cm_2, \ldots, cm_n\}$	Interruption allowance	Selected soft logic	Proj. dur. (day)	Total cost ($)	Interruption dur. (day)	CIF
Objective 1: Minimizing duration								
1	{3,2,2,2,2,2,2,1,2,2}	{2,1,2,1,1,1,1,2,1,1}	{0,0,0,0,0,0,0,0,0,0}	1	55.8	1299192	0	N/A
Objective 2: Minimizing cost								
1	{2,1,1,1,1,1,1,1,2,2}	{1,1,1,1,1,1,1,1,1,1}	{0,0,0,0,0,0,0,0,0,0}	1	68.84	1239200	0	N/A

5. Conclusions

Creating a feasible, effective, and optimal timetable for repetitive projects stands as a crucial challenge for the project success. This study embarked on a meticulous exploration of pertinent literature to identify pivotal factors influencing scheduling in the repetitive projects. Subsequently, an innovative heuristic multi-objective optimization model was devised to concurrently minimize the project duration, cost, and interruption duration. This research enriches the body of knowledge on repetitive project scheduling in the following ways:

Literature Review Enhancement: By furnishing a comprehensive review of literature pertaining to optimization in repetitive project scheduling, this research equips scholars with a reliable foundation to discern key considerations and limitations prevalent in earlier studies.

Innovative Optimization Model: The development of a novel optimization model is a significant contribution, as it accommodates factors like learning and forgetting effects, soft logic between activities, seamless crew work continuity, integration of work interruption in specific activities, diverse crew formations, and multiple construction methods for each activity. The model also encompasses all Critical Path Method (CPM) scheduling capabilities and takes into account various construction costs such as direct, indirect, delay damages, and early completion incentive fees.

Metaheuristic Optimization Method: This research introduces an effective metaheuristic approach to schedule and optimize repetitive projects. The model's versatility enables simultaneous minimization of duration, cost, and interruption duration in multi-mode. Additionally, it can operate in single mode, optimizing one objective function at a time, thereby enhancing flexibility for project planners.

Impactful Factors: Integration of learning and forgetting effects in repetitive scheduling significantly reduces project duration.

Soft Logic Consideration: Incorporating soft logic into the model enhances its value, leading to shorter project durations without incurring additional costs. Optimal selection of soft logic between activities is pivotal in achieving this outcome.

To sum up, the main contribution of the study is the integration of learning effects, soft logic and work interruption allowances into the optimization process, significantly reducing project time and cost, thus enabling more accurate and reliable optimum solutions.

Additionally, the developed model was validated using a previous case study, demonstrating its superior accuracy. The model's distinctive features ensure its practicality in optimizing real construction repetitive projects. This research holds significant implications for both industry practitioners and scholars, providing effective solutions for multi-constraint, multi-objective repetitive scheduling challenges. Moreover, it serves as a springboard for future researchers, encouraging exploration of non-typical durations in activities, considering resource transfer time, and cost between different units for further optimization endeavors.

Conflict of Interest

The authors declare that they have no conflict of interest.

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