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AN IMPROVED TIME-COST TRADE-OFF MODEL WITH OPTIMAL LABOR PRODUCTIVITY

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Abstract. Optimization of the time-cost trade off (TCT) has received considerable attention for several decades. However, few studies have considered improving performance/productivity of existing crews. To shorten the gap to real-world applications, this study presents an improved TCT model that considers variable productivity using genetic algorithms (GAs). Through an illustrative case and a real world case, the results demonstrate that improving labor productivity of selected activities by allocating existing crews and management can yield an optimized solution. As such, a decision maker can implement a better optimized technique to reduce a project duration under budget while reducing the risk of liquidated damages. The main contribution of this study is to apply managerial improvement of labor productivity to TCT optimization, the project duration can be reduced owing to improved productivity of existing crews rather than inefficient overmanning, overlapping or costly substitution. In the end, three important managerial insights are presented and future research is recommended.

Keywords: labor productivity, time-cost trade-off, optimization, genetic algorithm.

Introduction

It is an established fact that projects are almost always behind schedule (Gerk & Qassim, 2008). Therefore, optimizing the performance of complex construction projects has received considerable attention. Determining how to complete projects on time and under budget has become the most important goal in the optimization field. Furthermore, as well as minimizing project costs, to decrease the risk of contract-specified liquidated damages (LD), contractors attempt to complete projects earlier than the stipulated duration because LD will impact total project costs if the contractor fails to meet the contract completion date.

Various studies have considered time-cost trade off (TCT) optimization using a variety of methods. Most researchers consider the straight relationship between time and cost no matter minimizing cost within granted duration or compressing schedule under budget. It is intuitively assumed that direct costs will increase with schedule acceleration. However, such an assumption is deficient because labor productivity as a critical factor, which generally influences project time and cost is rarely considered when evaluating optimization of project execution. Furthermore, even though current TCT optimizations could provide instant effect on improving project performance, side effects such as rework, fatigue or costly pay might be inevitable. Accordingly, the critical factor should be further considered in TCT optimizations.

Previous researches have revealed that labor productivity can be improved through management such as training, process improvement or incentive etc. To address this issue, the objective of this study is to presents an improved TCT model that considers variable productivity relative to the working environment and management. The proposed model addresses the influence of variable productivity on project duration and direct cost by establishing the interaction among labor resource, deliverable, duration and direct cost. Genetic algorithms (GAs) is used to search for and identify optimal/near optimal productivity and scheduling. Therefore, the model can reduce the project duration without side effect and thereby decrease the risk of LD without going over the original direct cost. This study presents an illustrative case and a real world case to validate the proposed optimization model.

The remainder of this paper is organized as follows. Studies related to the TCT problem and labor produc-

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*Corresponding author. E-mail: *u0315918@nkfust.edu.tw* tivity are discussed in Section 1. The formulation of the proposed model is given in Section 2, and the selection and use of implementation methodology are explained in Section 3. An illustrative case and a real world case are described in Section 4, and analysis results are provided and discussed in Sections 5 and 6, respectively. Final section presents conclusions and recommendations for potential future research.

1. Literature review

Allocation of optimized time and cost involves complicated planning and decision making, including resources, environment, techniques, and proper methods (Hegazy, 1999). Previous studies have proposed various project optimization methods. Those studies focused on resource allocation optimization (Chan, Chua, & Kannan,1996; Berthaut, Pellerin, Perrier, & Hajji, 2011a; Berthaut, Greze, Pellerin, & Hajji, 2011b; Chen & Shahandashti, 2009; Florez, Castro-Lacouture, & Medaglia, 2013), the TCT by crashing (Hegazy, 1999), the time-profit trade-off by crashing (Senouci & El-Rayes, 2009), the time-cost-quality trade-off by crashing (El-Rayes & Kandil, 2005; Cristobal, 2009), the overlapping-rework trade-off (Krishnan, Eppinger, & Whitney, 1997; Peña-Mora & Li, 2001; Hossain, Chua, & Liu, 2012; Hazini, Dehghan, & Ruwanpura, 2013; Khoueiry, Srour, & Yassine, 2013; Hossain & Chua, 2014; Dehghan, Hazini, & Ruwanpura, 2015), concurrent crashing and overlapping (Roemer & Ahmadi, 2004), the crashing, overlapping and substitution trade-off (Gerk & Qassim, 2008), time float allocation (Chen, 2011; Kuo, 2013), working space allocation optimization (Cho & Hastak, 2013) and minimizing disruption cost (Altuwaim & El-Rayes, 2018). Notable optimization studies are compared in Table 1.

Almost all these studies considered that reducing a project's duration (i.e., schedule acceleration) will inevitably incur cost increase under a TCT framework. However, for a multi-objective problem, decision makers can employ techniques that can quantify and control the decision variables to find an optimization solution that incurs minimum cost.

Based on previous studies, optimization techniques for the TCT can be classified as (1) crashing (acceleration by overmanning, overtime, or shift time); (2) fast-tracking (concurrent engineering by evaluating the magnitude of evolution and sensitivity from upstream to downstream); and (3) substitution (improvement by utilizing better resources and advanced technologies). These techniques can reduce time; however, each of them has side effects. For example, crashing might cause fatigue, fast-tracking might accompany rework, and substitution could be costly. Furthermore, although previous studies have provided a variety of robust optimization models applicable to manufacturing and construction industries, few have investigated labor productivity.

Peña-Mora and Li (2001) established a feedback model to fast-track construction projects using system dynamics. They altered the labor productivity assumption, which has been considered a constant in previous studies. In their dynamic model, productivity determined by the function of schedule pressure, experience level with a phase, the effect of fatigue, and the normal productivity will eventually affect both project duration and cost; Roemer and Ahmadi (2004) indicated that means to increase work intensities (i.e., crashing) throughout a project include working overtime, adding staff, or utilizing more experienced staff or better equipment. El-Rayes and Kandil (2005) developed a multi-objective optimization model and analyzed the time-cost-quality trade-off between two crew formations comprised of eight resource utilization configurations with different levels of productivity. Senouci and El-Rayes (2009) considered crew performance relative to a time-profit trade-off model. To optimize project execution, the performance generated by eight crew formations are assumed in the present model. Hossain et al. (2012), Hossain and Chua (2014) identified redesign and rework as productivity loss that is incurred by overlapping. They also evaluated the trade-off between overlapping and redesign/rework (i.e., productivity loss) and quantified the probability of redesign/rework. Kuo (2013) searched for an optimal schedule by substituting three resources with different efficiencies. Float reallocation can be more appropriate after considering float consumption and cost in the optimized schedule.

Even though these studies considered productivity change, optimal productivity cannot be determined via simulated dynamic models. In optimization, changeable productivities are primarily utilized from the perspective of external resource substitution. It does not contribute to the improvement of productivity nor accumulation of competence for the existing resource although worker's sustainability has been continuously emphasized (Florez et al., 2013). Furthermore, the influence of the environment and management processes on labor productivity has not been considered relative to the TCT. Typically, in construction projects, labor costs are more than 40% of the total project budget (Hanna, Russell, Gotzion, & Vandenberg, 1999). If the productivity of existing crew can be improved, it is possible to reduce a project's duration without increasing costs or reduce project costs within the scheduled duration, particularly for large construction projects with long durations.

Therefore, this study presents an integrated technique to directly improve the labor productivity of existing resources and reduce time through management initiatives, such as improving processes, decreasing waste, and providing training and incentives.

Labor productivity is calculated as the man hours (mh) per unit of work (Thomas & Yiakoumis, 1987). For example, labor productivity for a concrete foundation is 20 mh/m^3. In practice, labor productivity is primarily influenced by the environment and management (Thomas & Yiakoumis, 1987; Thomas & Raynar, 1997), and such influences affect project time and cost. The environment can be classified as external (e.g., weather) (Thomas, Riley, &

Table 1. Comparison of major research in optimization

Researcher	Optimization	Technique	Methodology	Validation	Industry	Phase	Productivity
Chan et al. (1996)	Time-cost trade off	Resource scheduling	Genetic algorithm	2 test cases	Construction	Construction	Not involved
Li and Love (1997)	Time-cost trade off	Crashing	Genetic algorithm	1 test case for concrete culvert	Construction	Construction	Not involved
Krishnan et al. (1997)	Time-quality trade off	Fast-tracking	Nonlinear programming	2 test cases for door development and pager	Manufacturing	Design	Not involved
Hegazy (1999)	Time-cost trade off	Crashing	Genetic algorithm	1 test case	Construction	Construction	Not involved
Peña-Mora and Li (2001)	Time-cost trade off	Fast-tracking	System dynamics	1 real world case for building	Construction	Construction	Flexible productivity
Roemer and Ahmadi (2004)	Time-cost trade off	Crashing and fast-tracking	Algorithm	1 test case	Manufacturing	Design	Identified as work intensity
El-Rayes and Kandil (2005)	Time-cost-quality trade off	Crashing	Genetic algorithm	1 test case	Construction	Construction	8 feasible options
Gerk and Qassim (2008)	Time-cost trade off	Crashing, fast-tracking and substitution	Mixed-integer nonlinear programming	4 real world cases for manufacturing	Manufacturing	Design-production-commissioning	Not involved
Senouci and El-Rayes (2009)	Time-profit trade off	Crashing	Genetic algorithm	2 test cases	Construction	Construction	8 feasible options
Berthaut et al. (2011a, 2011b)	Time-cost trade off	Fast-tracking	Nonlinear 0-1 integer programming	1 test case	Construction	Construction	Not involved
Hossain et al. (2012)	Time-cost trade off	Fast-tracking	DSM + Genetic algorithm	1 test case for aerospace and automation	Construction	Design	Identified redesign as loss in productivity
Cho and Hastak (2013)	Time-cost trade off	Fast-tracking	Genetic algorithm	1 test case, 1 real world case	Construction	Design-construction	Not involved
Hazini et al. (2013)	Time-cost trade off	Crashing, fast-tracking and substitution	Heuristic method	1 test case	Construction	Design	Flexible productivity
Kuo (2013)	Time-cost trade off	Float consumption	Genetic algorithm	1 test case	Construction	Construction	Identified as 3 resource efficiencies
Khoueiry et al. (2013)	Time-cost trade off	Fast-tracking	Nonlinear programming	1 real world case	Construction	Design-construction	Not involved
Hossain and Chua (2014)	Time-cost trade off	Fast-tracking	Genetic algorithm	1 test case	Construction	Design-construction	Identified rework as loss in productivity
Dehghan et al. (2015)	Time-cost trade off	Fast-tracking	Genetic algorithm	1 real world case	Construction	Design	Not involved
Klansek (2016)	Time-cost trade off	Fast-tracking	Mixed-integer nonlinear programming	1 test case	Construction	Construction	Not involved
Altuwaim and El-Rayes (2018)	Time-cost trade off	Fast-tracking	Genetic algorithm	1 test case	Construction	Construction	Not involved

Sanvido, 1999) and working environment (e.g., crowded working space) (Thomas, 2000). Previous studies identified management as a critical factor influencing labor productivity (Rojas & Aramvareekul, 2003; Mojahed & Aghazadeh, 2008; El-Gohary & Aziz, 2014). Consequently, time or duration can be reduced effectively by improving the work environment and management in order to improve labor productivity.

Thomas, Sanvido, and Sanders (1989) suggested that contractors should consider the trade-offs between investing cost and disruptions saving. It would be beneficial to improve labor productivity and reduce time and cost through a management system that involves process improvement and information feedback (Sanvido, 1988), material control during construction (Thomas et al., 1989), shortening the decision-making process in the design and construction phase (Peña-Mora & Li, 2001), and incentives (Chokor, Asmar, & Paladugu, 2017).

2. Model formulation

Improving productivity through management has been proved a feasible and fundamental method for large construction projects with long durations in previous researches. However, improvement takes time and incurs costs; thus, all possible improvement activities may not be implemented under time and budget constraints. Considering multi-objective decisions with TCTs, decision makers will prioritize the most efficient alternative (e.g., improvement with shorter time or lower cost). Consequently, the objective of the proposed model is to help decision makers find an improvement alternative that provides optimal productivity and minimizes time and direct costs.

This section presents a generic formulation and objective function for the proposed model, which provides an optimal improvement strategy to reduce the project duration.

According to the critical path method (CPM), the original contract duration (*CD*) is computed as follows:

$$CD = \sum_{i=1}^{l} \left(OD_i^{UPQ} \right). \tag{1}$$

The optimal objective is to minimize project duration (*PD*), the objective function is as follows:

$$\text{Minimize } PD = \sum_{j=1}^{l'} \left(OD_j^{U'P''Q''} + MD_j^{U'P'Q'} \right) \tag{2}$$

Subject to < *CD*; and

$$Q = Q' + Q'',$$

where OD_i^{UPQ} is the original duration of activity (*i*) on the critical path (CP) using labor resource (*U*) with productivity (*P*) to complete the quantity of work (*Q*) , the original CP includes *l* activities. After optimization, a new CP composed of *l*′ activities might generate according to their logic relationships and minimized duration. Where $OD_j^{U'P''Q''}$ is the new duration of activity (*j*) on the CP using labor resource (*U*′) with improved productivity (*P*″) to complete the quantity of work (*Q*″), and $MD_j^{U'P'Q'}$ is the improvement duration of activity (*j*) on the CP using labor resource (*U*′) with productivity (*P*′) to complete the quantity of work (*Q*′). Generally, productivity (*P*″) after improvement is better than productivity (*P*) before improvement and productivity (*P*′) during improvement (i.e. $P'' < P < P'$). Total quantity of work (*Q*) is the quantity of work (*Q*′) completed during improvement period plus the quantity of work (*Q*″) completed after improvement.

Referring to the factor model presented by Thomas and Raynar (1997), the various factors that influence labor productivity can be categorized into four variables.

Labor productivity (*P*) is expressed as follows:

$$P = \frac{mh}{q} = f\left(E, M, \bar{L}, \bar{W}\right), \tag{3}$$

where $\frac{mh}{q}$ is the input man hours (*mh*) per output work quantity (*q*), *E* is the environment identified as working environment allowance to constraint the resource usage, *M* is the management method identified as improvement of labor productivity, *L* is the skill required to fulfil the work, and *W* is the work content such as work scope or work complexity. In this study, *L* and *W* are constants because it is assumed that the labor is qualified to complete the work and the work content is specified as a contract requirement.

In this study, congestion factor (*C*) is a function of actual labor usage (*U*) versus labor allowance (*A*) in a work environment (*E*). When actual labor usage is more than labor allowance in a work environment, congestion factor is more than 1. The improvement factor (*I*) is an index of measuring the improvement effect through management.

The labor productivity (*P*″) after improvement through management equals improvement factor (*I*) multiplies labor productivity (*P*). The optimal labor productivity (*O*) is defined as the value considering both congestion factor (*C*) and labor productivity after improvement (*P*″). The value is determined by GAs.

The relations among congestion factor (*C*), improved labor productivity (*P*″), improvement factor (*I*), and the optimal labor productivity (*O*) are presented as follows:

$$C = f\left(U, A \middle| E\right); \tag{4}$$

$$P'' = I \cdot P; \tag{5}$$

$$O = C \cdot P''. \tag{6}$$

The duration (*D*) of an activity is expressed as follows:

$$D = \frac{Q \cdot P}{DMH}, \tag{7}$$

where *Q* is work to be done, DMH is daily manpower multiplied by daily straight time (default: eight hours). When *Q* is constant, *D* will decrease if labor productivity (*P*) decreases or MH increases (i.e., daily manpower increases).

The project direct labor cost (*PC*) with optimal duration can be computed as follows:

$$PC = \sum_{x=1}^{n} [DC_x^n + MC_x^n + IC_x^n] \quad (8)$$

Subject to $PC < CB$,

where DC_x is direct labor cost, MC_x is labor mobilization/demobilization cost, IC_x is improvement cost, and CB is direct labor cost of contract budget.

To sum up the notations used in the proposed model, actual labor usage (U) and improvement factor (I) are defined as 2 sets of key decision variables which jointly decide the optimization result. The range of labor usage and improvement factor with time and cost will be further evaluated under resource availability and manager's expertise. In other words, if over-crowding in a work environment is not possible, labor usage might be allocated as much as resource availability after optimization. The other notations such as normal labor productivity (P), work to be done (Q), working environment labor allowance (A), direct labor cost (DC_x), labor mobilization/demobilization cost (MC_x) and improvement cost (IC_x) are regarded as activity's properties which should be predetermined in a project.

Note that the following considerations and assumptions should be made in advance:

1. The cost of improving productivity through management (IC_x) is identified as one of direct cost because crew should be involved in the improvement process.
2. An overtime policy is excluded because it will increase costs and decrease productivity. Moreover, overtime will not be considered if the project duration can be reduced by improving productivity.
3. Since weather is unpredictable and uncontrollable, its impact is not considered in the model.
4. Decision makers are assumed to be risk-averse. To avoid LD, they attempt to complete a project as quickly as possible and under budget rather than minimize the cost within the contract completion date.
5. Construction is a labor-intensive industry; therefore, to simplify the model, the only resource considered in this study is labor.
6. The existing crew in the proposed model is sufficient, therefore, substitution of external crew is not considered.

3. Methodology

Several methodologies have been used to evaluate the optimization problem relative to the construction projects, including nonlinear integer programming (Gerk & Qassim, 2008; Klansek, 2016), 0-1 integer programming (Cristobal, 2009; Florez et al., 2013), the heuristic method/rule of thumb (Hazini et al., 2013), GAs (Chan et al., 1996; Li & Love, 1997), and dynamic programming (Peña-Mora & Li, 2001). Although heuristic methods can determine optimum degree of activity accelerating and overlapping in schedule compression, they might not guarantee a global optimum (Hazini et al., 2013). In addition, mathematical programming (i.e. integer programming) could provide the optimal solution but it could not be applicable to industry practitioners owing to difficulties of formulating construction projects with complicated schedule. Hegazy (1999) compared the heuristic method, mathematical programming model, and GAs for TCT analysis and noted that having mechanisms of simulating natural evolution and survival-of-the-fittest, GAs have been used to solve several engineering and construction management problems. Furthermore, GAs can solve problems with discrete time-cost relationships. The results obtained by GAs model do not indicate an exponential growth in the computational time required for larger problems (Chan et al., 1996). In terms of scheduling optimization, GAs have provided a more efficient way to search for optimal/near optimal solutions compared to traditional methods evaluated by schedulers (Dehghan et al., 2015). Referring to previous researches, the comparison of three major techniques is shown in Table 2. Therefore, considering the multi-objective TCT problem in this study, GAs as a mature method are used for 2 cases' optimization. It can further assist project scheduler for optimizing large real projects.

In the process of the TCT with optimal productivity, three steps are taken by the decision maker: (1) determine the magnitude of improving productivity depending on how much time and cost are necessitated for improvement of each activity; (2) allocate optimal resources in a specific environment for each activity to carry out the work; and (3) search for an optimal productivity plan from possible solutions as an optimization benchmark for project execution.

Representation of problem in GAs can be solved by a finite-length string which is analogous to a chromosome in a biological system. Each individual chromosome represents a random solution that encompass many genes. The optimized solution is generated through objective function and GAs procedure. Generally, the GAs procedure is as follows: (1) generate an initial population of random solutions in a parent generation; (2) search for solution with excellent fitness; (3) regenerate an offspring population of solutions by crossover and mutation operators; and (4) re-evaluate and search for optimized solution within the child generation. This iterative process is terminated when the optimized solution is found, i.e., all termination criteria in the GAs model are satisfied. The GAs procedure is shown in Figure 1. The detailed implementation and description of GAs can be found in the literature (Goldberg, 1989).

In this study, each chromosome represents a management improvement strategy, and a gene represents 2 sets of key decision variables: actual labor usage and improvement factor, as shown in Figure 2.

Generally, two major modules exist in GAs to solve the TCT. The time module minimizes time under the current budget, and the cost module minimizes cost within a limited time. In this study, the time module is analyzed to search for the optimization acceleration and the cost module is used to illustrate the optimization curve of TCT.

The most popular programs used to analyze GAs include the MATLAB GAs Module, the Microsoft Excel Evolutionary Solver, and the Palisade Evolver. This study uses Microsoft Excel Evolutionary Solver and Palisade Evolver add-in for Microsoft Excel which both are suitable programs for applying a wide variety of variables and conducting complex and iterative computations. Microsoft Excel used as a GAs platform provides flexibility to the researcher to easily change variables and review and analyze the results, and it is quite compatible with Microsoft Project (Dehghan et al., 2015).

Table 2. Comparison of existing techniques for TCT analysis (adapted from Hegazy, 1999)

	Heuristic methods	Mathematical programming models	Genetic algorithms
Description	– Simple rule of thumb	– Linear/Non-linear programing; integer programming; or dynamic programming	– Optimization search procedures that mimic natural evolution and reproduction
Examples	– Hazini et al. (2013)	– Cristobal (2009) – Florez et al. (2013) – Klansek (2016)	– Chan et al. (1996) – Li and Love (1997) – Dehghan et al. (2015)
Advantages	– Easy to understand – Provide good solutions – Used for large-size projects	– May provide optimal solutions	– Robust search algorithm – Can use discrete relation between time and cost – Applicable to large problems without exponential growth in the computational time – Efficient way to search for optimal/near optimal solution
Disadvantages	– Lack mathematical rigor – Do not guarantee a global optimal solution – Mostly assume linear, rather than discrete, relationship between time and cost	– Difficult to formulate – The gradient-descent approach often terminates in local minimum – Applies to small problems only – Mostly assume linear, rather than discrete relationship between time and cost	– Random search is time consuming – Cannot tell when or if an optimal solution is obtained

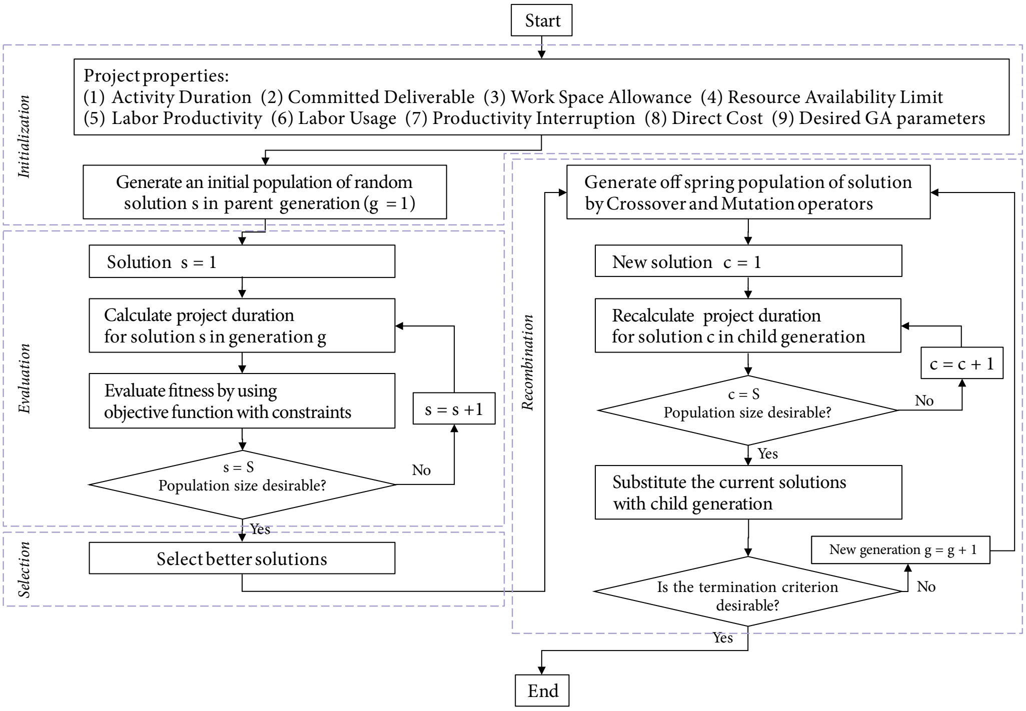


Figure 1. Genetic algorithm procedure for minimizing project duration

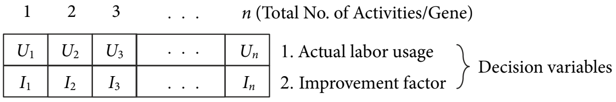


Figure 2. Representation of chromosome for GA application in this study

4. Case validation

In this section, 2 cases are examined involving working environment and variable productivity in TCT optimization problem to demonstrate the effectiveness of the proposed model. For better understanding the nature of proposed model, the first case is illustrative and simplified. The second case is a real construction project considering more activities with complicated relationships.

4.1. Case study I

The first case comprises 10 activities with different properties depicted in Table 3. The relationships are all assumed to be Finish-to-Start with zero lag time because they are determined by characteristics of each activity, which do not vary during optimization process and affect the final result. The only 4 paths in this model is easier validated by scheduler as a traditional method instead of GAs optimization (Figure 3).

Considering the working environment constraint, the appropriate amount of available labor is identified according to normal conditions for each activity, i.e., the working environment allowance (A_x). The normal labor productivity (P_x) for each activity is identified respectively. The actual labor usage (U_x) is initially equal to the working environment allowance (A_x). The manager should allocate labor with different skills to implement the given activity. Moreover, labor cannot be substituted among different activities, e.g., the labor working on activity 01 cannot be allocated to activity 02. To simplify the model, the direct labor cost is assumed to be $2,000 per day, and the cost of mobilization and demobilization for each labor is also assumed to be $2,000.

It is practical that the minimum time fraction is 0.5 day in the construction industry (Li & Love, 1997). However, any decimal value reduction of duration in the developed model is acceptable to reflect optimal productivity. Two kinds of results are presented in the next section.

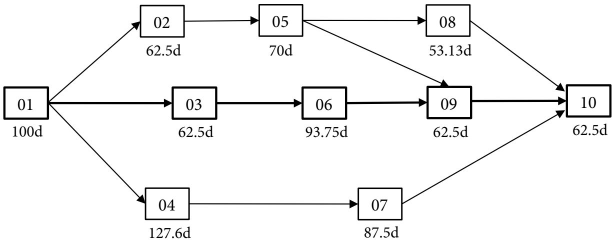


Figure 3. Project network diagram

The duration of each activity is computed based on Eqn (7). For example, the duration of activity 01 is 100 days (i.e., 320×25÷10÷8). According to the CPM, the initial CP of the case project is 01→03→06→09→10, and its duration is 381.25 days. The project direct labor cost is $17,513,500 (direct labor cost $17,287,500 + mobilization/demobilization cost $226,000). If the minimum unit of 0.5 days is considered, the original duration of the project is 383 days. The project direct labor cost is $17,596,000 (direct labor cost $17,370,000 + mobilization/demobilization cost $226,000).

To reduce the project duration, the decision maker may allocate more manpower to accelerate the schedule if labor availability is sufficient. However, as more manpower is allocated, the working environment becomes increasingly crowded. As a result, labor productivity may deteriorate. Previous studies have revealed that overmanning causes inefficiencies due to high labor density and congestion (Thomas, 2000). In this study, the ratio of actual labor usage (U_x) to working environment allowance (A_x) is defined as congestion factors (C_x), which influence the normal labor productivity (P_x). The congestion factors (C_x) are assumed as follows:

$$\begin{aligned} U_x/A_x &\leqq 1 \;, && C_x = 1; \\ 1 < U_x/A_x &\leqq 1.2, && C_x = 1.1; \\ 1.2 < U_x/A_x &\leqq 1.5, && C_x = 1.2; \\ 1.5 < U_x/A_x & \;, && C_x = 1.5. \end{aligned} \tag{9}$$

Table 3. Project basic information: Case I

Activity (x)	Original duration (OD_x) (day)	Finish date (CD) (date)	Vol. of work to be done (Q_x) (unit)	Resource availability limit (R_x) (manpower)	Labor usage (U_x) (manpower)	Working environment allowance (A_x) (manpower)	Labor productivity (P_x) (mh/q)	Direct labor cost (DC_x) (dollar)	Mobilization / demobil. cost (MC_x) (dollar)
01	*100.00*	*100.00*	*320*	*20*	*10*	*10*	*25*	*2,000,000*	*20,000*
02	62.50	162.50	250	20	15	15	30	1,875,000	30,000
03	*62.50*	*162.50*	*400*	*20*	*16*	*16*	*20*	*2,000,000*	*32,000*
04	127.60	227.60	350	20	12	12	35	3,062,500	24,000
05	70.00	232.50	560	20	10	10	10	1,400,000	20,000
06	*93.75*	*256.25*	*300*	*20*	*8*	*8*	*20*	*1,500,000*	*16,000*
07	87.50	315.10	500	20	10	10	14	1,750,000	20,000
08	53.13	285.63	340	20	16	16	20	1,700,000	32,000
09	*62.50*	*318.75*	*300*	*20*	*6*	*6*	*10*	*750,000*	*12,000*
10	*62.50*	*381.25*	*200*	*20*	*10*	*10*	*25*	*1,250,000*	*20,000*
Total								17,287,500	226,000

The decision maker will become more familiar with each activity after reviewing its details, such as working environment constraint, and execution process. The time and cost expenses can be evaluated, and the magnitude of improving productivity through management can be further identified as improvement factor (I_x). In previous empirical investigations, the reduced labor productivity losses, reduced schedule delays and reduced waste costs ranged from 5% to 32% (Sanvido, 1988; Thomas et al., 1989, 1999, 2003; Chokor et al., 2017).

As a result, improvement factor (I_x) is assumed to increase the output of work to the maximum 20% in this illustrative case. The magnitude ranges from 1/(1+20%) to 1/(1+10%), 1/(1+10%) to 1 and 1. Note that better improvement results in both increased work performance and longer improvement duration and higher cost. Because labor would spend more time learning or being trained instead of simply working during improving period, the work done with labor productivity (P_x') during the period is conservatively assumed to be 80% of the work done with the original productivity (P_x). In other words, completing a quantity of work would take longer during the improving period, the labor productivity becomes worse accordingly. For example, if labor productivity (P_x) of an activity is 25 mh/q, labor productivity (P_x') during improving period is 31.25 mh/q (25 mh/0.8q). Besides, the improvement cost (IC_x) is assumed 20% higher than direct labor cost (DC_x).

The above assumptions for each activity in next real world case were further evaluated by experienced practitioners through an interview. After improvement, the remaining work will be done at labor productivity (P_x'') in consideration of improvement factor (I_x). The improvement factor, duration and cost are assumed as shown in Table 4.

4.2. Case study II

In the second case, the proposed model is used to analyze a real world case which is an ultra-supercritical boiler construction project implemented by a general contractor in Taiwan. The construction period was from 2013/9/3 to 2016/9/1 (1,094 days). Owing to the confidentiality of the case project, the project direct labor cost (budget) was US$ 57,637,738 (direct labor cost US$ 57,520,338 + mobilization/demobilization cost US$ 117,400) through a factor transformation. The project primary schedule involved 9 major disciplines comprises 22 activities with 55 relationships and 3 relationship types with lag time, i.e. FS, SS and FF (Figure 4).

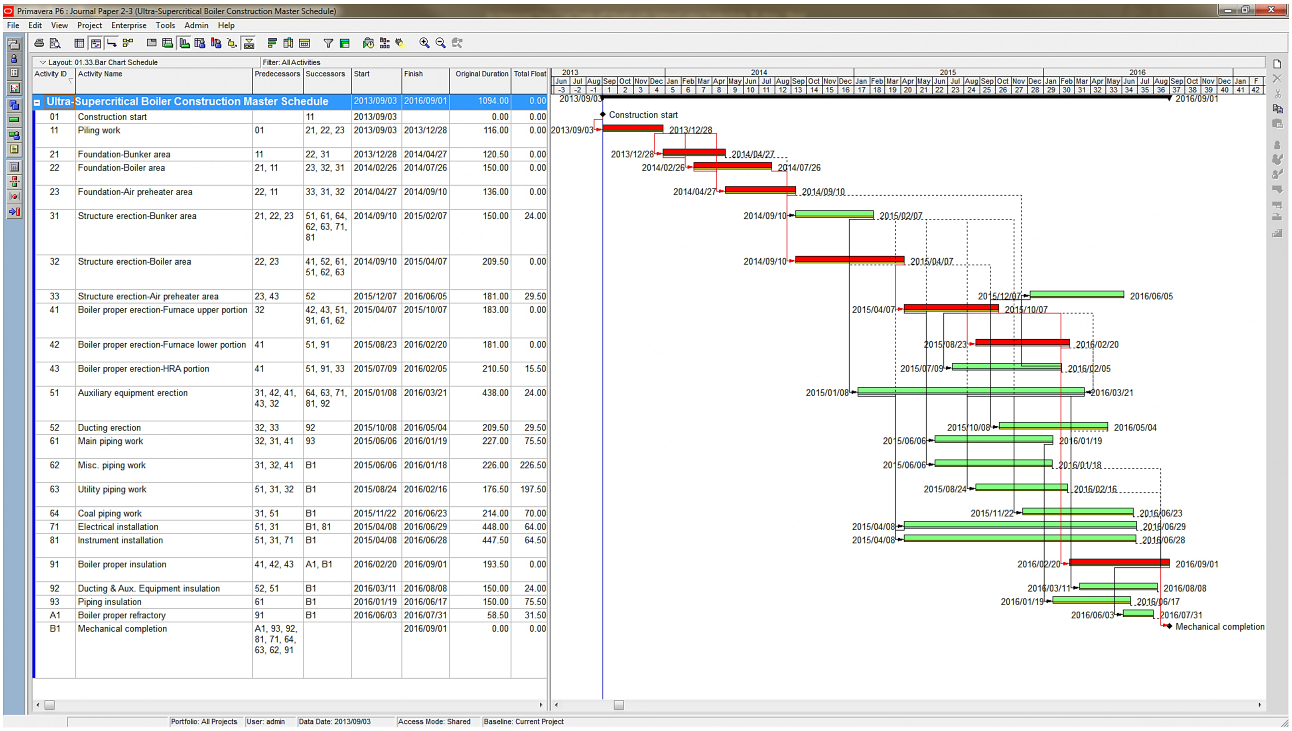
There are total 220 paths in the schedule. In practice, the primary schedule is developed for overview and integration of comments from each discipline. Once the schedule is configured, each activity can be further developed to detailed schedule. The project experienced practitioners including project control manager, construction manager and subcontractor's superintendent were invited to evaluate the possibility of improving overall schedule. In the construction period, acceleration methods such as crashing, fast tracking and substitution were also jointly used to reduce the schedule, but only the improvements relative to labor productivity were separated to demonstrate the individual effect. After explaining the TCT proposed model to project practitioners, the parameters of congestion factor in case I can be applied to case II. The work done ratio with labor productivity (P_x') during the improving period was concluded as 80% of the work done with the original productivity (P_x). However, the improvement factor could be optimized to maximum 10% after reviewing the all feasible improvement and identifying the improvement durations for each activity. The improvement cost (IC_x) is 10% higher than direct labor cost (DC_x). The project basic information and major improvements of activities are shown in Tables 5 and 6.

Table 4. Improvement factor versus duration and cost: Case I

Activity	Improvement Factor (I_x)	Improvement duration (day)	Improvement cost ($/day)	Activity	Improvement Factor (I_x)	Improvement duration (day)	Improvement cost ($/day)
01	$I_{01} = 1$	0	0	06	$I_{06} = 1$	0	0
	$1 > I_{01} \geqq 1/1.1$	24	57,600		$1 > I_{06} \geqq 1/1.1$	14	33,600
	$1/1.1 > I_{01} \geqq 1/1.2$	36	86,400		$1/1.1 > I_{06} \geqq 1/1.2$	28	67,200
02	$I_{02} = 1$	0	0	07	$I_{07} = 1$	0	0
	$1 > I_{02} \geqq 1/1.1$	14	33,600		$1 > I_{07} \geqq 1/1.1$	7	16,800
	$1/1.1 > I_{02} \geqq 1/1.2$	24	57,600		$1/1.1 > I_{07} \geqq 1/1.2$	14	33,600
03	$I_{03} = 1$	0	0	08	$I_{08} = 1$	0	0
	$1 > I_{03} \geqq 1/1.1$	7	16,800		$1 > I_{08} \geqq 1/1.1$	14	33,600
	$1/1.1 > I_{03} \geqq 1/1.2$	18	43,200		$1/1.1 > I_{08} \geqq 1/1.2$	28	67,200
04	$I_{04} = 1$	0	0	09	$I_{09} = 1$	0	0
	$1 > I_{04} \geqq 1/1.1$	14	33,600		$1 > I_{09} \geqq 1/1.1$	7	16,800
	$1/1.1 > I_{04} \geqq 1/1.2$	35	84,000		$1/1.1 > I_{09} \geqq 1/1.2$	14	33,600
05	$I_{05} = 1$	0	0	10	$I_{10} = 1$	0	0
	$1 > I_{05} \geqq 1/1.1$	7	16,800		$1 > I_{10} \geqq 1/1.1$	21	50,400
	$1/1.1 > I_{05} \geqq 1/1.2$	10	24,000		$1/1.1 > I_{10} \geqq 1/1.2$	35	84,000

Table 5. Project basic information: Case II

Activity (x)	Activity Description	Start date	Finish date	Original duration (OD_x) (day)	Vol. of work to be done	Unit	Resource availability limit (R_x) (manpower)	Labor usage (U_x) (Man-power)	Working environment allowance (A_x) (manpower)	Labor productivity (P_x) (mh/q)	Direct labor cost (DC_x) (US$)	Mobilization / demobil. cost (MC_x) (US$)	Major improvement via management
01	*Construction start*	*2013/9/3*	–	–	–	–	–	–	–	–	–	–	–
11	*Piling work*	*2013/9/3*	*2013/12/28*	*116.00*	*27,720*	*M*	*20*	*18*	*18*	*0.6*	*6,003,000*	*1,800*	*Owner inspection*
21	*Foundation-bunker area*	*2013/12/28*	*2014/4/27*	*120.50*	*5,060*	*M3*	*100*	*63*	*63*	*12*	*1,442,385*	*6,300*	*Site access way*
22	*Foundation-boiler area*	*2014/2/26*	*2014/7/26*	*150.00*	*9,000*	*M3*	*100*	*90*	*90*	*12*	*2,565,000*	*9,000*	*Site access way*
23	*Foundation-air preheater area*	*2014/4/27*	*2014/9/10*	*136.00*	*8,420*	*M3*	*100*	*93*	*93*	*12*	*2,403,120*	*9,300*	*Site access way*
31	Structure erection-bunker area	2014/9/10	2015/2/7	150.00	3,830	Ton	80	64	64	20	1,440,000	6,400	Lifting arrangement
32	*Structure erection-boiler area*	*2014/9/10*	*2015/4/7*	*209.50*	*10,470*	*Ton*	*200*	*125*	*125*	*20*	*3,928,125*	*12,500*	*Lifting arrangement*
33	Structure erection-air preheater area	2015/12/7	2016/6/5	181.00	3,470	Ton	60	48	48	20	1,303,200	4,800	Lifting arrangement
41	*Boiler proper erection-Furnace upper portion*	*2015/4/7*	*2015/10/7*	*183.00*	*9,145*	*DB*	*50*	*25*	*25*	*4*	*1,944,375*	*2,500*	*Resolution of nonconformity*
42	*Boiler proper erection-Furnace lower portion*	*2015/8/23*	*2016/2/20*	*181.00*	*10,483*	*DB*	*50*	*29*	*29*	*4*	*2,230,825*	*2,900*	*Resolution of nonconformity*
43	Boiler proper erection-HRA portion	2015/7/9	2016/2/5	210.50	42,907	DB	150	102	102	4	9,125,175	10,200	Reduction of nonconformity
51	Auxiliary equipment erection	2015/1/8	2016/3/21	438.00	5,500	Ton	100	55	55	35	4,215,750	5,500	Timely technical advice
52	Ducting erection	2015/10/8	2016/5/4	209.50	3,215	Ton	60	48	48	25	2,011,200	4,800	Lifting arrangement
61	Main piping work	2015/6/6	2016/1/19	227.00	37,760	DB	60	50	50	2.4	2,553,750	5,000	Welding training
62	Misc. piping work	2015/6/6	2016/1/18	226.00	31,630	DB	60	42	42	2.4	2,040,780	4,200	Welding training
63	Utility piping work	2015/8/24	2016/2/16	176.50	16,000	DB	30	17	17	1.5	525,088	1,700	Daily coordination
64	Coal piping work	2015/11/22	2016/6/23	214.00	410	Ton	20	6	6	25	224,700	600	Temporary storage sequence
71	Electrical installation	2015/4/8	2016/6/29	448.00	300,000	M	100	67	67	0.8	4,202,240	6,700	Daily coordination
81	Instrument installation	2015/4/8	2016/6/28	447.50	330,000	M	120	83	83	0.9	5,199,950	8,300	Daily coordination
91	*Boiler proper insulation*	*2016/2/20*	*2016/9/1*	*193.50*	*13,000*	*M2*	*80*	*42*	*42*	*5*	*1,422,225*	*4,200*	*Material preparation*
92	Ducting & Aux. equipment insulation	2016/3/11	2016/8/8	150.00	24,000	M2	120	80	80	4	2,100,000	8,000	Material preparation
93	Piping insulation	2016/1/19	2016/6/17	150.00	4,500	M2	20	15	15	4	393,750	1,500	Daily coordination
A1	Boiler proper refractory	2016/6/3	2016/7/31	58.50	80	M3	20	12	12	70	245,700	1,200	Mixer arrangement
B1	*Mechanical completion*	–	*2016/9/1*	–	–	–	–	–	–	–	–	–	–
Total											57,520,338	117,400	



Activity ID	Activity Name	Predecessors	Successors	Start	Finish	Original Duration	Total Float
	Ultra-Supercritical Boiler Construction Master Schedule			2013/09/03	2016/09/01	1094.00	0.00
01	Construction start		11	2013/09/03		0.00	0.00
11	Piling work	01	21, 22, 23	2013/09/03	2013/12/28	116.00	0.00
21	Foundation-Bunker area	11	22, 31	2013/12/28	2014/04/27	120.50	0.00
22	Foundation-Boiler area	21, 11	23, 32, 31	2014/02/26	2014/07/26	150.00	0.00
23	Foundation-Air preheater area	22, 11	33, 31, 32	2014/04/27	2014/09/10	136.00	0.00
31	Structure erection-Bunker area	21, 22, 23	51, 61, 64, 62, 63, 71, 81	2014/09/10	2015/02/07	150.00	24.00
32	Structure erection-Boiler area	22, 23	41, 52, 61, 51, 62, 63	2014/09/10	2015/04/07	209.50	0.00
33	Structure erection-Air preheater area	23, 43	52	2015/12/07	2016/06/05	181.00	29.50
41	Boiler proper erection-Furnace upper portion	32	42, 43, 51, 91, 61, 62	2015/04/07	2015/10/07	183.00	0.00
42	Boiler proper erection-Furnace lower portion	41	51, 91	2015/08/23	2016/02/20	181.00	0.00
43	Boiler proper erection-HRA portion	41	51, 91, 33	2015/07/09	2016/02/05	210.50	15.50
51	Auxiliary equipment erection	31, 42, 41, 43, 32	64, 63, 71, 81, 92	2015/01/08	2016/03/21	438.00	24.00
52	Ducting erection	32, 33	92	2015/10/08	2016/05/04	209.50	29.50
61	Main piping work	32, 31, 41	93	2015/06/06	2016/01/19	227.00	75.50
62	Misc. piping work	31, 32, 41	B1	2015/06/06	2016/01/18	226.00	226.50
63	Utility piping work	51, 31, 32	B1	2015/08/24	2016/02/16	176.50	197.50
64	Coal piping work	31, 51	B1	2015/11/22	2016/06/23	214.00	70.00
71	Electrical installation	51, 31	B1, 81	2015/04/08	2016/06/29	448.00	64.00
81	Instrument installation	51, 31, 71	B1	2015/04/08	2016/06/28	447.50	64.50
91	Boiler proper insulation	41, 42, 43	A1, B1	2016/02/20	2016/09/01	193.50	0.00
92	Ducting & Aux. Equipment insulation	52, 51	B1	2016/03/11	2016/08/08	150.00	24.00
93	Piping insulation	61	B1	2016/01/19	2016/06/17	150.00	75.50
A1	Boiler proper refractory	91	B1	2016/06/03	2016/07/31	58.50	31.50
B1	Mechanical completion	A1, 93, 92, 81, 71, 64, 63, 62, 91			2016/09/01	0.00	0.00

Portfolio: All Projects | User: admin | Data Date: 2013/09/03 | Access Mode: Shared | Baseline: Current Project

Figure 4. Master schedule of ultra-supercritical boiler construction

Table 6. Improvement factor versus duration and cost: Case II

Activity	Improvement factor (I_x)	Improvement duration (day)	Improvement cost (US\$/day)	Activity	Improvement factor (I_x)	Improvement duration (day)	Improvement cost (US\$/day)
11	$I_{11} = 1$ $1 > I_{11} \geqq 1/1.05$ $1/1.05 > I_{11} \geqq 1/1.1$	0 15 29	0 47,438 91,713	52	$I_{52} = 1$ $1 > I_{52} \geqq 1/1.05$ $1/1.05 > I_{52} \geqq 1/1.1$	0 26 52	0 5,720 11,440
21	$I_{21} = 1$ $1 > I_{21} \geqq 1/1.05$ $1/1.05 > I_{21} \geqq 1/1.1$	0 15 30	0 3,135 6,270	61	$I_{61} = 1$ $1 > I_{61} \geqq 1/1.05$ $1/1.05 > I_{61} \geqq 1/1.1$	0 28 57	0 6,930 14,108
22	$I_{22} = 1$ $1 > I_{22} \geqq 1/1.05$ $1/1.05 > I_{22} \geqq 1/1.1$	0 19 38	0 3,971 7,942	62	$I_{62} = 1$ $1 > I_{62} \geqq 1/1.05$ $1/1.05 > I_{62} \geqq 1/1.1$	0 28 57	0 6,622 13,481
23	$I_{23} = 1$ $1 > I_{23} \geqq 1/1.05$ $1/1.05 > I_{23} \geqq 1/1.1$	0 17 34	0 3,553 7,106	63	$I_{63} = 1$ $1 > I_{63} \geqq 1/1.05$ $1/1.05 > I_{63} \geqq 1/1.1$	0 22 44	0 4,235 8,470
31	$I_{31} = 1$ $1 > I_{31} \geqq 1/1.05$ $1/1.05 > I_{31} \geqq 1/1.1$	0 19 38	0 3,135 6,270	64	$I_{64} = 1$ $1 > I_{64} \geqq 1/1.05$ $1/1.05 > I_{64} \geqq 1/1.1$	0 27 54	0 5,198 10,395
32	$I_{32} = 1$ $1 > I_{32} \geqq 1/1.05$ $1/1.05 > I_{32} \geqq 1/1.1$	0 26 52	0 4,290 8,580	71	$I_{71} = 1$ $1 > I_{71} \geqq 1/1.05$ $1/1.05 > I_{71} \geqq 1/1.1$	0 56 112	0 8,624 17,248
33	$I_{33} = 1$ $1 > I_{33} \geqq 1/1.05$ $1/1.05 > I_{33} \geqq 1/1.1$	0 23 45	0 3,795 7,425	81	$I_{81} = 1$ $1 > I_{81} \geqq 1/1.05$ $1/1.05 > I_{81} \geqq 1/1.1$	0 56 112	0 8,624 17,248
41	$I_{41} = 1$ $1 > I_{41} \geqq 1/1.05$ $1/1.05 > I_{41} \geqq 1/1.1$	0 23 46	0 10,753 21,505	91	$I_{91} = 1$ $1 > I_{91} \geqq 1/1.05$ $1/1.05 > I_{91} \geqq 1/1.1$	0 24 48	0 4,620 9,240
42	$I_{42} = 1$ $1 > I_{42} \geqq 1/1.05$ $1/1.05 > I_{42} \geqq 1/1.1$	0 23 45	0 10,753 21,038	92	$I_{92} = 1$ $1 > I_{92} \geqq 1/1.05$ $1/1.05 > I_{92} \geqq 1/1.1$	0 19 38	0 3,658 7,315
43	$I_{43} = 1$ $1 > I_{43} \geqq 1/1.05$ $1/1.05 > I_{43} \geqq 1/1.1$	0 26 53	0 12,155 24,778	93	$I_{93} = 1$ $1 > I_{93} \geqq 1/1.05$ $1/1.05 > I_{93} \geqq 1/1.1$	0 19 38	0 3,658 7,315
51	$I_{51} = 1$ $1 > I_{51} \geqq 1/1.05$ $1/1.05 > I_{51} \geqq 1/1.1$	0 55 110	0 10,588 21,175	A1	$I_{A1} = 1$ $1 > I_{A1} \geqq 1/1.05$ $1/1.05 > I_{A1} \geqq 1/1.1$	0 7 15	0 2,695 5,775

5. Result of analysis

5.1. Case I

Extreme data test

If the decision maker determines to improve labor productivity through management on all activities. The results show that when improvement factor (I_x) performs the maximum output valued at 0.833 (1/1.2), the project duration will be reduced from 381.25 days to 361.38 days; however, the project direct labor cost increases from $17,513,000 to $17,591,183. On the other hand, if the decision maker decides to mobilize all available labor to reduce the schedule, the project duration will become 302.34 days, but the project direct labor cost increases to $24,658,750. Note that both decisions cannot reduce the project duration and stay under budget simultaneously.

Optimization results

The optimization results analyzed using Palisade Evolver are shown in Table 7. As can be seen, the project duration is reduced from 381.25 days to 342.49 days (i.e., a reduction of 38.76 days; 10.2%). The project direct labor cost is reduced from $17,513,500 to $17,499,482 (12,721,482 + 230,000 + 4,548,000).

If the optimization is further evaluated using the minimum unit of duration, i.e., 0.5 days, the project duration is reduced from 383 days to 347 days (i.e., a reduction of 36 days; 9.4%). The project direct labor cost is reduced from $17,596,000 to $17,570,400.

The duration of each activity is reduced sequentially in the optimization process, and after optimization, the final CP remains on 01→03→06→09→10.

5.2. Case II

Extreme data test

Following the test in case I, decision maker might improve labor productivity through management on all activities as the maximum improvement or mobilize all available labor to accelerate the schedule. The two extreme strategies are both accelerated and schedules (i.e. 1071 and 992 days) are less than 1,094 days. However, the costs (i.e. US$ 57,796,274 and 73,594,450) are over budget (US$ 57,637,738).

Optimization results

The optimization results analyzed using Palisade Evolver are shown in Table 8. As can be seen, the project duration under 0.5 days' minimum unit is reduced from 1094 days to 1047.5 days (i.e., a reduction of 46.5 days; 4.3%). The project direct labor cost is reduced from US$57,637,738 to US$57,619,505 (43,970,770 + 106,200 + 13,542,535).

The duration of each activity is reduced sequentially in the optimization process, and after optimization, the final CP changes from 01→11→21→22→23→32→41→42→91→B1 to 01→11→21→22→23→31→51→81→92→B1.

To sum up the results, either the simplified test case or the real world case can apply the improved TCT model to find the optimal solution. The first illustrative case is further discussed in the next section.

6. Discussion

It is worth improving productivity if (1) the reduced duration of the project schedule is greater than the increased duration of improvement on the CP, and (2) the increased

Table 7. Optimization with optimal productivity: Case I

Activity (x)	Activity duration (OD_x) (day)	Improvement duration (MD_x) (day)	Finish date (PD) (date)	Remaining work to be done (Q_x'') (unit)	Work done during improving period (Q_x') (unit)	Resource availability limit (R_x) (manpower)	Labor usage (U_x) (man-power)	Working environment allowance (A_x) (manpower)	Congestion factor (C_x)	Improvement factor (I_x)	Labor productivity (P_x) (mh/q)	Optimal productivity (O_x) (mh/q)	Direct labor cost (DC_x) (dollar)	Mobilization /demobil. cost (MC_x) (dollar)	Improvement cost (IC_x) (dollar)
01	*59.33*	*36*	*95.33*	*227.84*	*92.16*	*20*	*10*	*10*	*1.0*	*0.83*	*25.00*	*20.83*	*1,186,667*	*20,000*	*864,000*
02	46.76	14	156.09	205.20	44.80	20	15	15	1.0	0.91	30.00	27.35	1,402,834	30,000	504,000
03	*51.73*	*7*	*154.06*	*364.16*	*35.84*	*20*	*16*	*16*	*1.0*	*0.91*	*20.00*	*18.18*	*1,655,273*	*32,000*	*268,800*
04	105.89	14	215.23	319.28	30.72	20	12	12	1.0	0.91	35.00	31.84	2,541,435	24,000	403,200
05	51.78	10	217.87	496.00	64.00	20	10	10	1.0	0.84	10.00	8.35	1,035,590	20,000	240,000
06	*59.46*	*28*	*241.52*	*228.32*	*71.68*	*20*	*8*	*8*	*1.0*	*0.83*	*20.00*	*16.67*	*951,334*	*16,000*	*537,600*
07	63.99	14	293.22	436.00	64.00	20	10	10	1.0	0.84	14.00	11.74	1,279,785	20,000	336,000
08	54.62	14	286.49	286.24	53.76	20	12	16	1.0	0.92	20.00	18.32	1,310,838	24,000	403,200
09	*38.84*	*14*	*294.36*	*237.28*	*62.72*	*20*	*7*	*6*	*1.1*	*0.83*	*10.00*	*9.17*	*543,767*	*14,000*	*235,200*
10	*27.13*	*21*	*342.49*	*119.36*	*80.64*	*20*	*15*	*10*	*1.2*	*0.91*	*25.00*	*27.28*	*813,960*	*30,000*	*756,000*
Total	–	–	–	–		–	–	–	–	–	–	–	12,721,482	230,000	4,548,000

Table 8. Optimization with optimal productivity: Case II

Activity (i)	Activity duration (OD_x) (day)	Improvement duration (MD_x) (day)	Finish date (PD) (date)	Remaining work to be done (Q_x'') (unit)	Work done during improving period (Q_x') (unit)	Resource availability limit (R_x) (manpower)	Labor usage (U_x) (man-power)	Working environment allowance (A_x) (manpower)	Congestion factor (C_x)	Improvement factor (I_x)	Labor productivity (P_x) (mh/q)	Optimal productivity (O_x) (mh/q)	Direct labor cost (DC_x) (dollar)	Mobilization /demobil. cost (MC_x) (dollar)	Improvement cost (IC_x) (dollar)
01	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
11	*84.00*	29	*113.00*	*22,152.00*	*5,568.00*	*20*	*18*	*18*	*1.0*	*0.91*	*0.6*	*0.55*	*4,347,000*	*1,800*	*1,650,825*
21	*208.50*	30	*351.50*	*4,580.00*	*480.00*	*100*	*30*	*63*	*1.0*	*0.91*	*12*	*10.92*	*1,188,450*	*3,000*	*188,100*
22	*153.00*	38	*364.00*	*7,621.87*	*1,378.13*	*100*	*68*	*90*	*1.0*	*0.91*	*12*	*10.91*	*1,976,760*	*6,800*	*540,056*
23	*99.00*	34	*366.00*	*6,733.60*	*1,686.40*	*100*	*93*	*93*	*1.0*	*0.91*	*12*	*10.91*	*1,749,330*	*9,300*	*660,858*
31	*108.50*	38	*512.50*	*3,051.76*	*778.24*	*80*	*64*	*64*	*1.0*	*0.91*	*20*	*18.20*	*1,041,600*	*6,400*	*401,280*
32	153.00	52	571.00	8,390.00	2,080.00	200	125	125	1.0	0.91	20	18.18	2,868,750	12,500	1,072,500
33	193.00	45	1041.50	2,966.00	504.00	60	35	48	1.0	0.91	20	18.19	1,013,250	3,500	259,875
41	121.00	46	738.00	7,010.60	2,134.40	50	29	25	1.1	0.91	4	4.00	1,491,325	2,900	623,645
42	133.00	45	871.00	8,395.00	2,088.00	50	29	29	1.0	0.92	4	3.67	1,639,225	2,900	610,088
43	189.50	26	863.50	38,830.20	4,076.80	150	98	102	1.0	0.96	4	3.82	7,892,675	9,800	1,191,190
51	*318.00*	*110*	*910.50*	*4,393.71*	*1,106.29*	*100*	*55*	*55*	*1.0*	*0.91*	*35*	*31.82*	*3,060,750*	*5,500*	*1,164,625*
52	157.00	52	952.50	2,589.34	625.66	60	47	48	1.0	0.91	25	22.73	1,475,800	4,700	537,680
61	187.50	57	875.50	30,920.00	6,840.00	60	45	50	1.0	0.91	2.4	2.18	1,898,438	4,500	634,838
62	334.00	57	1022.00	28,134.00	3,496.00	60	23	42	1.0	0.91	2.4	2.18	1,651,630	2,300	310,052
63	271.50	44	1016.00	14,310.40	1,689.60	30	9	17	1.0	0.91	1.5	1.36	427,613	900	76,230
64	194.00	54	1038.50	340.88	69.12	20	5	6	1.0	0.91	25	22.73	169,750	500	51,975
71	358.50	112	1043.00	244,448.00	55,552.00	100	62	67	1.0	0.91	0.8	0.73	3,111,780	6,200	1,069,376
81	*363.00*	*112*	*1047.50*	*269,470.22*	*60,529.78*	*120*	*76*	*83*	*1.0*	*0.91*	*0.9*	*0.82*	*3,862,320*	*7,600*	*1,310,848*
91	124.50	48	1043.50	9,928.00	3,072.00	80	50	42	1.1	0.91	5	5.00	1,089,375	5,000	462,000
92	*109.00*	38	*1047.50*	*19,136.00*	*4,864.00*	*120*	*80*	*80*	*1.0*	*0.91*	*4*	*3.64*	*1,526,000*	*8,000*	*585,200*
93	130.00	38	1043.50	3,709.60	790.40	20	13	15	1.0	0.91	4	3.64	295,750	1,300	95,095
A1	69.00	15	1037.50	69.03	10.97	20	8	12	1.0	0.91	70	63.68	193,200	800	46,200
B1	–	–	*1047.50*	–	–	–	–	–	–	–	–	–	–	–	–
Total	–	–	–	–	–	–	–	–	–	–	–	–	43,970,770	106,200	13,542,535

cost of improvement is less than the reduced project direct labor cost. The optimization results show that the reduction of the original project duration, i.e., 144.76 days, is greater than the increase of improvement, i.e., 106 days. In addition, the increased improvement cost of $4,548,000 is still less than the decreased project direct labor cost of $4,562,018. Consequently, the feasibility of the proposed optimization technique is corroborated.

6.1. Resource allocation trade-off

Furthermore, from a resource allocation perspective, when the actual labor usage (U_x) is greater than the working environment allowance (A_x), labor productivity deteriorates because of congestion in the working environment. Therefore, the actual labor usage in most activities is less than the working environment allowance, e.g., activities 01–08. However, labor usage in some activities is still greater than the working environment allowance, e.g., activities 09 and 10. This reveals that bearing the productivity loss due to congestion to reduce the project duration can become an optimized solution if the project direct labor cost after improvement is still under the original budget. The similar result can be validated in case II (e.g., activities 41 and 91).

6.2. Selective improvement

Although improving productivity through management can feasibly reduce the project duration, not all activities are worth improving in consideration of the TCT. The optimized result from the previous section demonstrates that the improvement factors for activities 02, 03, 04, 08, and 10 are approximately 0.91 (1/1.1), which does not maximize improvement. The similar result can be validated in case II (e.g., activities 43). It is concluded that selective improvement of activities can achieve optimization using GAs.

In the beginning of the project, the contractor may not be familiar with the working environment for each activity. The amount of the project direct labor cost in the contract may not be estimated according to optimum resource allocation and labor productivity. The optimized project duration with labor usage and optimal productivity obtained via GAs can be achieved without going over budget while reducing the risk of LD, as shown in Figure 5 (diagonal area).

Table 9 presents the original resource allocation and six sets of optimization without going over budget. Although the optimal set 6 with acceleration rate (10%) is the best option, the decision maker can still arrange flexible labor usage as other optimization sets depending on actual acceleration goal (acceleration rate %) as long as the cost is still under budget.

6.3. Comparison with previous techniques

In previous TCT optimization techniques, the project total cost is generally composed of direct and indirect cost which are negatively and positively related to the project duration. When the duration is compressed, the indirect cost is reduced, but the direct cost is inevitably increased owing to inefficiency by crashing or rework by fast-tracking. As a result, the total cost presented as a concave could achieve the minimum with the optimal reduction of time. However, the direct cost might not be necessarily increased with the schedule acceleration if the efficiency of resource utilization can be improved as the proposed model. Consequently, the total cost can be further reduced once considering indirect cost simultaneously.

To illustrate the advance of proposed model and major difference from previous researches on direct cost, the variation rate on time and direct cost optimization using major TCT techniques and methodologies are presented for a comparative review (As shown in Table 10). It reveals that in consideration of optimal labor productivity, the direct cost can even reduce after optimization.

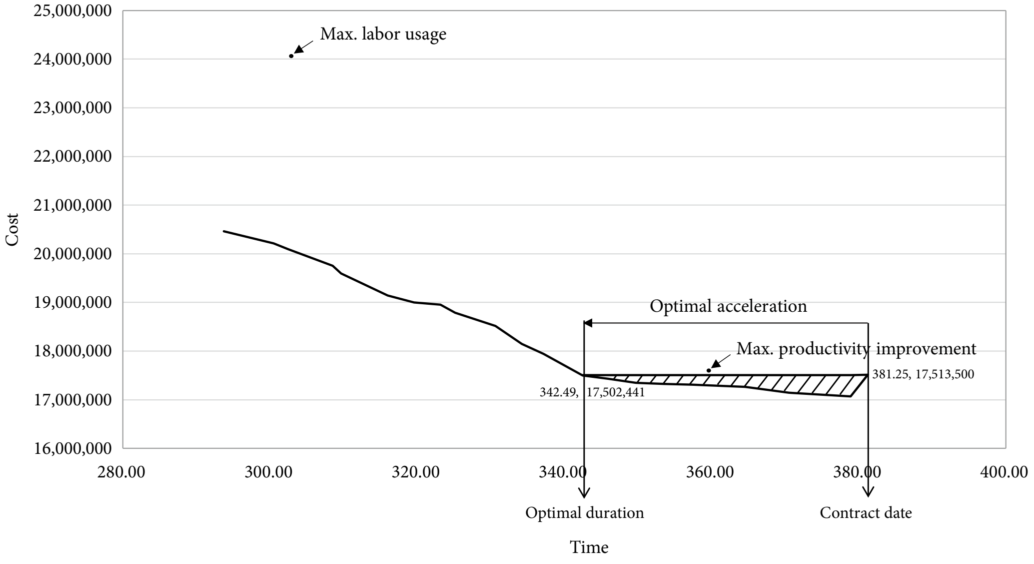


Figure 5. Optimization of time-cost trade off curve

Table 9. Optimal sets for schedule acceleration

Variable of activity	Original	Optimal set 1	Optimal set 2	Optimal set 3	Optimal set 4	Optimal set 5	Optimal set 6
U_{01}	10	10	10	10	10	10	10
U_{02}	15	12	13	13	14	13	15
U_{03}	16	14	15	15	16	16	16
U_{04}	12	11	12	12	12	12	12
U_{05}	10	9	9	9	9	10	10
U_{06}	8	8	8	8	8	8	8
U_{07}	10	10	9	9	10	10	10
U_{08}	16	13	13	13	13	13	12
U_{09}	6	6	6	6	6	7	7
U_{10}	10	10	11	13	14	14	15
I_{01}	1	0.84	0.84	0.83	0.83	0.83	0.83
I_{02}	1	0.93	0.93	1.00	1.00	1.00	0.91
I_{03}	1	0.92	0.92	0.91	0.91	0.91	0.91
I_{04}	1	0.91	0.91	0.91	0.91	0.91	0.91
I_{05}	1	0.83	0.83	0.83	0.83	0.83	0.84
I_{06}	1	0.83	0.83	0.83	0.83	0.83	0.83
I_{07}	1	0.83	0.83	0.83	0.83	0.83	0.84
I_{08}	1	1.00	1.00	1.00	1.00	1.00	0.92
I_{09}	1	0.83	0.83	0.83	0.83	0.83	0.83
I_{10}	1	0.91	0.91	0.91	0.91	0.91	0.91
Time (day)	381.25	370.54	364.54	357.32	349.72	345.96	342.49
Acceleration rate, %	0%	2%	4%	6%	8%	9%	10%
Cost (dollar)	17,513,500	17,143,458	17,265,557	17,307,283	17,349,602	17,428,361	17,499,482

Table 10. Comparison of optimization rate between various TCT techniques and methodologies

Researcher	TCT Technique	Methodology	Variation rate on time optimization	Variation rate on cost optimization
Li and Love (1997)	Crashing	GAs	−24.2%	+70.1%
Hegazy (1999)	Crashing	GAs	−34.9%	+6.5%
El-Rayes and Kandil (2005)	Crashing	GAs	−16.1%	+59.0%
Klansek (2016)	Fast-tracking	Mixed-integer nonlinear programming	−23.7%	+12.6%
This study case I	Management-improve productivity	GAs	−10.2%	-0.08%
This study case II	Management-improve productivity	GAs	−4.3%	-0.03%

Comparing with previous TCT optimization techniques and proposed model in this study, even though the effect of previous techniques is instant, relevant side effects are major concerns as shown in Figure 6. Although time acceleration through management might take longer time such as improving process, decreasing waste, training or incentive, they can not only fulfil the optimization without side effect, but also accumulate the competence of the existing crews.

6.4. Expert judgement

In order to further emphasize the superiority and robustness of the proposed model using GAs, referring to Dehghan et al. (2015) research, two schedule professionals (one has 15 years of work experience and the other has 30 years) were invited in the experiment to optimize the results. After explaining the purpose of optimization and required information such as maximum resource usage, maximum improvement of each activity, they were requested to maximum the schedule acceleration under budget for case I. For experiment time, there is half hour for the illustrative case. The best results provided by two professionals were as follows:

One schedule professionals reduced 16.27 days with $107,315 saving, the other reduced 22.28 days with $22,892 saving when the time is up. However, comparing

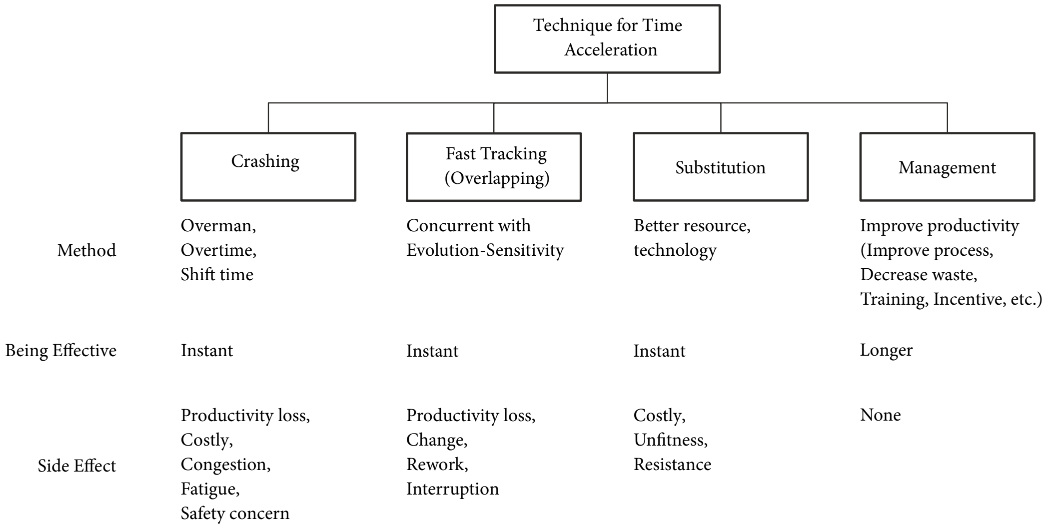


Figure 6. Optimization technique for time acceleration

Table 11. Comparison of optimization results between GAs and expert experiments

Case I	Original project duration (day)	Original project direct cost (dollar)	Optimized project duration (day)	Optimized project direct cost (dollar)	Reduction of project duration (day)	Reduction of project direct cost (dollar)	Critical path changed (Yes/No)	Computation time (minute)
GAs	381.25	17,513,500	342.49	17,499,482	38.76	14,018	No	8
Expert 1	381.25	17,513,500	363.73	17,406,085	16.27	107,415	No	30
Expert 2	381.25	17,513,500	357.73	17,490,508	22.28	22,992	No	30

with optimization result using GAs, GAs performed a better optimization result (i.e. 38.76 days with 14,018 saving) with better efficiency (i.e. within 10 minutes). The comparison between GAs and expert experiments is shown in Table 11. Detail information and several rounds of computation are provided in Appendix 1.

Conclusion and recommendation

In most previous studies, the TCT was typically executed by optimization techniques of crashing by increasing external resources, overlapping activities or substitution of external resources. However, improving the productivity of existing crews was not considered among those techniques. After reviewing previous critical studies, this paper has presented an optimization technique for reducing a project duration. The improved TCT model considers variable productivity influenced by the working environment and management to search for an optimized solution using GAs on the most popular program platform (i.e. Microsoft Excel) instead of a specific program. Therefore, applying the proposed model to real projects will be easier for researcher and practitioner.

Through an illustrative case and a real world case, the results demonstrate that the decision maker can reduce a project duration under the original budget, while avoiding side effects presented in current optimization techniques, such as rework or fatigue. The optimized solutions with variable productivity under different working environment constraints can be considered a benchmark and direction for further improvement.

Although improving productivity though management seemed to be commonplace in industry, few studies have examined the factor in the TCT optimization. Ultimately, the effect of improvement is feasible in the long term, and even in a given period as long as the increased duration of the improvement is less than the decreased project duration.

The main contribution of this study is to apply managerial improvement of labor productivity to TCT optimization which has not been addressed in previous researches. As a result, the project duration can be reduced owing to improved productivity of existing crews rather than inefficient overmanning, overlapping or costly substitution. Furthermore, it would be beneficial for organizational learning and competitiveness in the long term development. This study also recommends that the decision maker shall employs the proposed optimization technique as their initial consideration to reduce a project duration and decrease the risk of LD when addressing the TCT problem under limited budget.

This study has also presented three important managerial insights from the proposed model:

1. Rather than thorough improvement, selective improvement among the project activities is considered critical in the process of the optimization. GAs

can help practitioners optimize improvements in a large construction project.

2. Although labor productivity deteriorate when the allocated labor usage is greater than the given working environment allowance, the allocation will be still adopted to reduce the project duration under TCT optimization.
3. Reducing the project duration does not necessarily increase the project direct labor cost. In consideration of tight schedule pressure, the cost the contractor pays for acceleration through the proposed TCT model with optimal productivity may not exceed direct labor cost of contract budget. This insight can be shared with owners and contractors when evaluating reasonable duration and compensation relative to project acceleration.

This study contributes to the body of knowledge and bridges the proposed model to a real-world application. However, the following limitations shall be considered:

1. The effectiveness of improvement through management necessitates time delay. Because of the uniqueness of a construction project, this study cannot identify how long the duration of a project can be applied into the model.
2. The evaluation of the improvement factor depends on schedulers with different experience. It may incur additional burden and time in the beginning of construction works.

Future research can expand the proposed model to be more complete, such as combining other acceleration techniques or resources, considering fuzzy logic to reduce bias when evaluating the improvement factor, or distinguishing environment and management into more specific variables to examine the influence of optimal productivity.

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Disclosure statement

Data generated or analyzed during the study are available from the corresponding author by request.

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Notation

C – congestion factor; a function of actual labor usage (U) versus labor allowance (A) in a work environment (E);

CB – contract budget;

CD – original contract duration;

D – duration of an activity;

DC_x – direct labor cost;

E – working environment allowance;

I – improvement factor; an index of measuring the improvement effect through management;

IC_x – cost of improving productivity through management;

L – skill required to fulfil the work;

M – management method identified as improvement of labor productivity;

MC_x – labor mobilization/demobilization cost;

$MD_j^{U'P'Q'}$ – improvement duration of activity (j);

mh – input man hours (mh) to measure labor productivity;

q – unit output work quantity (q) to measure labor productivity;

O – optimal labor productivity; the value considering both congestion factor (C) and labor productivity after improvement (P'');

OD_i^{UPQ} – original duration of activity (i) on the critical path;

$OD_j^{U'P''Q''}$ – new duration of activity (j) on the critical path after optimization;

P – labor productivity;

P' – labor productivity during the improvement period;

P'' – improved labor productivity after improvement;

PC – project direct labor cost;

PD – project duration;

Q – work quantity;

Q' – quantity of work during the improvement period;

Q'' – quantity of work after optimization;

U – labor resource usage;

U' – labor resource usage during the improvement period;

W – work content such as work scope or work complexity.

APPENDIX

GAs execution details

Laptop attributes are listed as follows to show operation environment:

- Processor: Intel(R) Core™ i5 CPU M460 @ 2.53GHz;
- Installed memory (RAM): 6.00 GB;
- System type: 64-bit Operating System;
- Operation system: Windows 7 Professional.

The following GAs parameters using 2 programs were fine-tuned in the proposed model to obtain the good performance. The optimization solution time, duration and cost in 2 cases are presented as the average value of the best 10 experiments:

1. GAs parameters using Microsoft Excel Evolutionary Solver:
   - Convergence: 0.0001;
   - Mutation rate: 0.9;
   - Population size: 100;
   - Random seed: 0;
   - Maximum time without improvement: 240 seconds.

   Case I:
   - Optimization solution time: 529 seconds;
   - Optimization duration: 344.03 day;
   - Optimization cost: $17,493,421.

   Case II:
   - Optimization solution time: 677.07 seconds;
   - Optimization duration: 1,054.36 day;
   - Optimization cost: US$ 1,152,457,692.
2. GAs parameters using Palisade Evolver:
   - Optimization runtime: maximum change 0.1%.

   Case I:
   - Population size: 100;
   - Crossover rate: 0.8;
   - Mutation rate: 0.05;
   - Optimization solution time: 467 seconds;
   - Optimization duration: 342.95day;
   - Optimization cost: $17,497,252.

   Case II:
   - Population size: 50;
   - Crossover rate: 0.8;
   - Mutation rate: 0.1;
   - Optimization solution time: 477 seconds;
   - Optimization duration: 1052.6 day;
   - Optimization cost: US$ 1,152,258,095.