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Simplified Solution of Time-Cost Trade-off Problem for Building Constructions by Linear Scheduling

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ABSTRACT

Time-cost trade-off is an important optimization problem for contractors, because its optimum solution minimizes the total project cost. Formation of the time-cost trade-off problem causes an important workload, since the problem requires preparation of different construction cost and duration alternatives of the activities. Previous studies focused on the optimum solution of the problem and ignored the difficulties of the preparation of the different construction alternatives for the activities, which is a very difficult task for contractors. In this study, the creation of construction alternatives consisting of different time and cost values is automated. Quantity take-off of construction items is computed by user-defined dimensions of structural elements. Workmanship and material requirements are computed by pre-defined job descriptions and quantity take-off values. Different construction alternatives are formed by assigning different crew sizes and the corresponding construction durations are computed by estimating the job efficiency of the crew by regression models derived from the literature. Precedence relationships of the main construction items are pre-defined and the construction schedule is formed by a line of balance in terms of work days. The problem is optimized by a genetic algorithm the parameters of which are fine-tuned by experimental design. The developed approach is implemented on a spreadsheet application and the total optimization process including data entry is completed in one and a half hour on a desktop computer with i5 CPU. This study contributes to relevant literature by proposing a systematic approach for the formation of construction alternatives of the time-cost trade-off problem. The proposed approach can be beneficial for contractors and project managers to form and solve the time-cost trade-off problem with minimum endeavor and cost.

KEYWORDS: Time-cost trade-off, Genetic algorithm, Line of balance, Optimization, Experimental design.

INTRODUCTION

There is an inverse correlation between the completion time of activities and their direct costs. The shortening of activity duration can be accomplished by assigning more staff, utilizing larger or more construction machines or working overtime. In addition to this, construction methods which cost more than traditional methods but enable the completion of construction works in a shorter time is sometimes preferred. This approach shortens the activity duration in exchange for a rise in direct costs. Utilization of tunnel formwork and tower crane instead of conventional wooden formwork or the acceleration of ground consolidation with electrolysis instead of applying surcharge load can be given as examples of more expensive but faster construction techniques. Consequently, the completion of an activity earlier than its normal time causes an increase in its direct cost. Accelerating activities increases direct costs, but shortens the project duration, which reduces the indirect costs consisting of the security, cleaning, lighting, … etc. costs of the construction site. A trade-off needs to be made between the increase in direct costs and the sum of benefits which are the reduction in the total indirect cost, as well as the income obtained by completing the project before the scheduled completion time. Time-cost

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trade-off problem (TCTP) aims to prepare a construction schedule which provides the minimum total cost. Because of the importance of the problem, obtaining the optimum solution of the problem is thoroughly examined in the literature.

Initial solutions to the TCTP consist of manual calculation techniques (Kelley and Walker, 1959; Fulkerson, 1961; Kelley, 1961). Barber and Boardman (1988) proposed heuristic algorithms with linear cost curves for the solution of the TCTP. The mentioned algorithms provide the optimum solution for continuous crashing cost functions, but they do not guarantee convergence to the global optimum for non-linear or discrete crashing alternatives. Consequently, beside the heuristic methods, meta-heuristic algorithms are also implemented for the solution of the TCTP. Hooshyar et al. (2008) presented an algorithm with a smart mutation operator to solve the TCTP. Eshtehardian et al. (2009) adapted a GA for the solution of the discrete fuzzy TCTP. Lee et al. (2010) implemented a GA for the solution of the TCTP. Bettemir (2009) as well as Sonmez and Bettemir (2012) and Bettemir and Sonmez (2015) utilized genetic algorithms with simulated annealing for the solution of the TCTP.

Sakellaropoulos and Chassiakos (2004) solved the TCTP by considering the activity priority relationships and time constraints on the activities. Ammar (2011) established a TCTP to maximize the net present value of the cash flow. Ke et al. (2009) and Ke (2014) solved the stochastic TCTP by creating a hybrid intelligent algorithm combining stochastic simulation and genetic algorithm. Kang et al. (2015) formed a TCTP which considers FS, FF, SS and SF precedence relationships between activities. Bettemir and Bulak (2022) solved the TCTP by considering non-working days and the effect of climate.

Tareghian and Taheri (2007) solved the time-cost-quality trade-off problem with the scattered electromagnetism algorithm. Yang (2007) and Rahimi and Iranmanesh (2008) solved the discrete TCTP with particle-swarm optimization algorithm. Anagnostopoulos and Kotsikas (2010) implemented simulated annealing, Geem (2010) utilized harmony search to solve the TCTP. Kim et al. (2012) proposed mixed integer linear programming that takes into account the potential loss of quality for the crashed activities. Zhang and Thomas Ng (2012) solved the TCTP by ant-colony optimization algorithm. Cha and Lee (2015) prepared a building information modeling (BIM)-based model to solve the TCTP. Bettemir and Birgönül (2016) proposed a network-analysis algorithm (NAA) inspired by the minimum-cost curve for the solution of discrete TCTP. The proposed NAA eliminates the inappropriate crashing options and reduces the search domain.

TCTP has many variants. Zhang and Xing (2010), Mungle et al. (2013), Tavana et al. (2014) and Wang et al. (2019) added quality. Banihashemi and Khalizadeh (2022) added quality and risk to the TCTP and solved the generated problem. Monghasemi et al. (2015) investigated the effects of activity crashing on time, cost and quality parameters.

Hegazy and Ersahin (2001) proposed an integrated scheduling approach which considers the solution of the TCTP, resource allocation, resource leveling and cash-flow optimization problems. Moussourakis and Haksever (2004) solved the resource-constrained TCTP with a fixed project deadline. Chen and Weng (2009) implemented a GA to solve the resource-constrained TCTP. Senouci and El-Rayes (2009) presented a multi-objective optimization model for establishing an efficient resource utilization and construction schedule. Afruzi et al. (2014), Rostami et al. (2014) and Cheng and Tran (2016) solved the resource-constrained TCTP. Al-Shihabi and AlDurgam (2020) added the credit-limit parameter to the TCTP and solved the problem by integer linear programming.

A contract should distribute risks fairly (Shehadeh et al., 2022). Governmental instruments may ease the execution of necessary construction facilities (Alshboul et al., 2022). This may reduce the adverse consequences of COVID-19 on construction firms (Shehadeh et al. 2022). Determination of project duration accurately is important, since delays can lead to liquidation damages (Alshboul et al., 2022).

Abdel-Basset et al. (2020) designed a framework to address the scheduling problem aiming to minimize project costs under uncertain environmental conditions by using neutrosophic numbers to estimate activity durations. Albayrak (2020) proposed a hybrid algorithm by embedding GA operators into the standard PSO to solve the TCTP. The hybrid algorithm has better diversity and search capabilities. Liu et al. (2020) solved the least-cost project deadline problem by the discrete symbiotic organism search algorithm, which mimics the symbiotic interaction among organisms in the ecosystem. Bettemir and Yücel (2021) developed an application for the solution of the TCTP.

The literature review illustrates that TCTP is thoroughly studied by researchers. However, to form the TCTP, it is necessary to prepare crashing alternatives for the activities in addition to the normal construction modes. The formation of a crashing alternative requires calculating the resource requirements for the assigned activity duration and performing cost analysis. Bid preparation or planning steps have very tight timetables; therefore, performing several time and cost analyses for every construction activity creates an important amount of workload and stress on construction managers. Consequently, during the preparation of the construction schedule, a few crashing alternatives could be formed for some of the activities and the construction alternatives that would affect the result might be neglected in order to decrease the workload of the formation of the TCTP. The mentioned drawback significantly reduces the implementation of the TCTP for construction scheduling.

This study proposes a framework to prepare and solve the TCTP for building constructions with minimum human endeavor to eliminate the afore-mentioned shortcomings. A spreadsheet application is prepared to compute the quantity take-off (QTO) of the construction items with minimum data entrance from the user. Job definitions of frequently utilized construction items are defined to the spreadsheet application and they are matched with the corresponding QTO data. The workmanship and material requirements are computed by considering the QTO data and the related job definitions.

In the literature, efficiencies of the workers *versus* crew size relationships for construction items exist. These models are based on regression or artificial neural-network models (Sanders and Thomas, 1993; Thomas and Sakarcan, 1994; Sonmez and Rowings, 1998).

In this study, construction alternatives are formed by assigning different crew sizes for the execution of the task and the job efficiency is determined by considering the crew size. The construction duration of the activity was computed by considering the required workmanship, crew size and job efficiency. This approach automates the preparation of the crashing alternatives. Furthermore, in this study, a framework which creates different construction alternatives consisting of construction duration and crew size was also developed. The precedence relationships among the construction activities are defined and the automated scheduling application which prepares the construction schedule of a multi-story building is prepared by the line of balance method. The overhead cost and opportunity cost of the construction are defined as the final data to form the TCTP. The problem is solved by a GA which is programmed by Visual Basic programming language.

The developed framework significantly reduces the required cost, endeavor and time to prepare the TCTP. The proposed approach would encourage especially small-and medium-size contractors to solve the TCTP to minimize their construction costs. The mentioned target group cannot employ high skilled project planners which can implement advanced project-planning techniques (Okudan et al., 2022). The utilization of the proposed approach would reduce the total construction cost and may increase the profits of small- and medium-size contractors. This would reduce their vulnerabilities against natural disasters or pandemics.

Beside the provided benefits, the proposed approach has some limitations. The main limitation of the framework is the requirement of a manual data entrance which is error-prone and time-consuming. An automated data-import property should be added to the framework. The quantity take-off computations assume that the structural and architectural elements have simple and regular shapes and connections, which may not always be the case. Therefore, a more robust QTO algorithm should be developed and implemented. The scheduling algorithm assumes that the QTO of construction items and thus the corresponding activity durations are the same at each floor. A resourceful scheduling algorithm should be developed to take different workmanship requirements into account without increasing the number of parameters. The mentioned drawbacks can be eliminated as a future study to improve the benefits of the proposed approach.

In the following section of the manuscript, preparation of the construction alternatives, implementation of GA for the solution of the TCTP and determination of GA parameters are explained. Thereafter, the feasibility of the proposed method is shown by a case study and then, the results are presented and discussed, showing the benefits and the shortcomings of the method used.

METHODOLOGY

In this study, a framework is developed to calculate the quantity take-off of construction items, to estimate the resource requirements of the activities, to prepare the construction schedule, to generate different construction alternatives and to prepare the construction schedule which provides the minimum total project cost by solving the TCTP. The quantity take-off of construction items is computed according to the entered data which defines the dimensions of the structural and architectural elements. Span lengths, column and beam dimensions, wall thicknesses, slab thickness, spacing, diameters and lengths of the reinforcement bars, length and spacing of stirrups, door-window dimensions and other relevant data are defined. The data representing the dimensions of structural elements is stored as variables. Parametric computation automatically updates the quantity take-off values. This prevents manual recalculations because of design changes and reduces the human endeavor through the construction planning phase. This is an important benefit, because frequent design changes affect the success of the project (Ibrahim and Elshwadfy, 2021). However, the implementation of the developed framework is limited to apartment-or residence-type buildings the floor plans of which do not change at each floor.

QTO of concrete, reinforcement steel, formwork, interior and exterior walls, plastering, painting and floor covering is computed by pre-defined QTO formulations. To illustrate, the length of the pleated reinforcement is computed by assuming the length of penetration to neighboring slabs as 2 meters, since it is difficult to detect the span of the neighboring slab without forming semantic relationships. The details of the computations can be obtained from Bettemir et al. (2019), Yücel (2019) and Bettemir (2018).

In order to simplify the scheduling computations, the quantity take-off data was assumed to be the same for each floor of the building. This makes the implementation of the line of balance scheduling possible, since the workmanship requirement becomes the same at each floor, which simplifies the optimization process by reducing the number of parameters. Each construction item, such as masonry, plastering, painting and floor covering, is represented by one parameter which is the construction duration of the corresponding item for one floor.

Constant workmanship assumption decreases the number of parameters to prepare the construction schedule to 1 nth compared with variable activity durations at each floor, where n is the number of floors. If the durations of the activities are allowed to change at each floor, the linearity of the schedule will be deteriorated. This would change the method to Critical Path Method (CPM), where the duration of each activity is a parameter and the predecessor relationships are defined for each activity. This situation causes the determination of values of hundreds of parameters during the optimization process. The possibility of obtaining the optimum solution decreases when the optimization process is complicated. The uncertainties of the labor productivity and other factors which affect the duration of construction are higher than the uncertainty caused by the mentioned assumptions.

Quantity take-off values obtained for each construction item are matched with the relevant job descriptions to compute the amount of material, workmanship and machinery necessary to carry out the construction item. Computations of the mentioned requirements are illustrated in Eq. 1.

$$\begin{aligned} Man.hour_i &= QTO_i * UWR_i \\ Machine.hour_i &= QTO_i * UMaR_i \\ Material_i &= QTO_i * UMR_i \end{aligned} \qquad (1)$$

In Eq. 1, i represents the i^{th} construction item, UWR, $UMaR$ and UMR are the unit workmanship, unit machine-hour and unit material requirements for the i^{th} construction item, respectively. QTO_i is the quantity take-off amount of the i^{th} construction item. The mentioned unit quantities are obtained from the job description of the corresponding construction item. The crashing alternatives are formed by Eq. 2.

$$D_{i,j} = \left\lceil \frac{Man.hour_i}{DWT * CS_j * \eta_j} \right\rceil \qquad (2)$$

In Eq. 2 $D_{i,j}$ is the duration of the j^{th} construction mode of the i^{th} construction item, DWT is the daily working time in terms of hours, CS_j is the crew size of the j^{th} construction mode and η_j is the job efficiency of the j^{th} construction mode. In Eq. 2, the mathematical symbol $\lceil\ \rceil$ represents the round-up operator. The job efficiency is computed by the approximation of the regression model of Sonmez and Rowings (1998) represented in Eq. 3.

$$\eta = 1.25 - 0.038(CS - 2) \tag{3}$$

In this study, the construction alternatives are prepared by taking the crew sizes as 3, 5, 7, 9, 11, 13, 15 and 17. This approach produces 8 construction alternatives for each construction item. Material cost is assumed to be not affected by the construction duration. The labor costs of the construction items are computed as given in Eq. 4.

$$LC_{i,j} = CS_j * D_{i,j} * ULC_i \tag{4}$$

In Eq. 4, $LC_{i,j}$ is the labor cost of the the j^{th} construction mode of the i^{th} construction item, ULC_i is the unit labor cost of the i^{th} construction item. The unit prices of each construction worker, construction material and construction machinery are user-defined. The construction alternatives are prepared by implementing Eqs. 1 to 4 for each construction item.

In order to reduce the number of parameters in the optimization process, the line of balance scheduling method was implemented because of the existence of repetitive activities on each floor. The linear schedule was prepared in two phases. In the first phase, formwork, reinforcement works, scaffolding for the formwork, concreting, removal of formwork and curing tasks are grouped as reinforced-concrete works. Masonry, mechanical, electrical and plumbing (MEP) works, plastering, painting, door and window frames, ceramic and parquet floor covering tasks are handled as unique activities. The activities are assumed to be executed from the ground floor to the top floor without interruption. The start time of an activity is computed as given in Eq. 5.

$$START_i = MAX\left\{\left(START_{i\_pred} + BT + D_{i\_pred,k}\right);\left(FINISH_{i\_pred} + BT - (F-1) * D_{i,j}\right)\right\} \tag{5}$$

In Eq. 5, $START_{i\_pred}$ represents the start time of the predecessor of the i^{th} activity, BT is the buffer time added in order to ensure the prevention of spatial conflicts, $D_{i\_pred,k}$ is the duration of the predecessor of the i^{th} activity in its k^{th} construction mode, $FINISH_{i\_pred}$ is the finish time of the predecessor of the i^{th} activity, F is the number of floors of the building. The first precedence relationship defined in Eq. 5 allows the start of the successor activity if only its predecessor is finished at the entrance floor. The second precedence relationship permits the start of the successor activity at the top floor if only the predecessor activity is finished at the top floor. The first logical expression ensures that the predecessor activity has already been finished and the successor activity can start at the entrance floor. The second logical case is necessary, because if the successor activity is executed faster than the predecessor activity, the successor activity may be able to catch up with the predecessor activity after the construction of several floors. The latest of the two computed times is assigned as the start time of the activity. Finish time of the i^{th} activity with the j^{th} construction mode is computed by Eq. 6.

$$FINISH_i = START_i + F * D_{i,j} \tag{6}$$

The construction schedule is prepared and the construction duration is determined when the start and finish times of all of the activities are determined.

Linear scheduling (LS) is an appropriate method for the scheduling of construction projects consisting of repetitive activities, such as high-rise building construction. The construction schedule can be prepared swiftly by organizing the work items by only considering the corresponding activity’s start time at the first floor and finish time at the last floor. The number of floors does not complicate the scheduling task. In this study, activities are not allowed to be interrupted and spatial overlaps are prevented by adding buffers. However, activity durations should be determined appropriately to prevent an impractical construction schedule. Figure 1 illustrates the linear schedule of a 20-floor hypothetical building construction in which the durations of the activities are incompatible.

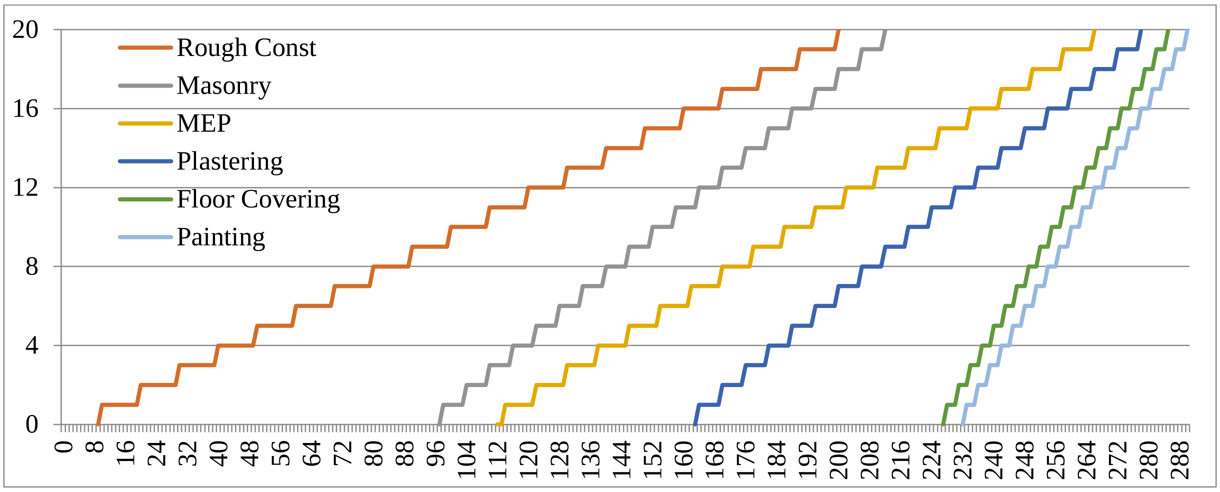

Figure (1): Linear schedule of a 20-floor hypothetical building construction

In Figure 1, masonry is executed faster than rough construction; therefore, its commencement is delayed to prevent a spatial overlap. Activity MEP runs slower than masonry; therefore, there is a long time gap between the finish times of masonry and MEP activities. The afore-mentioned time gaps between the start times of rough construction and masonry as well as finish times of masonry and MEP extend the duration of the construction project. Line of balance (LoB) provides an improved schedule by organizing the durations of the activities. The activity durations are kept as close as possible to each other to minimize time lags between consecutive activities. The balanced construction schedule of the same construction project is shown in Figure 2.

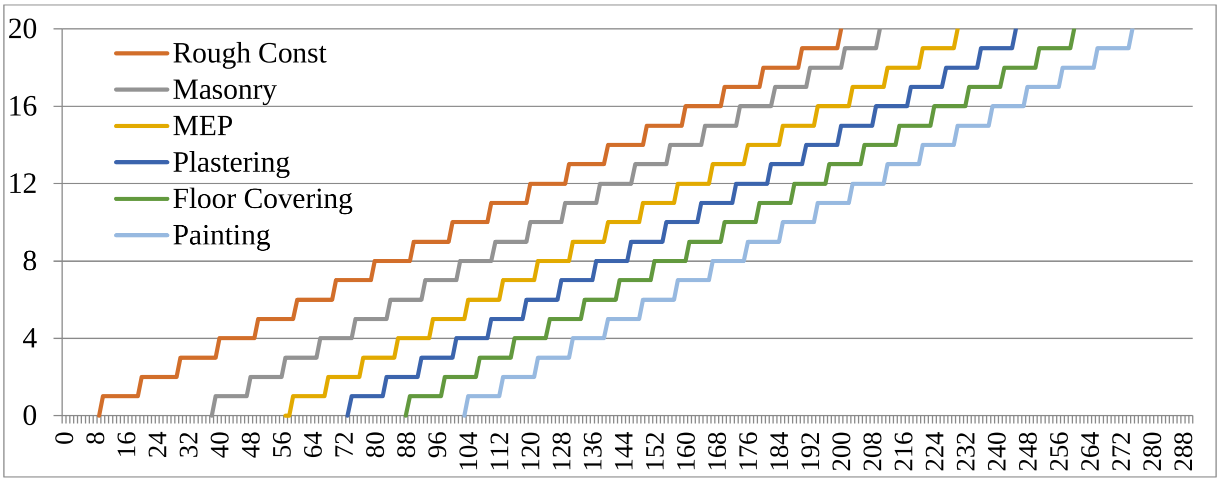

Figure (2): Balanced schedule of a 20-floor hypothetical building construction

In Figure 2, all of the activities are executed at the same rate except for rough construction which runs one day slower than the other activities. Figure 2 illustrates that LoB minimizes the time lags between the activities. Project duration is shortened even though many activities are implemented slower than the previous case. However, all of the activities cannot be executed at the same rate, since the workmanship requirements or the difficulties of the activities are not the same.

In LS or LoB, precedence relationships among the activities are defined in a location-based manner to prevent spatial conflicts. The successor activity can begin if its predecessor is completed and the predefined buffer time expires. The classification of activities as critical or non-critical is not possible, since every activity is critical and the scheduling is complex because of the defined relationships in Eq. 5 and Eq. 6. This is because crashing or retarding an activity can prolong the project completion time. In Fig. 2, if an activity is crashed, its start time and thus the start times of its successors will be delayed. If an activity is retarded, its finish time will be delayed as expected. Determination of the most appropriate activity durations is a challenge. Crashing an activity increases the total labor cost of the activities. If the mentioned crashing is compatible with the durations of the remaining activities, the duration of the project shortens. The decision requires a trade-off between the cost of the activities and the duration of the project. The construction duration is converted into money by considering the overhead cost and the opportunity cost of the construction. The time cost trade-off problem defined in Eq. 7 aims to minimize the objective function.

$$min\sum_{i=1}^{n}\left(\sum_{j=1}^{m}\left(LC_{i,j}*\delta_{i,j}\right)+CC_i\right)+T*\left(OH+OC\right) \tag{7}$$

In Eq. 7, $\delta_{i,j}$ represents the Kronecker delta function and ensures that the labor cost of only the assigned construction mode is added. CC_i is the constant cost items such as material costs for the i^{th} activity, T is the project duration, OH is the daily overhead cost and OC is the daily opportunity cost, m is the number of construction alternatives. The restrictions are defined in Eqs. 8 and 9.

$$\sum_{j=1}^{m}\delta_{i,j}=1 \tag{8}$$

$$\delta_{i,j}\in\{0,1\} \tag{9}$$

The daily overhead cost fluctuates during the construction period, but to simplify the problem, an average daily value of indirect costs is assigned for *OH* and it is assumed to remain constant throughout the construction.

In this study, the TCTP is formed by considering the total labor cost paid to the workers, the general expenses of the construction and the total rental income to be obtained after the completion of the construction. A specified deadline is not considered. The search space consists of a combination of 8 different construction alternatives, which can be assigned to rough construction, masonry, MEP, exterior and interior plastering, exterior and interior painting and floor-covering works. The total project cost is calculated by summing the labor costs, general expenses and the opportunity cost of the facility. It is aimed to obtain the construction schedule which gives the lowest total cost.

The minimum of the objective function is searched by the GA. The implementation of the GA consists of accomplishments of the population generation, crossover, mutation and natural-selection operators. The population is formed by individuals consisting a potential feasible solution for the analyzed problem. The individuals represent the assigned values for the input parameters of the problem. In this study, the input parameters are the eight different construction modes defined for each construction item. Therefore, an integer random number between 1 and 8 is generated to assign the construction mode for each activity. This procedure is repeated number of activity times to produce an individual. Then, the population is formed by generating the population size comprising many individuals.

The quality of the individuals is improved by the crossover and mutation operators. The crossover operator couples randomly selected two individuals which are parents and pairs them by selecting a random location of the individuals. Coupling is executed by sorting the individuals according to the value of the objective function computed by Eq. 7. Then, corresponding crossover coupling value is computed by Eq. 10.

$$COCV_i=\left(1.5*P-RANK_i\right)*\left(2+rand(1)\right) \tag{10}$$

In Eq. 10, $COCV_i$ is the crossover coupling value of the i^{th} individual, P is the population size, $RANK_i$ is the rank of the i^{th} individual sorted ascendingly according to the value of the objective function, *rand (1)* is a randomly generated real number between 0 and 1. The coupling is done by matching the first and second individuals, i^{th} and $i+1^{st}$ individual … etc. The coupling is executed until the *crossover ratio * population size* individuals are coupled. The mentioned coupling function always couples the population best even though the smallest random number is generated for the population best. If zero is generated for the population best, the population best still surpasses the worst half of the population even though one is generated for it. Consequently, the coupling function given in Eq. 10

ensures the involvement of better quality individuals in the crossover operator and couples the individuals randomly. An integer random number between 1 and the number of parameters is generated for every matched couple to detect the crossover point. Two new individuals are generated by swapping the assigned construction modes at the crossover point. The computation of the objective functions of the new individuals finishes the crossover operator.

Real random numbers between 0 and 1 are generated for each individual to detect the individuals to be mutated. The individuals are sorted in ascending order and the first *mutation rate * population size* individuals are mutated. One integer random number between 1 and the number of parameters is generated for each selected individual to detect the position of the mutation. Another integer random number is generated between -1 and 1 to determine the change in the activity-execution mode. The execution mode of the corresponding activity is incremented by 1 if the random number is equal to 1 and *vice versa*. The computation of the objective functions of the mutated individuals finishes the mutation operator.

The natural selection operator terminates as many individuals as the sum of the individuals generated by the crossover and mutation operators. The individuals are sorted according to their objective function values and survival values are assigned as given in Eq. 11.

$$SV_i = \left(1.5 * P * (1 + COR + MR) - RANK_i\right) * \left(2 + rand(1)\right) \tag{11}$$

In Eq. 11, SV_i is the survival value of the i^{th} individual, COR is the crossover rate and MR is the mutation rate. The individuals are sorted descendingly according to their SV_i values. The first population-size individuals are kept and the remaining ones are terminated. This completes one cycle of the GA and the GA cycles are repeated until the stopping criteria are met.

Experimental Design

The assigned values for the population size, crossover and mutation rate affect the success of the optimization process. Therefore, the experimental design is conducted to determine the suitable values for the afore-mentioned parameters. Details of the experimental design can be obtained from Bettemir (2011). The analysis is conducted by examining [100 and 150] for the population size, [0.5; 0.7; 0.9] for the crossover rate and [0.05; 0.10; 0.20] for the mutation rate. The examined values make 18 combinations. Each combination is repeated 5 times and the averages of the obtained values are given in Figure 3. The optimization process is stopped when the number of schedule evaluation reaches 10000.

Figure 3 provides valuable information related to the crossover and mutation rates. The GA provides better results when intermediate values are assigned for both the crossover and mutation operators. The optimization process gives worse results when marginal values are assigned to the parameters. The total cost reduces when the population size is taken as 150 instead of 100. The significance of the results is measured by conducting a hypothesis test and the test results are illustrated as a bar chart in Figure 4.

The hypothesis test reveals that increasing the population size decreases the objective function. The significance of the decrease is valid for $\alpha=0.005$. Increasing the crossover value may reduce the objective function, but the result is not significant. Increasing the mutation rate increases the objective function when the significance interval is taken as 5%. The cross-correlation of the parameters is not significant, but it can be inferred that increasing all of the input parameters might have a beneficial correlative effect. The best result is obtained when crossover rate is 70%, mutation is 10% and population size is 150. The authors suggest assigning the mentioned values for the optimization process. The graphs represented in Figures 3 and 4 support that the obtained results are not coincident.

CASE STUDY

The proposed approach is implemented on a hypothetical facility which consists of 15 stories. Data given in Table 1 is entered to the developed spreadsheet application to compute the QTO values.

QTO values are computed by the pre-defined volume and void computation procedures for each construction item. The QTO values are also computed manually and it is seen that the deviation from the exact values is around 2% to 5% (Yücel, 2021). The mentioned values are less than the error margins of the state-of-the-art commercial QTO software (Ergen and

Bettemir, 2022; 2023).

QTO values are multiplied by the corresponding job definitions as defined in Eq. 1 and workmanship requirements are computed. Workmanship requirements are obtained from the unit-price index values published by the Ministry of Environment, Urbanization and Climate Change of the Turkish Republic (MEUCCTR). The utilized values may deviate from the workmanship requirements of the construction firms. In this case, each contractor can enter his/her unit workmanship values.

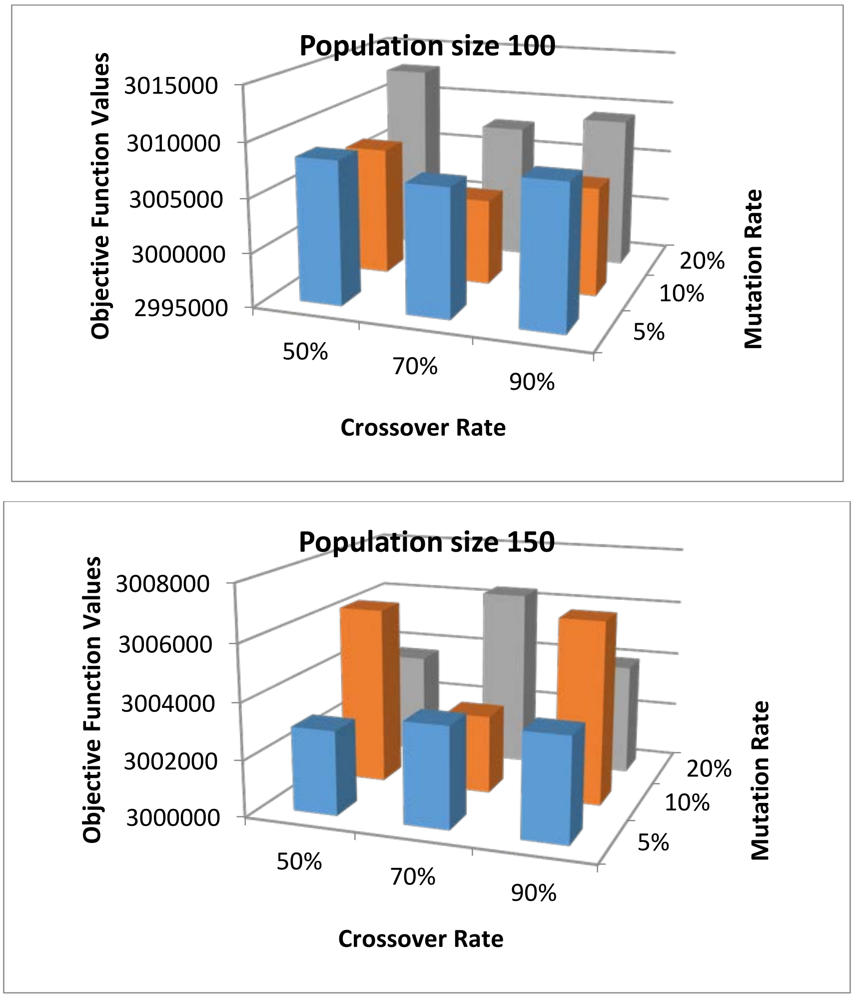

Figure (3): Results of experimental design

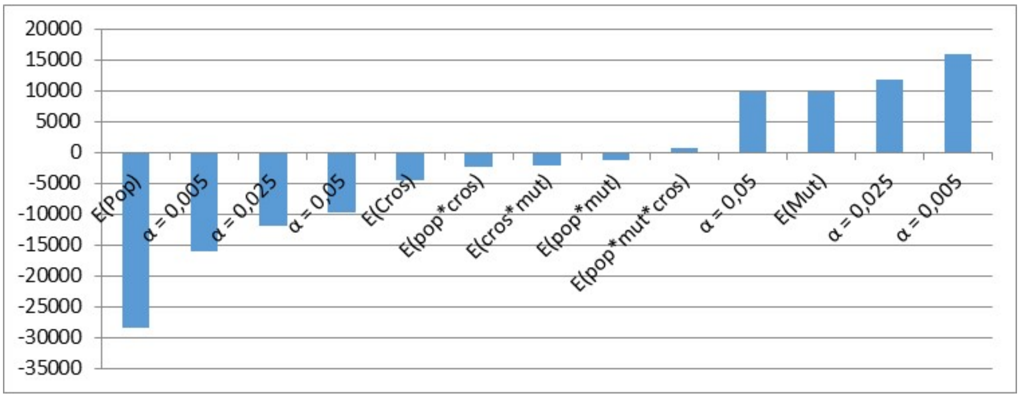

Figure (4): Significance of the results of the experimental design

Table 1. Entered data for the quantity take-off

Project Data			Beam Longitudinal Bar	4	Ø16	**Data of Door-Window-Wall**		
Span Length of A	700	cm	Beam mounting rebar	2	Ø12	Width of Entrance Door	300	cm
Span Length of B	650	cm				Height of Entrance Door	230	cm
Span Length of C	600	cm	Rebar spacing at slabs	30	cm			
Span Length of D	550	cm	Bent-up spacing at slabs	30	cm	Width of Window Type 1	400	cm
Span Length of E	625	cm				Height of Window Type 1	160	cm
Dilation	10	cm	Ø8	0,395	kg/m	Thickness of W. Frame Type 1	12	cm
			Ø10	0,617	kg/m	Width of Window Type 2	50	cm
Data for Concrete Q. Take-off			Ø12	0,888	kg/m	Height of Window Type 2	50	cm
Width of Column	70	cm	Ø14	1,208	kg/m	Thickness of W. Frame Type 2	7	cm
Length of Column	70	cm	Ø16	1,578	kg/m			
Wid. of Co. at Dilation	35	cm	Ø18	1,998	kg/m	Height of Lintel	20	cm
Len. of Co. at Dilation	70	cm						
Floor Height	300	cm	Stirrup Spa. at Col-Beam	10	cm	Thick. Exterior Wall	25	cm
Thickness of Beam	70	cm	Stirrup Spacing at Jo.	8	cm	Thick. Interior Wall	15	cm
Width of Beam	30	cm	Stirrup Sp. at Midspan	12	cm			
Thick. of Shear Wall	30	cm	Anchorage Length	20	cm	Height of Door Type 1	210	cm
Thickness of Slab	16	cm	Length of Stirrup (Bs F)	288	cm	Width of Door Type 1	100	cm
Height of Fire Doors	210	cm	No. of Long. Reinf.	24		Thick. Door FrameType 1	3	cm
Width of Fire Doors	110	cm				Width. Door FrameType 1	12	cm
Width of Elevator	200	cm	Stirrup Spa. at Jo.	10	cm			
Length of Elevator	400	cm	St. Spa. at Mdsp. (Beam)	20	cm	Height of Separator Walls	230	cm
Thick. of Elv. Sh. Wl.	20	cm	Beam Long Reinf. (Top)		4Ø14	Length of Separator Walls	200	cm
			Beam Long Reinf.		4Ø18	Thick. of Separator Walls	10	cm
Data for ReinF QTO			Anchorage L. (Beam)	15	cm	No. of Toilets	6	
Concrete Cover Bel. G	4	cm	Length of Stirrup (Beam)	198	cm	Width of Window Type 2	90	cm
Concrete Cover Av. G	3	cm				Height of Window Type 2	210	cm
Column Reinforcement	24	Ø16	Length of Stirrup (U. Fl)	296	cm	Thickness of W. Frame Type 2	2	cm
Lap Splice Length	110	cm	Length of Stirrup (Beam)	206	cm			
Stirrup Spacing at Jo.	6	cm				Thick. of Separator Walls Ty 2	10	cm
Stirrup Sp. at Midspan	12	cm	Shear-wall X Dir. Spacing	20	cm			
Diameter of Stirrup	8	mm	Shear-wall Y Dir. Spacing	30	cm	Height of Baseboard	8	cm
			Lap Splice L. (Ver SW)	60	cm			
			Lap Splice L. (Hor SW)	52,5	cm			

The daily wages of workers are taken as \$160 for the form worker, \$170 for the reinforcing iron and rebar workers, \$130 for the mason, \$140 for the laminate parquet floorer, \$140 for the ceramic tile floorer, \$140 for the granite floorer, \$150 for the plasterer and \$155 for the painter. Cost and duration of the construction alternatives are computed by implementing Eqs. 2 to 4. Computed construction alternatives are presented in Table 2.

The examined structure is a typical apartment-type building. The same construction plan is used at each floor to limit the construction costs. Therefore, constant QTO assumption becomes valid for the apartment buildings constructed for the middle-income class.

The TCTP is defined with 3000\$ daily overhead and opportunity cost. The schedule contains 19 activities which have 8 construction alternatives. The mentioned problem makes 8^{19} feasible scheduling alternatives. The optimization is conducted by 150, 10%, 70% assigned GA for the population size, mutation and crossover, respectively. The optimization process is terminated after performing 10.000 schedule evaluations and the obtained convergence graph is presented in Figure 5.

The optimization process provides the {4, 6, 6, 1, 2, 2, 1, 2, 1, 1, 2, 4, 1, 3, 1, 5, 7, 1, 4} crashing alternatives as the obtained best solution. The start and finish times of the activities with respect to work day are given in Table 3.

Table 2. Automated prepared construction alternatives for each construction activity

	1st Alt			2nd Alt			3rd Alt			4th Alt			5th Alt			6th Alt			7th Alt			8th Alt		
Job ID	**Dur**	**CS**	**Cost**	**Dur**	**CS**	**Cost**	**Dur**	**CS**	**Cost**	**Dur**	**CS**	**Cost**	**Dur**	**CS**	**Cost**	**Dur**	**CS**	**Cost**	**Dur**	**CS**	**Cost**	**Dur**	**CS**	**Cost**
1	39	3	18720	25	5	20000	19	7	21280	16	9	23040	15	11	26400	14	13	29120	13	15	31200	13	17	35360
2	30	3	14400	19	5	15200	15	7	16800	13	9	18720	11	11	19360	10	13	20800	10	15	24000	10	17	27200
3	30	3	14400	19	5	15200	15	7	16800	13	9	18720	11	11	19360	10	13	20800	10	15	24000	10	17	27200
4	19	3	9690	13	5	11050	10	7	11900	8	9	12240	7	11	13090	7	13	15470	7	15	17850	6	17	17340
5	17	3	8670	11	5	9350	9	7	10710	7	9	10710	7	11	13090	6	13	13260	6	15	15300	6	17	17340
6	17	3	8670	11	5	9350	9	7	10710	7	9	10710	7	11	13090	6	13	13260	6	15	15300	6	17	17340
7	10	3	3900	6	5	3900	5	7	4550	4	9	4680	4	11	5720	4	13	6760	3	15	5850	3	17	6630
8	12	3	4680	8	5	5200	6	7	5460	5	9	5850	5	11	7150	4	13	6760	4	15	7800	4	17	8840
9	9	3	3510	6	5	3900	5	7	4550	4	9	4680	4	11	5720	3	13	5070	3	15	5850	3	17	6630
10	9	3	3510	6	5	3900	5	7	4550	4	9	4680	4	11	5720	3	13	5070	3	15	5850	3	17	6630
11	7	3	2940	4	5	2800	3	7	2940	3	9	3780	3	11	4620	3	13	5460	2	15	4200	2	17	4760
12	9	3	3780	6	5	4200	5	7	4900	4	9	5040	4	11	6160	4	13	7280	3	15	6300	3	17	7140
13	10	3	4200	7	5	4900	5	7	4900	4	9	5040	4	11	6160	4	13	7280	4	15	8400	4	17	9520
14	9	3	3780	6	5	4200	4	7	3920	4	9	5040	3	11	4620	3	13	5460	3	15	6300	3	17	7140
15	9	3	3780	6	5	4200	5	7	4900	4	9	5040	4	11	6160	3	13	5460	3	15	6300	3	17	7140
16	38	3	17100	25	5	18750	19	7	19950	16	9	21600	14	11	23100	13	13	25350	13	15	29250	12	17	30600
17	40	3	18000	26	5	19500	20	7	21000	17	9	22950	15	11	24750	14	13	27300	13	15	29250	13	17	33150
18	18	3	8370	12	5	9300	9	7	9765	8	9	11160	7	11	11935	6	13	12090	6	15	13950	6	17	15810
19	19	3	8835	13	5	10075	10	7	10850	8	9	11160	7	11	11935	7	13	14105	7	15	16275	6	17	15810

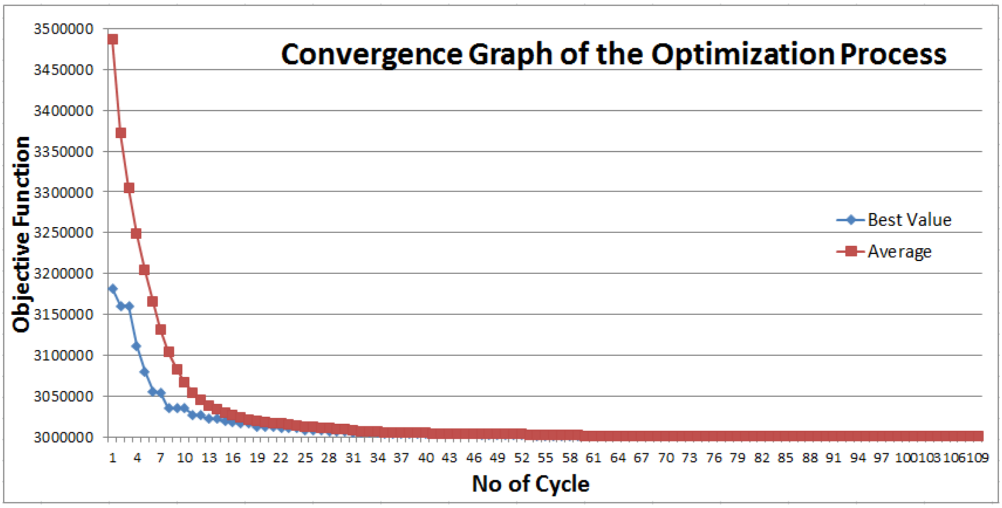

Figure (5): Convergence graph of the optimization process

Table 3. Activity start and finish times of the activities after the optimization process

Activity	Start	Finish
Excavation and Insulation	1	33
Reinforced Concrete Structure	34	340
Interior Masonry	218	348
MEP	259	354
Plastering	279	488
Painting	358	496
Flooring (Parquet)	436	500
Flooring (Ceramic)	430	500

DISCUSSION OF RESULTS

In this study, a framework to prepare and solve the TCTP is developed and tested. The framework computes the bid of quantities (BoQ) with minimum human endeavor, estimates the workmanship requirements of the construction activities and prepares different construction cost and duration alternatives for each activity. The framework prepares the construction schedule by considering the pre-defined precedence relationships among the activities. The construction schedule is optimized by a fine-tuned GA and total project cost is reduced. The developed framework is programmed as a spreadsheet application and the optimization process is executed by a macro-script. The proposed approach provides golden opportunities for small - and medium-scale contractors who do not use automated quantity take-off software and do not implement BIM or sophisticated project-management techniques.

The proposed approach provides very accurate QTO results comparable with the accuracies of the state-of-the-art QTO software. The proposed approach requires manual data entry to define the geometry of the building and structural elements. The assumptions made to compute the QTO cause 2% to 5% error (Yücel, 2019). The unit workmanship requirements may deviate significantly depending on the climate and construction-site conditions. Contractors may use their own unit workmanship requirements by considering their previous job data or implement artificial neural network models (Oral et al., 2012; Kaya et al. 2014; Oral et al., 2016). Workmanship requirements can be estimated by time-series analysis or Fourier series as well (Al-Omari et al., 2022; Khasawneh et al., 2022).

QTO values are assumed to be the same at each floor, which is a critical issue of the developed framework. Constant QTO value assumption reduces the required data entry as such the same data given in Table 1 should be entered at each floor. Moreover, the activity durations will change with respect to the floors. This situation also affects the schedule and deteriorates the linearity of the schedule. This leads to the assignment of unique activity durations for each floor, since particular activity duration may provide lower total project cost. As a result of this, the number of parameters increases significantly, which makes the optimization process more complex.

The contribution of this study is to develop a framework system which can be implemented by small- and medium-scale contractors to form and optimize the TCTP. The mentioned system significantly reduces the workload of the preparation of the problem, which is a critical issue during the bid-preparation process. The theoretical contribution of the study is limited, but the methodological contribution of the study can be listed as the suggestion of proper parameter values for the GA and the development of an automated application to compute QTO, prepare and solve the TCTP.

The target group of this study is limited to small-and medium- scale contractors. Therefore, the data entry and analysis process is kept as simple as possible. The assumption of constant QTO values at every floor is valid for mass housing projects and moderately budgeted apartment buildings, which limits different design alternatives to prevent cost increase.

Gene expression (GEP) algorithms can also be implemented to predict the efficiencies of the construction workers. GEP produces better results than regression models (Alshboul et al., 2022a). This study can also be implemented to form and optimize the construction of green buildings. The cost of green buildings can be estimated by machine learning (Alshboul et al., 2022b)

LoB represents the construction schedule with less number of activities, so that the constraints between the activities are relatively easy to define. This approach enables the utilization of effective construction scheduling methods which help reduce the total construction cost (Wong and Mohammed Ahmed, 2018).

The most appropriate values are determined by the experimental design for the population size, crossover and mutation rates of the GA. Hence, this study may assist researchers and schedulers to reduce the computational burden of the optimization process conducted by the GA. The fine-tuned GA is implemented on a developed spreadsheet application. When the convergence graph is examined, it is seen that a significant cost reduction is achieved compared to the initial solution and it converges to the optimum or near-optimum solution at the end.

Although this study provides the afore-mentioned benefits to the literature, there are some required improvements. In the created spreadsheet application and algorithm, earthworks and foundation works are only shown in the schedule and they are not included in the optimization process. In addition, different construction alternatives are not created for the activities related to the roof, elevator and electrical components and these activities are not included in the optimization process too. This is based on the assumption which implies that these activities would be performed by the sub-contractor with only one work-schedule alternative. As a future study, it is aimed to realize the QTO of roof, mechanical and electrical installation works and prepare construction alternatives for them.

In order to facilitate data entry and quantity take-off and scheduling calculations, it is assumed that the values assigned for the first floor are valid for all of the upper floors. During the building construction, construction crews are kept at a constant size from the first floor to the top floor. For this reason, the assumption is reasonable. However, it is not always possible to design all of the floors with the same architectural plan, such that floor covering or some of the interior design may differ. The mentioned simplifications on the architectural project and schedule reduce the number of parameters and simplify the optimization process. Activity times are the same at each floor and the execution of the activities cannot be interrupted by constraints that limit the scheduler to control and to judge the schedule as much as the CPM. The stated situations represent an important shortcoming for construction companies that carry out more than one construction project at the same time, but they are insignificant for small-scale contractors. The mentioned shortcoming can be eliminated as a future work.

CONCLUSION

In this study, a framework which computes QTO values, estimates workmanship requirements, prepares and solves the TCTP is developed and implemented. The proposed approach can be beneficial for small-and medium-scale housing contractors who construct buildings with similar floor plans at each floor. The main benefit of the proposed approach is providing the QTO values by entering approximately 100 data related to the structure. The construction schedule is prepared and optimized to reduce the total project cost. Data entry and the optimization process require only one and a half hour and cost very little. The developed system reduces the required cost and endeavor of the planning phase and minimizes the total construction cost. Small-and medium-sized contractors may have important benefits and become more resilient if they implement the proposed approach.

QTO computations require manual data entry which is error-prone. Data extraction from technical drawings would reduce the required time for the data entry and would prevent errors. QTO computations have simplifying assumptions which lead up to 5% deviation from the exact values. A robust and detailed QTO algorithm can reduce the error margin. The scheduling algorithm assumes that the QTO values and workmanship requirements are the same at each floor. The computation of QTO at each floor requires an automated data-entry process. Moreover, different workmanship amounts would lead to different activity durations and prevent the implementation of simple scheduling and optimization techniques. The implementation of robust optimization algorithms would increase the computation time and require talented staff to implement and interpret. This may hinder the target group to implement an enhanced system.

List of Abbreviations

TCTP:	Time-Cost Trade-off Problem
NAA:	Network Analysis Algorithm
QTO:	Quantity Take-off
CPM:	Critical Path Method
$D_{i,j}$:	Duration of the jth construction mode of the ith item
DWT:	Daily Working Time
CSj:	Crew size of the jth construction mode
ηj:	Job efficiency of the jth construction mode
UWRi:	Unit Workmanship Requirement of the ith activity
UMaRi:	Unit Machinery Requirement of the ith activity
UMRi:	Unit Material Requirement of the ith activity
LCi,j:	Labor Cost of the jth construction mode of the ith construction item
ULCi:	Unit Labor Cost of the ith construction item
MEP:	Mechanical, Electrical and Plumbing works
BT:	Buffer Time
F:	Number of Floors of the Building
i-pred:	Predecessor of the ith activity
LoB:	Line of Balance
LS:	Linear Schedule
CCi:	Constant Cost of the ith activity
OH:	Daily Overhead Cost
OC:	Overhead Cost
m:	Number of construction activities
T:	Project Duration
GA:	Genetic Algorithm
P:	Population Size
COCVi:	Crossover Coupling Value of the ith individual
COR:	Crossover Rate
MR:	Mutation Rate

SVi:	Survival Value of the i^{th} individual
BoQ:	Bid of Quantities
CPU:	Central Processing Unit
GEP:	Gene Expression

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