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Implementation of a Heuristic Algorithm for the Solution of Discrete Time Cost Trade-off Problem

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ABSTRACT

Time cost trade-off problem aims to minimize the total project cost by crashing the critical activities. This problem is solved by mathematical programming and meta-heuristic algorithms. However, construction sector has minimum priority on the theoretical knowledge to implement robust optimization algorithms. For this reason aforementioned optimization algorithms can be hardly implemented for the private construction companies. The nature of the time cost trade-off algorithm is not challenging and can be solved heuristically. In this study, a spreadsheet application is developed by utilizing in-app excel functions to identify the critical activities of the project and the paths of the project. The construction schedule is entered to the spreadsheet application as acticity on arrow diagram and the logical relationships between the activities are defined. Forward and backward pass computations are given as formulations which includes the actual activity durations. The developed application calculates the crashing costs of the critical activities and highlights the activities with the cheapest crashing costs. Prepaperd spreadsheet application implements a heuristic solution algorithm which is based on minimum cost slope of the construction activities. The user can easily execute the proposed or user selected crashing alternative and the schedule is updated according to the selection. The application is tested on 6 activity project and the optimum solution is obtained by crashing the activities sequentially. The proposed technique can be utilized to reduce the total project cost of the construction sector.

1. Introduction

The process of optimizing time and cost aims to complete the project in the least cost and in the shortest time by making the optimal construction alternative choice for each activity. This process is defined as the time-cost trade-off problem. Completing an activity in less time than its normal completion time determined to have the lowest direct cost may result in an increase in direct costs; however, reducing the duration of critical activities may also shorten the total duration of the project. Although shortening the project duration increases direct costs, the reduction in indirect costs and the benefits of early completion can lead to a reduction in total project cost. Therefore, determining the optimal construction options for the construction alternatives and the project completion time is critical. The time-cost trade-off problem (TCTP) contributes to minimizing the total cost by creating a work schedule that will complete the project at the lowest cost and in the appropriate time, and thus stands out as an optimization problem.

A review of the literature shows that advanced meta-heuristic algorithms such as genetic algorithm (GA), multi-objective particle swarm optimization (MOPSO), differential evolution (DE) and simulated annealing have been used to solve the TCTP problem. These techniques are difficult to understand for most civil engineering students and practitioners and are generally not included in the undergraduate curriculum. The aim of this study is to present a simpler and practical solution method that engineering students and professionals can easily understand and apply. To this end, it is planned to develop a comprehensible spreadsheet model for the solution of TCTP without resorting to complex algorithms. This model can be used as a practical tool during the planning and management of construction projects and will have a wide range of applications both academically and industrially. Thus, it is aimed to make optimization studies in civil engineering more widespread and to overcome the difficulties encountered in existing methods. In addition, unexpected situations may arise during the implementation phase of projects. This study aims to enable quick adjustments to be made with common and easily accessible tools such as MS Excel, without the need to redo the time-cost trade-off analysis. Thus, project managers will be able to generate fast and effective

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solutions to unexpected situations or changes without the need to remodel the project from scratch. These small-scale adjustments will increase the efficiency of the project and provide time and cost advantages.

2. Literature Review

Compared to traditional linear and discrete trade-off models, a new model is proposed in [1] that represents the correlation of activity duration and cost in a more realistic way. This model provides a more accurate approach for solving construction project duration reduction problems with two different configurations, depending on the cooperation of resources, at the lowest total cost. In the study, the implementation of acceleration and fast-tracking strategies using Genetic Algorithm (GA) for a fictitious project with 10 activities is investigated. The total duration of the project is 200 days and the direct cost is 5000 monetary units (m.u.). The daily indirect cost is 25 m.u. and the initial cost is assumed to be 10,000 m.u. In the first scenario all activities were done with collaborative resources, while in the second scenario non-collaborative resources were used. The dhortening of the construction duration levels and project cost were found to be lower in the projects with collaborative resources. In the buffer time strategy, the compression level achieved with non-collaborative resources was 14.8%, while it increased to 26.9% with collaborative resources. The total time surplus achieved with fast-tracking was lower than with buffer time. When both techniques were used together, the program duration was lower and the total cost decreased from 9365 m.u. to 9271 m.u.

An optimization model that examines construction projects in terms of time, cost, risk and quality was proposed in [2]. This model analyzes the effects of cost, risk and quality on project duration while handling uncertainties with fuzzy logic. The NSGA-II metaheuristic algorithm and goal programming method were used to solve the model. The model was applied to the construction of an oil storage tank by validation with small size problems. For large-sized and NP-hard problems, solutions were found with the NSGA-II algorithm and the results showed that the algorithm gave results close to the optimum solution [2].

A multi-objective optimization model for multiple shift scheduling in construction projects was developed in [3]. The model aims to minimize the negative effects of project duration, cost and number of shifts. In the case study, a construction project with 15 activities is analyzed. In the first case, using only the day shift, the project duration was 38 days and the cost was $138,100. With two shifts, the project duration was 23 days and the cost was $148,500, and with three shifts, the project duration was reduced to 18 days and the cost was $165,100. In the three-shift system, the minimum project duration was completed in 18 days with a labor force of 70 days and the cost decreased by 5.3%. With a two-shift system, with a labor force of 50 days, the project duration was completed in 23 days and the cost decreased by 2.8%. The results show that the developed model improves project performance by optimizing the workforce [3].

An application has been developed that automates the creation of construction alternatives to obtain fast results without the need for human intervention by working on the spreadsheet [4]. When changes in the design are defined in the system, the process steps are automatically updated and the quantity calculations are renewed. In the study, two problems were defined: in the first one, each activity has 4 different construction alternatives and in the second one 5 different construction alternatives. For the solution of these problems, Genetic Algorithm was preferred because it is easier than mathematical programming and gives better results than heuristic methods. In the second problem, while lower costs were obtained with more alternatives, differentiation and increased variance in solution values were observed. This application allows professionals in the construction industry to easily identify time-cost trade-off problems and obtain the best results with GA, which can lead to significant cost savings [4].

A spreadsheet application that calculates quantities of construction materials with minimal input from the user was developed in [5]. This system facilitates the process of generating and optimizing the TCTP and alleviates the workload by reducing bid preparation difficulties. Suitable parameters for GA are proposed and an automated application is developed for the preparation and solving of TCTP by calculating QTO [5].

A spreadsheet application has been developed to arrange daily staffing and material quantities based on the linear progress of work packages [6]. By entering the required prices into this application, actual costs and progress payments can be calculated according to the work schedule. To illustrate, at a 5% profit rate, the cash flow is positive at month 14, while at a 15% profit rate it fluctuates and crosses the horizontal axis three times. This indicates that the contractor can cover most of the payments with its own resources or with low borrowing. The system updates cash flow changes due to deviations in the schedule with minimal human intervention, and cost increases due to job changes or inflation can be quickly calculated. By integrating all planning stages into the application, a system that calculates cash flow has been developed. This application saves cost and time in the planning process [6].

Bettemir and Bulak (2022) [7] developed a method that automates the steps of bill of quantities, activity durations, resource requirements, work schedule and construction cost determination in an integrated manner in the project management process. As a result of the experimental design performed on a simulated annealing genetic algorithm, the population size was set to 50, crossover and mutation rates were set to 72% and 80%, respectively, and the best parameters were found in 15 cycles. Moreover, the work schedule and bill of quantities calculation were automated so that the whole process can be recalculated when the building dimensions change. The method generates the schedule without the need to add additional time to the bidding period, avoiding loss of work efficiency. In this way, contractors can increase their productivity [7].

The problem of minimizing the total cost in project activities with specific time and cost modes is addressed in [8] and different variants of annealing simulation algorithms are investigated. The performance of the algorithms is ranked and the factors affecting the local optimum are identified. Confidence intervals of both algorithm variants are estimated by methods based on outlier statistics. The most efficient variant produces solutions close to the global optimum but is the slowest in terms of time [8].

The OMODE algorithm for shift scheduling in construction projects is used to optimize project duration, cost and shift utilization. The effectiveness of the OMODE algorithm was compared with NSGA-II, MOPSO and MODE algorithms with numerical examples in two projects and it was shown to be more efficient [9].

The Multi-Objective PSO (MOPSO) model was developed by adding the non-dominated sorting (NDS) process to PSO. This model aims to improve the efficiency of construction projects and facilitate management by simultaneously optimizing project duration and cost. The MOPSO approach shows the potential to improve the outcomes of projects [10].

A mixed integer linear programming (MILP) model was developed in [11] to balance the extension and acceleration processes of projects. This model is called the "discrete time, cost and credit tradeoff problem" (DTCCTP). Furthermore, a heuristic is proposed to find good solutions and to provide an upper bound on the project extension time. The algorithm is run until all activities are scheduled and the problem is considered infeasible if any activity cannot be scheduled. This method takes into account financial constraints while optimizing the project in terms of time and cost [11].

Fuzzy set theory can be used in project planning to quantify uncertainties and imprecisions. In this method, the durations of project activities are expressed in fuzzy durations instead of precise durations, and accordingly forward pass, early start and early finish calculations are made. Cash flow planning with fuzzy durations and costs and these calculations were made in [12] by developing a computer program. This program performs fuzzy calculations for activity durations and costs and displays the results in graphs and tables. It is possible to analyze the whole project or specific activities through the User Interface (GUI). The program performs risk analysis of fuzzy cash flows by evaluating optimistic and pessimistic scenarios. It calculates minDα and maxDα values for different α-cuts and determines risk levels by distributing activity costs [12].

A fast, simple and near-optimal network analysis algorithm (NAA) was proposed in [13] to solve the discrete TCT problem. While NAA achieved the global optimum for small and medium-sized projects, it showed small deviations from the global optimum for larger projects. Deviations of $2450 and $4750 from the optimal solution were observed for projects with 63 activities, respectively. However, the computational demand of NAA is much lower than meta-heuristic algorithms. NAA is an effective method for achieving fast convergence and reaching the global optimum. It also achieves better results than integer programming and branch-and-bound methods and is easier to implement. Therefore, NAA is a suitable optimization method for the discrete TCT problem [13].

Harmony search algorithm (HSA) gives satisfactory results in acceptable times in the search space with infinite solutions, is investigated in [14]. Investigations on discrete data have shown that the HSA method offers an alternative solution to optimization problems.

Tabu Search Algorithm is also used for the solution of TCTP. The algorithm tested on a seven-variable minimization problem in [15], where nonlinear functions are optimized with the tabu search algorithm, obtained significant results. The Nelder-Mead algorithm was used to avoid erroneous results. Although Nelder-Mead is usually used for continuous functions, in this study it was successfully used as an auxiliary method for discontinuous functions.

In foundation design, determining the base dimensions of the lugs by trial and error is time consuming [16]. Therefore, a genetic algorithm (GA) was proposed in [16] to solve this problem. The objective function is to minimize the foundation volume and the foundation dimensions are calculated by considering the linear variation of the base pressure. The crossover operator increases the diversity among chromosomes and if there are similar chromosomes, a new starting population is created. This process is repeated until the chromosomes diverge. By checking the limiters, individuals are ranked according to their success and individuals that fall outside the limiters are discarded. The number of replicates 1/50 of the population size provides the best result. The GA has successfully determined the optimum base sizes by taking into account the constraints. This method saves time compared to the manual solution and has the advantage of providing more than one solution [16].

In electric power systems, the optimum conditions to minimize active power losses in transmission lines are determined by genetic algorithm (GA). In an example power system, at the point where the active power loss is the lowest, the optimum voltage values at other busbars are calculated, but the oscillation bus is not taken into account. Genetic Algorithm (GA) and Newton-Raphson (NR) method were used to find these values and the total active power losses were compared with the results obtained. GA provided lower active power loss than NR method [17].

Finding the right combination of investments is an important problem in modern financial markets and this problem is called the portfolio optimization problem. Due to the investment in multiple assets and the non-linear structure, this problem is intended to be solved by genetic algorithm. The genetic algorithm is implemented with Excel solver; return, estimated return and average return values obtained from Monte Carlo simulation are used for asset returns. It is observed that the genetic algorithm has time disadvantages in scenario-based portfolio optimization problems. The Monte Carlo technique is used for decision making under uncertainty and has been shown to provide better results in terms of return and risk than other methods [18].

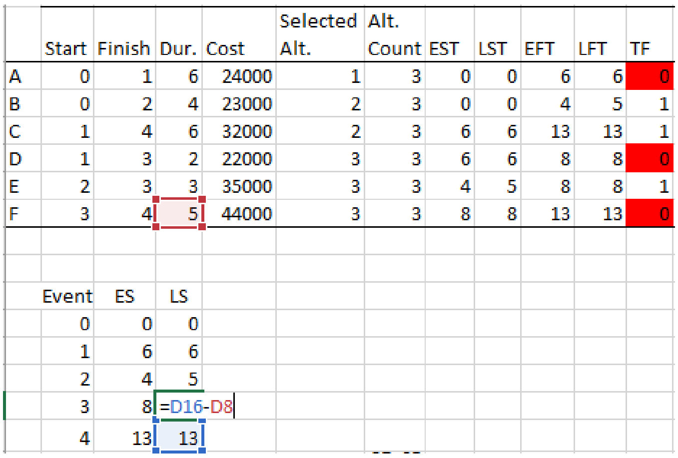
To optimize the traditional time-cost trade-off problem, a least-cost mathematical optimization model was developed in [19] by combining CPM, mathematical programming and DCF techniques. This model can be applied to all types of projects without limiting projects to specific techniques. This technique can be applied when projects are divided into prioritized activities with normal and collision time and cost data. Considering the value of time, the durations of the selected activities and the optimal project duration are different from traditional analysis. The use of DCF produces realistic results and enables sound decisions on project duration and cost [19]. Search domain of TCTP increases significantly when the project size increases. In order to keep computation time within reasonable limits an adaptive search domain is adopted for meta-heuristic approaches [20].

3. Method

In this study, a time-cost trade-off analysis of a construction project was conducted. In the analysis, critical activities were accelerated to shorten the total project duration and the relationship between the increase in direct costs and the decrease in indirect costs was evaluated. A network diagram was created by considering the constraint relationships between the activities.

The Early Event and Late Event times of the nodes are automatically calculated in a separate table for the selection of different construction alternatives of the activities which offers different construction duration and construction cost choices for the corresponding activity. The spreadsheet automatically assigns the duration and cost values and recalculates the construction schedule. In this way, when a different alternative is selected for any activity, the project completion time is automatically updated.

ES and LS calculations of the nodes are given in Figure 1.



	Start	Finish	Dur.	Cost	Selected Alt.	Alt. Count	EST	LST	EFT	LFT	TF
A	0	1	6	24000	1	3	0	0	6	6	0
B	0	2	4	23000	2	3	0	0	4	5	1
C	1	4	6	32000	2	3	6	6	13	13	1
D	1	3	2	22000	3	3	6	6	8	8	0
E	2	3	3	35000	3	3	4	5	8	8	1
F	3	4	5	44000	3	3	8	8	13	13	0

Event	ES	LS
0	0	0
1	6	6
2	4	5
3	8	=D16-D8
4	13	13

Figure 1. Preparation of excel application for the automated computation of activity start and finish times.

The calculation of the acceleration cost of the activity to be accelerated is shown in Figure 2. The cost of acceleration was calculated as presented in Equation 1.

$$CrashingCost = \frac{C_{next} - C_{current}}{D_{next} - D_{current}} \tag{1}$$

Where:

C_{next} is the cost of the next chosen construction alternative.

$C_{current}$ is the cost of the current chosen construction alternative.

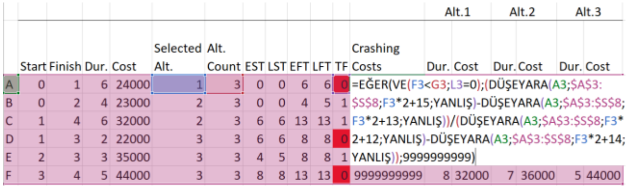
D_{next} is the duration of the next chosen construction alternative.

$D_{current}$ is the duration of the current chosen construction alternative.

The formula entered in the spreadsheet application to implement Eq. 1 is given the following statement.

```
“=IF(AND(F3<G3,L3=0),(VLOOKUP(A3,$A$3:$S$8,F3*2+15,FALSE)-VLOOKUP(A3,$A$3:$S$8,F3*2+13,FALSE))/(VLOOKUP(A3,$A$3:$S$8,F3*2+12,FALSE)-VLOOKUP(A3,$A$3:$S$8,F3*2+14,FALSE)),9999999999)”
```

In this way, the unit acceleration cost of the related activity in the project is calculated in TL/day and used to select the activities where the direct cost will increase the least. If the activity is not a critical activity, accelerating the activity will not provide an improvement in the project cost. In order to eliminate noncritical activities the defined equation assigns very high acceleration costs as shown in the equation defined to the MS Excel.



													Alt.1		Alt.2		Alt.3	
	Start	Finish	Dur.	Cost	Selected Alt.	Alt. Count	EST	LST	EFT	LFT	TF	Crashing Costs	Dur.	Cost	Dur.	Cost	Dur.	Cost
A	0	1	6	24000	1	3	0	0	6	6	0	=EĞER(VE(F3<G3;L3=0);(DÜŞEYARA(A3;$A$3:						
B	0	2	4	23000	2	3	0	0	4	5	1	$S$8;F3*2+15;YANLIŞ)-DÜŞEYARA(A3;$A$3:$S$8;						
C	1	4	6	32000	2	3	6	6	13	13	1	F3*2+13;YANLIŞ))/(DÜŞEYARA(A3;$A$3:$S$8;F3*						
D	1	3	2	22000	3	3	6	6	8	8	0	2+12;YANLIŞ)-DÜŞEYARA(A3;$A$3:$S$8;F3*2+14;						
E	2	3	3	35000	3	3	4	5	8	8	1	YANLIŞ));9999999999)						
F	3	4	5	44000	3	3	8	8	13	13	0	9999999999	8	32000	7	36000	5	44000

Figure 2. Computation of crashing costs of the activities

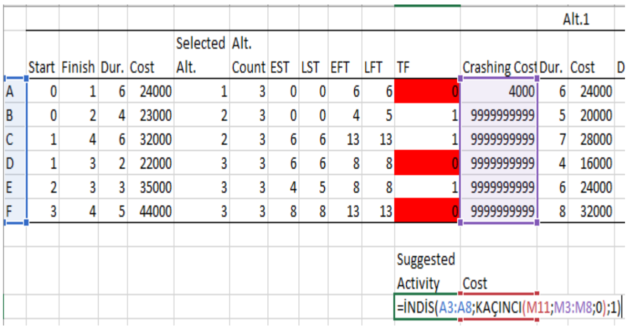
The spreadsheet, as shown in Figure 3, recommends the most suitable activity for acceleration. While making this recommendation, it recommends the activity with a total float time of 0, that is, the activity on the critical path in the network and the activity with the lowest acceleration cost. The activities on the critical path are prioritized. Since the critical path may change after each acceleration process, the duration of an activity is recalculated whenever it is updated. The total float time of activities is calculated as in Eq. 2.

$$TF = LFT - EST - Duration \tag{2}$$

Where TF is the total float, LFT is the late finish time and EST is the early start time. Also, LST is the latest start time and EFT is the earliest end time. The unit of time is days.

The formula used in the spreadsheet application to show the activity recommended for acceleration is expressed as "=INDEX(A3:A8,MATCH(M11,M3:M8,0),1)". In the expression the cell M11 represents the lowest crashing cost and the INDEX function finds and retrieves the activity with the cheapest acceleration cost.

The prepared spreadsheet detects the critical activities and computes the crashing cost of the critical activities if they have any crashing alternatives. The crashing alternative with minimum crashing cost is proposed by the developed application. The scheduler can assign the activity to be crashed by examining the proposed crashing alternatives.



													Alt.1		
	Start	Finish	Dur.	Cost	Selected Alt.	Alt. Count	EST	LST	EFT	LFT	TF	Crashing Cost	Dur.	Cost	D
A	0	1	6	24000	1	3	0	0	6	6	0	4000	6	24000	
B	0	2	4	23000	2	3	0	0	4	5	1	9999999999	5	20000	
C	1	4	6	32000	2	3	6	6	13	13	1	9999999999	7	28000	
D	1	3	2	22000	3	3	6	6	8	8	0	9999999999	4	16000	
E	2	3	3	35000	3	3	4	5	8	8	1	9999999999	6	24000	
F	3	4	5	44000	3	3	8	8	13	13	0	9999999999	8	32000	
											Suggested Activity	Cost			
											=İNDİS(A3:A8;KAÇINCI(M11;M3:M8;0);1)				

Figure 3. Automated illustration of critical activities and available crashing alternatives

4. Case Study

A network diagram showing the constraints between activities is given in Figure 4.

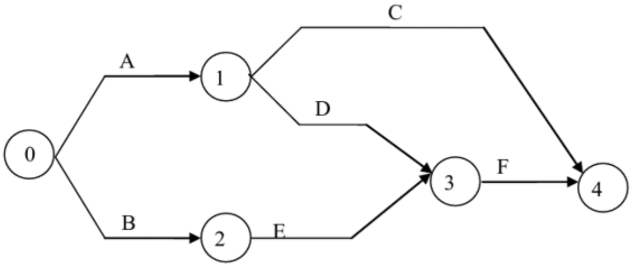


Figure 4. Hypothetic six activity project for the time cost trade of problem

The different duration and construction alternatives for each activity are presented in Table 1. Alternative 1 is the daytime work option. The project is completed with standard working time and the cost is the lowest. However, the duration is the longest. Alternative 2 is the daytime with overtime work option. By shortening the daytime period by adding overtime, the duration is reduced, but the cost is increased slightly since overtime payments are higher than the regular payments. Alternative 3 is the night + day double shift option. The night + day shift alternative is applied with the shortest duration but the highest cost. Costs increase due to acceleration. The unit of cost is TL and the daily overhead for this schedule is TL 10000.

Table 1. Construction cost and duration alternatives

	Alt.1		Alt.2		Alt.3	
	Dur.	Cost	Dur.	Cost	Dur.	Cost
A	6	24000	5	28000	4	34000
B	5	20000	4	23000	3	28000
C	7	28000	6	32000	5	38000
D	4	16000	3	18500	2	22000
E	6	24000	5	28000	3	35000
F	8	32000	7	36000	5	44000

In the spreadsheet application, the time-cost trade-off problem is solved by selecting suitable alternatives for the proposed activities. When the proposed activities are accelerated respectively, the results presented in Table 2 are obtained. In Table 2 CrA refers to the crashed activity. Direct costs are the cost of each activity for the selected alternative. Indirect costs are obtained by multiplying the daily cost by the total project duration. In the later phases of the optimization process the network has multi critical paths. In this situation acceleration of more than one activity can be necessary. In some of the table rows the total project duration becomes unchanged eventhough a critical activity is accelerated. In this situation the accelerated critical path becomes noncritical and the remaing critical path prevents the shortening of the project duration. The project duration is 19 time unit and with 334.000 TL total cost. The optimized project duration is 12 time units with 300.000 TL total project cost. The last row of the Table 2 cannot provide an improvement as all of the crashing options are evaluated. The short revision of the construction schedule provides shortening of 7 time units and 34.000 TL savings.

Table 2. Implemented crashing sequence for the solution of time cost trade-off problem

CrA	Dur.	Direct Cost	Indirect Cost	Total Cost	Critical Paths
NONE	19	144.000	190.000	334.000	B-E-F A-D-F
B	18	147.000	180.000	327.000	B-E-F A-D-F
F	17	151.000	170.000	321.000	B-E-F A-D-F
F	15	159.000	150.000	309.000	B-E-F
D	15	161.500	150.000	311.500	B-E-F A-D-F
E	14	165.500	140.000	305.500	B-E-F
D	14	169.000	140.000	309.000	B-E-F A-C
E	13	176.000	130.000	306.000	A-D-F A-C A-D-F
A	12	180.000	120.000	300.000	B-E-F A-D-F
C	12	184.000	120.000	304.000	B-E-F

5. Conclusion

Time-cost trade-off problems are a critical and complex problem that arise during the planning and management phases of civil engineering projects. This problem aims to balance the cost increase required to complete a project faster with the cost reduction required to complete a project in a longer time. Projects that are completed quickly often lead to high costs, while reducing costs often extends the duration. It therefore becomes imperative for project managers to find the optimal balance between time and cost.

Traditional methods require complex algorithms to solve these problems, and their implementation can be time-consuming and labor-intensive. Most solution processes involve specialized methods that are difficult to understand for non-technical civil engineering students and professionals. This study aims to develop an easy-to-use spreadsheet that can solve time-cost tradeoff problems faster and with less effort. This tool provides a practical solution to civil engineering students and professionals, allowing them to move away from the complex structure of algorithms and speed up their daily workflow.

During the construction process, deviations in the number of workers, material costs, equipment capacity and weather conditions can affect the optimized schedule and cause the initial solution to be suboptimal. By adopting a dynamic project management approach, this study aims to develop an algorithm that can take into account the changing conditions during the construction process and an application that can run this algorithm. Thus, optimal solutions can be provided by updating the work schedule in the light of changing data.

In this developed application, relationships between the data of the project and the time-cost trade-off problem are established and remodeled with various construction options. The developed application will facilitate the reconstruction and optimization of the solution with up-to-date data by transferring progress reports to the application during the project. This application enables continuous improvement of projects according to the current situation, saving both time and cost, thus enabling flexible and efficient management of construction projects.

Critical activities are one of the most important components of the time-cost trade-off problem and they determine the total duration of the project within the framework of the Critical Path Method (CPM). The developed heuristic algorithm aims to reduce the project cost by accelerating the critical activities. Therefore, projects where the number of critical activities is few and the project structure is less complex can be solved with the proposed heuristic algorithm and successful results can be obtained. In projects with low complexity, the proposed algorithm can work more efficiently and find the optimum solution easily. However, in large projects where the number of critical activities is very high and the project structure has a high level of dependency, the expected success may not be achieved due to reasons such as the dynamic change of critical paths and the rapid increase in trade-off scenarios as different construction alternatives of the activities are selected. Moreover, occurrence of multi-critical path creates significant number of combinations and reduces the possibility of detecting the correct crashing option. Therefore, the method can be improved further as a future study.

Declaration of Ethical Standards

The authors confirm that this study adheres to all ethical standards, including proper authorship attribution, accurate citation, appropriate data reporting, and the publication of original research.

Credit Authorship Contribution Statement

All authors contributed equally to the design and development of the study. A.N. Şengül was responsible for the development of the spreadsheet model and manuscript drafting. N. Doğan contributed to the formulation and testing of the heuristic algorithm. Ö.H. Bettemir provided supervision, technical guidance, and critical revision of the manuscript.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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Data Availability

All data generated or analyzed during this study are included in this published article. Additional data may be available from the corresponding author upon reasonable request.

References

[1] Ballesteros-Pérez, P., Elamrousy, K. M., & González-Cruz, M. C. (2019). Non-linear time-cost trade-off models of activity crashing: Application to construction scheduling and project compression with fast-tracking. Automation in Construction, 97, 229-240.

[2] Banihashemi, S. A., & Mohammad, M. (2022). Time-cost-quality-risk trade-off project scheduling problem in oil and gas construction projects: fuzzy logic and genetic algorithm. Jordan Journal of Civil Engineering, 16(2).

[3] Jun, D. H., & El-Rayes, K. (2010). *Optimizing the utilization of multiple labor shifts in construction projects.* Automation in Construction, 19(2), 109-119.

[4] Bettemir, O., & Yücel, T. (2021). *Zaman maliyet ödünleşim probleminin en az insan müdahalesi ile oluşturulup çözülmesi.* Uludağ Üniversitesi Mühendislik Fakültesi Dergisi, 26(2), 461-480.

[5] Bettemir, Ö. H., & Yücel, T. (2023). Simplified solution of time-cost trade-off problem for building constructions by linear scheduling. Jordan Journal of Civil Engineering, 17(2).

[6] Bettemir, Ö. H., Gündüz, E., Akkurt, O., Efe, H., & Arslan, M. A. (2019). *Detection of Variability of Cash-Flow of Construction Activities Due To Schedule*. Mühendislik Bilimleri ve Tasarım Dergisi, 7(1), 211-223, 10.21923/jesd.459948.

[7] Bettemir, Ö.H., & Bulak, Ö. (2022). *İnşaat sürecinin iş çizelgelemesi, yönetimi ve optimizasyonu.* Teknik Dergi, 33(6), 12945-12986.

[8] Anagnostopoulos, K. P., & Kotsikas, L. (2010). *Experimental evaluation of simulated annealing algorithms for the time–cost trade-off problem.* Applied Mathematics and Computation, 217(1), 260-270.

[9] Cheng, M. Y., & Tran, D. H. (2015). Opposition-based Multiple Objective Differential Evolution (OMODE) for optimizing work shift schedules. Automation in Construction, 55, 1-14.

[10] Agarwal, A. K., Chauhan, S. S., Sharma, K., & Sethi, K. C. (2024). *Development of time–cost trade-off optimization model for construction projects with MOPSO technique.* Asian Journal of Civil Engineering, 1-11.

[11] Al-Shihabi, S., & AlDurgam, M. M. (2020). The contractor time–cost–credit trade-off problem: integer programming model, heuristic solution, and business insights. International Transactions in Operational Research, 27(6), 2841-2877.

[12] Maravas, A., & Pantouvakis, J. P. (2012). *Project cash flow analysis in the presence of uncertainty in activity duration and cost.* International journal of project management, 30(3), 374-384.

[13] Bettemir, Ö. H., & Talat Birgönül, M. (2017). Network analysis algorithm for the solution of discrete time-cost trade-off problem. *KSCE Journal of Civil Engineering*, *21*, 1047-1058.

[14] Akkoyunlu, M. C., & Engin, O. (2011). *Kesikli Harmoni Arama Algoritmasi İle Optimizasyon Problemlerinin Çözümü: Literatür Araştirmasi.* Selçuk Üniversitesi Mühendislik, Bilim ve Teknoloji Dergisi, 26(4), 140-148.

[15] Cura, T. (2008). Doğrusal olmayan küresel optimizasyon problemleri için tabu arama algoritmasının kullanılması. İstanbul Üniversitesi İşletme Fakültesi Dergisi, 37(1), 22-38.

[16] Turğut, P. (2008). *Tekil temellerin optimum tasarımında genetik algoritma kullanımı.* Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi, 14(2), 213-222.

[17] Öztürk, A., & Duman, S. (2009). *Genetik Algoritma Kullanilarak Güç Sistemlerinde Optimal Çalişma Şartlarinin Belirlenmesi.* Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi, 24(3).

[18] Acar, E. (2021). Genetik algoritma kullanımı ile farklı getiri ölçümlerindeki yatırım optimizasyonu problemi. İnsan ve Toplum Bilimleri Araştırmaları Dergisi, 10(1), 266-288.

[19] Ammar, M. A. (2011). *Optimization of project time-cost trade-off problem with discounted cash flows.* Journal of Construction Engineering and Management, 137(1), 65-71.

[20] Bettemir, Ö. H., & Birgonul, M. T. (2025). Solution of discrete time–cost trade-off problem with adaptive search domain. Engineering, Construction and Architectural Management, 32(2), 1032-1052.