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The time-cost trade-off problem and its extensions: A state-of-the-art survey and outlook

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C H R O N I C L E

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A B S T R A C T

The time-cost optimization is amongst the most critical fields, which has an extensive range of implementation in project scheduling. Achieving a satisfactory balance between these factors can lead to an efficient construction project by reducing both the length of the project and costs at the same time. An effective balance can be achieved using various methods, depending on the situation. This study aims to incorporate the various algorithms used in the last 15 years to reach a satisfying balance between time and cost, including meta-heuristics, heuristics, and exact algorithms. A comprehensive view of the problems associated with time-cost optimization will be provided throughout this review to assist new and challenging researchers who are interested in this type of research. For this purpose, we have reviewed some objective functions and uncertainty techniques that could be employed in time-cost balancing problems. The literature review tables contain a variety of columns, including uncertainties such as fuzzy, probabilistic, interval, robust, and objective functions, along with cost and time, for the investigation of various types of balance issues. In the conclusion of this article, we will show the results of our literature review table using different types of graphic diagrams. For each main column of the table, we will show various types of diagrams to make the results easier to understand.

1. Introduction

Project scheduling is a mathematical subject in operation research that involves identifying each activity's start and finish times as a means of optimizing a specific objective, as well as considering resource constraints and priorities between activities in a projection of each industry (Mohagheghi et al., 2017).The preliminary research on time-cost balancing was carried out in 1950 and emphasized the importance of preparing a network using Critical Path Methods (CPM) (Robinson, 1975; Siemens, 1971). and Program Evaluation and Review Techniques (PERT) (Azaron et al., 2005), both of which are essential tools for project management.

In recent years, researchers have done numerous studies on a wide range of topics relating to project scheduling, as well as the extension of project scheduling to time scheduling, budget scheduling, and resource scheduling. Particularly, one of the most prevalent topics in time-scheduling problems is the optimization of both time and costs, which is commonly referred to as TCTP in the industry. Over the years, extensive research has been conducted on TCTPs, which are the most common type of project scheduling problem (Vanhoucke & Debels, 2007). A major objective of the TCTP is to define activities' best duration while keeping their total cost to a minimum (Feng et al., 1997). It is also important to mention that TCTP is considered a multi-objective optimization when both duration and costs are to be reduced (Albayrak & Özdemir, 2017). There are various ways we can reduce the implementation time of each activity within a project if we allocate adequate

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facilities, such as labor, equipment, and procedures, to each one, so we can find an optimal balance of time and cost. To put it another way, each decrease in activity duration increases the cost of the activity (Abbasnia et al., 2008).

There is generally a normal time or a crash time that is required for each activity to be completed. Normal time is the amount of time spent on any project activity without interruption. It is important to note that by applying crash time to activities, we will require more direct costs and resources to complete them. In Figure. 1, D_n and D_c show normal duration and crash duration. Aside from direct costs, indirect costs are also present for each activity. The direct costs of the activity include labor, materials, and any type of facility that is required during the activity. As the name implies, indirect costs refer to those costs that do not directly relate to the project's activities, such as organization, public utilities, and the hiring of equipment. Also, C_n and C_c indicate as normal costs and crash costs in Fig. 1.

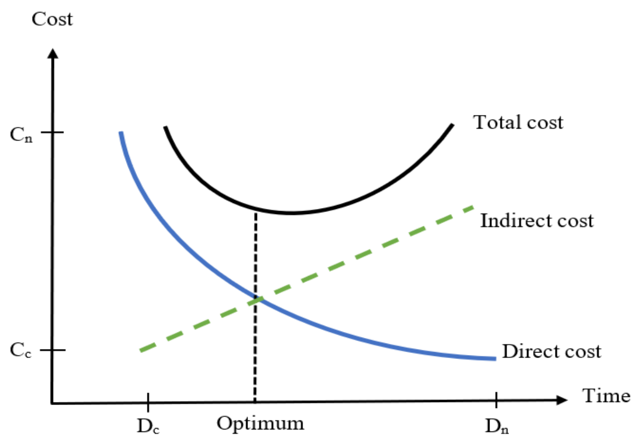

Fig. 1. The relationship between time and cost

As discussed previously, the cost slope is the extra direct cost associated with reducing an activity's normal duration by one unit. As well as this, crash costs and indirect costs are also inversely related; an increase in indirect costs will cause the project duration to be extended. We portray the time-cost relation in Fig. 1. It is clear from the total cost curve that a minimum value indicates the best or optimal project duration (Reda & Carr, 1989). This paper refers to a basic mathematical model that describes the TCTP, and we demonstrate its essential components. Indicators, variables, and parameters of the model are described below:

1.1. Sets and indices

J	Set of activities,
M	Set of modes,
$j = 1,2, \dots , n$	Index of activities,
$m = 1,2, \dots , M$	Index of modes,

1.2. Parameters

dc_{jm}	direct cost of activity *j* in mode *m*,
d_{jm}	Duration of activity *j* in mode *m*,
ic	Indirect cost,
T	Project deadline,
S_j	Start time of activity *j*,

S_k Start time of immediate activity *k* that occurs after activity *j*,

S_{n+1} Start time of activity *n+1* that occurs after last activity (*n*),

1.3. Variables

x_{jm} Binary variable taking the value of 1 if mode *m* is selected for executing activity *j*; otherwise, it is equal to 0,

$$\min \sum_{j=1}^{n} \sum_{m=1}^{m(j)} (dc_{jm} x_{jm}) + T * ic \tag{1}$$

subject to:

$$\sum_{m=1}^{m(j)} x_{jm} = 1 \qquad (j = 1, \dots, n), \tag{2}$$

$$\sum_{m=1}^{m(j)} d_{jm}\, x_{jm} + S_j \leq S_k \qquad (\forall k \in Sc_k;\ \forall j = 1, \dots, n), \tag{3}$$

$$S_{n+1} \leq T \tag{4}$$

$$S_j \geq 0 \qquad (\forall j \in N), \tag{5}$$

$$x_{jm} \in \{0,1\} \qquad (\forall m \in M;\ j = 1, \dots, n), \tag{6}$$

Based on the mentioned model, all project costs, including direct and indirect costs, are minimized. According to constraints (2), activity j must be linked with only one type of mode. Also, precedence constraints are displayed in the constraints (3). Constraint (4) states that the projects should not exceed the deadline time assigned to them. Finally, constraints (5) and constraints (6) show the type of the parameter and variable.

In the remaining sections of this paper, the purpose of the next section is to briefly outline the types of expansion of TCTP and the approaches that can be used to solve it. Section 3 shows a variety of different types of graphical results for the details of the literature review tables that were presented in part 2. As a final part of this study, we will review the summary and general findings of the study.

2. Literature Review

As reported in the literature, many models and approaches have been suggested to help project managers to plan and schedule their projects more efficiently. Numerous researchers have worked on this issue in recent decades. During this section, four studies that deal with time-cost trade-off extensions are discussed.

2.1. Time-Cost Trade-off Problem (TCTP)

Initially, Kelley Jr, (1961) considered a mathematical model to balance the linear relationship between cost and time. He provided a heuristic algorithm to gain optimal results. After that, many studies were done on this issue. Three mathematical models based on Integer Programming (IP) and Linear Programming (LP) were proposed by Jiang and Zhu, (2010) to enhance the performance of TCT. A Mixed Integer Nonlinear Programming (MINLP) was demonstrated by Klanšek and Pšunder, (2012) to identify the optimal duration of each activity. Li et al. (2015) suggested the model based on robust optimization of Mixed Integer Programming (MIP). They also considered time and cost as interval numbers. For discrete types of TCTP, Li et al. (2018) presented two heuristic methods that minimize project durations and costs. A nonlinear TCTP with activity crashing was introduced by Ballesteros-Pérez et al. (2019), and in order to optimize both objectives concurrently, they used a genetic algorithm (GA). Abdel-Basset et al. (2020) incorporated fuzzy uncertainty and neutrosophic numbers to deal with the uncertain conditions, and activity durations are estimated using trapezoidal neutrosophic numbers. Also, Elkalla et al. (2021) assumed fuzzy TCTP, and they used the nearest-symmetric trapezoidal fuzzy numbers

(TFN) for converting fuzzy numbers to solve the model. Finally, Dhawan et al. (2021) solved the TCTP by one of the meta-heuristic approaches called Simulated annealing (SA).

2.2. Time-Cost-Quality Trade-off Problem (TCQTP)

The TCTP problem is extendable by taking into account quality, which is an important factor that is affected by the reduction in time as well. Therefore, in TCTQPs, the overall goal is to implement projects in a short amount of time and with a minimum cost while maintaining a high level of quality. According to the literature, Babu & Suresh, (1996) argued that the failure of critical activities could negatively impact quality. Therefore, there is no doubt that quality should be evaluated along with time and cost in any project. In TCTPs, various approaches were implemented to address quality. To review the TCQTP, a survey study for gas and oil projects was carried out by Wood, (2017). His research was based on fuzzy multi-objective problems, and he solved them with a memetic multi-objective algorithm. Mrad et al. (2019) solved the TCQTP using a Monte-Carlo simulation based on a Mixed Integer Linear Programming (MILP) model. Banihashemi and Khalilzadeh, (2021) proposed the TCTQP by considering environmental impact and several execution modes for activities. They utilized the Data Envelopment Analysis (DEA) to trade-off between the objective function and reach the efficient execution mode. After that, Banihashemi et al. (2021) also suggested the TCQTP with environmental effects for industry projects. In their study, the problem was modeled as a single objective to obtain optimal results. Then, they use the Leopold matrix method to assess the environmental objectives. Hamta et al. (2021) assumed the quality function in the TCTP and handled the quality of the project in TCTP through a goal programming model. Finally, Sharma and Trivedi (2022) used a Non-Dominated Sorting Genetic Algorithm (NSGA-II) optimization approach that reduced both time and cost while at the same time increasing quality. They also weighed quality by using the Analytical Hierarchy Process (AHP) approach in TCQTP.

2.3. Time-Cost-Quality/Safety Trade-off Problem (TCQSTP)

According to relevant literature, kinds of research have included safety along with other objective functions. As an example, Ning and Lam (2013) suggested a model to trade-off safety along with cost in layout planning. Afshar and Zolfaghar Dolabi, (2014) have presented an analysis of the safety in TCTPs using NSGA-II to illustrate the importance of safety in construction projects. For the project's success, quality and safety are considered together, although there are few studies on this issue. For instance, Sharma & Trivedi, (2022) developed the TCQSTP by considering resource constraint and multi-mode activities. The real case study was a building construction project. They assumed fuzzy logic for safety parameters and used the NSGA-III. In addition, Panwar & Jha, (2021) integrated quality and safety to handle scheduling in construction projects. Based on this study, an NSGA-III approach was used to demonstrate how to generate an optimal balance.

2.4. Time-Cost-Quality-Energy-Environment Trade-off Problem (TCQEETP)

Recent developments have led to dramatic changes in the world. Many construction projects cause the emission of greenhouse gases and increase air pollution (Ali, et al., 2020). This pollution has a great impact on human life and increases climate change. Due to this, very few studies have included environmental impact reduction within the deadline and cost of the project or in other objective functions related to the project that was mentioned earlier in this article. For large-scale construction systems, Xu et al. (2012) presented multi-mode and fuzzy uncertainty balancing methods for trade-off discrete types of time-cost-environment factors. To determine the results, they used a genetic algorithm. A time-cost-quality-environment trade-off problem (TCQETP) has been proposed by Zheng, (2018), and he recommends using EBS-based GA for conducting optimizations. As mentioned previously, some other researchers investigated the TCQTP with considering environmental conditions. Tiwari, (2022) also solved the TCETP using NSGA-II. Furthermore, Lotfi, (2022) surveyed a full form of a trade-off as a TCQEETP by considering the resource constraint. They used robust optimization to deal with the uncertainty of the real case study as bridge construction. Also, the Augmented Epsilon Constraint (AUGEPS) was utilized to solve their model. In the other study, by incorporating Block Chain Technology (BCT) and risk into the resource-constrained TCQEETP model, Lotfi, (2022) improved the sustainability, resiliency, and agility of the project. To cope with uncertainty, they assumed robust stochastic programming (Özmen, 2011; Ben-Tal & Nemirovski, 2000), worst case scenarios, and conditional value at risk. Finally, they solved the proposed model with GAMS software for a real healthcare project.

Following the above discussion, the major purpose of this research is as follows:

1. Classification of approaches for solving TCTP based on an exact, heuristic, and meta-heuristic methods,
2. Considering the objective function from a single or a multidimensional perspective,
3. Investigating the types of uncertainties used for objective function in the literature review,
4. Use graphical results to display the results of this review.

Table 1
List of research to solve TCTP

References	Objective		Type of trade-off						Types of uncertainty	uncertain				Uncertain indices						Solution method				data type		Considerations
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Vanhoucke& Debels, (2007)	✓		✓	✓					✓													✓		✓		Neighbourhood Search
Azaron & Tavakkoli-Moghaddam, (2007)		✓	✓	✓						✓				✓						✓				✓		STEM
Azaron, et al., (2007)		✓	✓	✓						✓				✓						✓				✓		Goal programming
Azaron, et al., (2007)		✓	✓	✓						✓				✓								✓		✓		Simulated Annealing (SA)
Tareghian& Taheri, (2007)	✓		✓	✓	✓				✓													✓		✓		Electromagnetic scatter search
Xiong & Kuang, (2008)		✓	✓	✓					✓													✓		✓		Ant Colony Optimization
Abbasnia, et al., (2008)	✓		✓	✓								✓			✓							✓		✓		Nondominated Sorting Genetic Algorithm
Ghazanfari, et al., (2008)	✓		✓	✓								✓		✓							✓				✓	Goal programming

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Hooshyar, et al., (2008)	✓		✓	✓					✓														✓		✓	Genetic algorithm
Iranmanesh, et al., (2008)		✓	✓	✓	✓				✓														✓		✓	Fast Pareto Genetic Algorithm (Fast GA)
Eshtehardian, et al., (2008)		✓	✓	✓								✓			✓								✓		✓	Genetic algorithm
Rahimi & Iranmanesh, (2008)		✓	✓	✓	✓				✓														✓		✓	Particle Swarm Optimization (PSO)
Ng & Zhang, (2008)		✓	✓	✓					✓														✓		✓	Ant Colony Optimization
Senouci & Al-Derham, (2008)		✓	✓	✓					✓														✓		✓	Gensaietic algorithm
Eshtehardian, et al., (2009)		✓	✓	✓								✓		✓	✓								✓		✓	Genetic algorithm

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Afshar, et al., (2009)		✓	✓	✓					✓													✓		✓		Nondominated Archiving Ant Colony Optimization
Ke, et al., (2009)	✓		✓	✓						✓					✓							✓		✓		Integrating stochastic simulations and genetic algorithm
Ghazanfari, et al., (2009)		✓	✓	✓								✓		✓						✓				✓		Goal programming
Ghodsi, et al., (2009)		✓	✓	✓	✓						✓			✓	✓	✓				✓				✓		ε-constraint method
Hyari, et al., (2009)		✓	✓	✓					✓													✓			✓	Genetic algorithm
Zahraie & Tavakolan,(2009)		✓	✓	✓								✓		✓	✓							✓			✓	Nondominated Sorting Genetic Algorithm
Chen & Weng, (2009)		✓	✓	✓					✓													✓		✓	✓	A two-phase genetic algorithm

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty	uncertain				Uncertain indices						Solution method				data type		Considerations
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Ke, et al., (2010)	✓		✓	✓								✓		✓						✓				✓		Fuzzy simulation and genetic algorithm
Klerides & Hadjiconstantinou, (2010)	✓		✓	✓						✓				✓	✓					✓				✓		Stochastic integer programming
Hafızoğlu& Azizoğlu, (2010)	✓		✓	✓						✓										✓				✓		Branch and bound
Jiang & Zhu, (2010)	✓		✓	✓					✓											✓					✓	Integer Programming
Zhang & Xing, (2010)		✓	✓	✓	✓							✓		✓	✓	✓						✓		✓		Fuzzy particle swarm optimization
Zhang & Li, (2010)		✓	✓	✓					✓													✓		✓		Particle swarm optimization
Ammar, (2011)	✓		✓	✓							✓			✓	✓					✓				✓		Mathematical model
Chen & Tsai, (2011)	✓		✓	✓								✓		✓	✓					✓				✓		Mathematical model

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Wuliang & Chengen, (2009)	✓		✓	✓					✓													✓		✓		Improved genetic algorithm and branch and bound
Hazır, et al., (2010)	✓		✓	✓					✓											✓				✓		A two-stage robust scheduling algorithm
Geem, (2010)		✓	✓	✓					✓													✓		✓		Harmony Search
Hazır, et al., (2010)	✓		✓	✓					✓											✓				✓		Bender's decomposition-based
Anagnostopoulos & Kotsikas, (2010)	✓		✓	✓					✓													✓		✓		Experimental evaluation of simulated annealing algorithms
Mokhtari, et al., (2010)	✓		✓	✓						✓				✓							✓			✓		Cutting plane method and Monte Carlo (MC) simulation

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Hazır, et al., (2011)	✓		✓	✓							✓				✓					✓				✓		Benders Decom-position
Sonmez & Bettemir, (2012)	✓		✓	✓					✓														✓	✓		(GA), (SA), and Quantum Simu-lated Annealing techniques (QSA)
Klanšek & Pšunder, (2012)	✓		✓	✓					✓											✓				✓		Mixed-Integer Nonlinear Pro-gramming (MINLP)
Ke, et al., (2012)	✓		✓	✓						✓				✓						✓				✓		GA
Pour, et al., (2012)		✓	✓	✓	✓							✓				✓						✓		✓		A new hybrid GA
Xu, et al., (2012)		✓	✓	✓				✓				✓		✓								✓			✓	A fuzzy-based adaptive-hybrid GA
Fallah-Me-hdipour, et al., (2012)		✓	✓	✓	✓				✓													✓		✓		(NSGA)-II

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Ozcan-Deniz, et al., (2012)		✓	✓	✓				✓	✓													✓			✓	(NSGA)-II
Son, et al., (2013)	✓		✓	✓					✓											✓				✓		Model for Mixed Scenario
Mungle, et al., (2013)		✓	✓	✓	✓				✓													✓		✓		A fuzzy clustering-based GA (FCGA) approach
Ghoddousi, (2013)		✓	✓	✓					✓													✓		✓		(NSGA-II)
Ke & Ma, (2014)	✓		✓	✓								✓		✓	✓								✓	✓		Hybrid intelligent algorithm
Tavana, (2014)		✓	✓	✓	✓				✓													✓		✓		Multi-Objective evolutionary algorithm
Afruzi, (2014)		✓	✓	✓	✓				✓													✓		✓		Multi-Objective Imperialist Competitive Algorithm (MOICA)

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Said & Haouari, (2015)	✓		✓	✓									✓	✓							✓					A hybrid simulation-optimization
Li, et al., (2015)	✓		✓	✓							✓			✓	✓					✓				✓		Mixed-integer programming
Monghasemi, et al., (2015)		✓	✓	✓	✓				✓													✓	✓		✓	Multi-criterion decision-making and NSGA-II
Khalili-Damghani, et al., (2015)		✓	✓	✓	✓				✓											✓	✓			✓		A mixed-integer mathematical
Saif, et al., (2015)		✓	✓	✓	✓				✓													✓		✓		Problem data-based optimization (PDBO)
Cheng, et al., (2015)		✓	✓	✓				✓	✓													✓		✓		The opposition-based multiple-objective differential evolution (OMODE)
Aminbakhs& Sonmez, (2016)		✓	✓	✓					✓													✓		✓		A discrete PSO

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Meier, et al., (2016)		✓	✓	✓					✓													✓			✓	ε- a multi-objective evolutionary algorithm
Aminbakhsh & Sonmez, (2017)		✓	✓	✓					✓													✓		✓		A new PSO
Zheng, et al., (2017)		✓	✓	✓				✓	✓													✓			✓	Hybrid GA
Hosseini-Nasab, et al., (2017)		✓	✓	✓	✓							✓		✓	✓	✓						✓		✓		Super GA (SGA)
Zheng, et al., (2017)		✓	✓	✓	✓			✓	✓											✓		✓	✓		✓	Fuzzy programming and GA
Agdas, et al., (2018)	✓		✓	✓					✓													✓		✓		GA
Li, et al., (2018)		✓	✓	✓					✓												✓	✓	✓	✓		(NSGA-II) and the steepest descent heuristic
Kosztyán, & Szalkai, (2018)		✓	✓	✓	✓					✓				✓	✓	✓				✓				✓		A matrix-based method

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Toğan & Eirgash, (2019)		✓	✓	✓					✓											✓		✓	✓	✓		Teaching-Learning Based Optimization (TLBO) and the Modified Adaptive Weight Approach (MAWA)
Eirgash, (2019)		✓	✓	✓					✓													✓		✓		TLBO
Haghighi, et al., (2019)	✓		✓	✓							✓	✓		✓	✓					✓				✓		Mathematical model
Abdel-Basset, et al., (2020)	✓		✓	✓								✓		✓							✓			✓		Mathematical model
Liu, et al., (2020)		✓	✓	✓					✓													✓		✓		Discrete Symbiotic Organisms Search (DSOS)
Sonmez, et al., (2020)		✓	✓	✓					✓												✓			✓		A new activity un crashing heuristic
Albayrak, (2020)		✓	✓	✓					✓													✓	✓	✓		PSO and GA

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Lotfi, et al., (2022)		✓	✓	✓	✓		✓	✓					✓	✓	✓			✓	✓	✓					✓	ε-constraint
Van Eynde & Vanhoucke, (2022)		✓	✓	✓					✓											✓	✓		✓	✓		A reduction tree approach
Tiwari, et al., (2022)		✓	✓	✓				✓	✓													✓			✓	NSGA-III
Sharma & Trivedi, (2022)		✓	✓	✓	✓				✓													✓			✓	AHP and NSGA-II
Dhawan, et al., (2022)		✓	✓	✓					✓													✓			✓	Simulated annealing-based
Nguyen, et al., (2022)		✓	✓	✓	✓							✓		✓	✓	✓						✓		✓		Symbiotic Organism Search (SOS)
Lotfi, et al., (2022)		✓	✓	✓	✓		✓	✓					✓	✓	✓	✓		✓	✓	✓					✓	Blockchain Technology (BCT)

Table 1
List of research to solve TCTP (Continued)

References	Objective		Type of trade-off						Types of uncertainty					Uncertain indices						Solution method				data type		Considerations
										uncertain																
	Single	Multi	Time	Cost	Quality	Safety	Energy	Environment	Deterministic	Probable	Interval	fuzzy	Robust	Time	Cost	Quality	Safety	Energy	Environment	exact	heuristic	meta-heuristic	hybrid	example	real	
Sharma & Trivedi, (2022)		✓	✓	✓	✓	✓						✓					✓					✓			✓	NSGA III
Banihashemi & Khalilzadeh, (2021)		✓	✓	✓	✓			✓	✓											✓					✓	DEA approach
Ammar, (2020)	✓		✓	✓					✓											✓				✓	✓	Zero-one programming
Banihashemi, et al., (2021)		✓	✓	✓	✓			✓	✓											✓				✓		Mathematical model
Panwar & Jha, (2021)		✓	✓	✓	✓	✓			✓													✓		✓		NSGA III
Elkalla, et al., (2021)	✓		✓	✓								✓		✓	✓					✓				✓		simplex method
Banihashemi, et al., (2021)		✓	✓	✓				✓				✓		✓	✓				✓	✓					✓	Combined Compromise Solution (CoCoSo)
Hamta, et al., (2021)		✓	✓	✓	✓				✓											✓				✓		Goal programming
Luong, et al., (2021)		✓	✓	✓	✓				✓													✓		✓		Opposition-based Multiple Objective Differential Evolution (OMODE)

3. Graphical Results

The present section contains several charts that illustrate the graphical results for the different types of columns in the reported tables according to the literature. Therefore, multi-mode and multi-objective strategies have been considered by researchers progressively in recent years (Fig. 2), and time and cost are the two more widespread parameters in multi-objective functions (Fig. 3). Due to solutions methods of TCTP, there has been a surge of interest in using metaheuristic methods (Fig. 6) and more emphasis on Genetic Algorithms (GA).

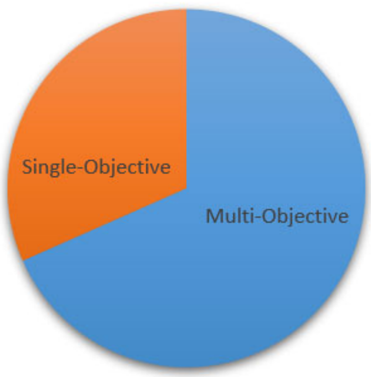

Fig. 2. Distribution of the types of objective functions

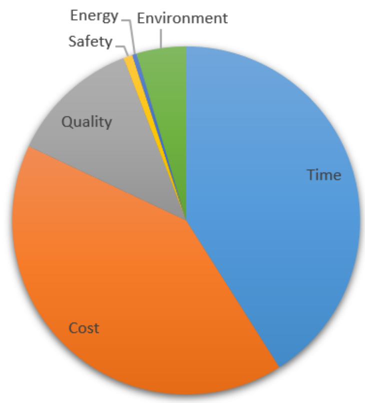

Fig. 3. Distribution of the parameters in the TCTP

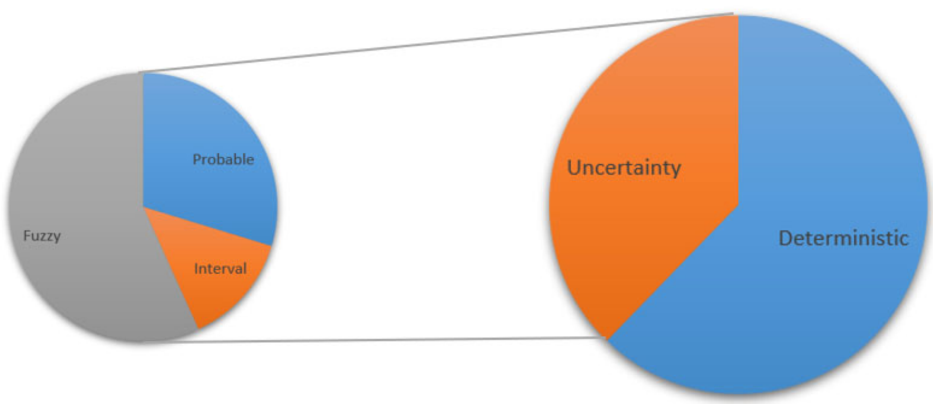

Fig. 4. Distribution of type uncertainty

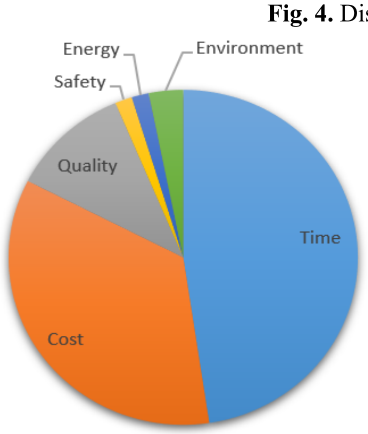

Fig. 5. Distribution of uncertainty parameters

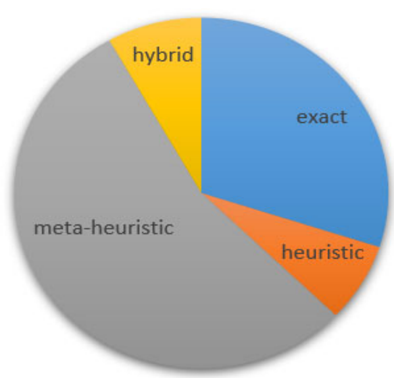

Fig. 6. Distribution of solution methods

On the other hand, the use of metaheuristic approaches has increased as the models have become more complex. According to Fig. 4, fuzzy uncertainty is more commonplace than different types of uncertainty shown in the tables. Additionally, applied to real world situations, time and cost are two main factors that are less meticulous than they would be in the real-world, and in this way, these factors are more uncertain than others (Fig. 5).

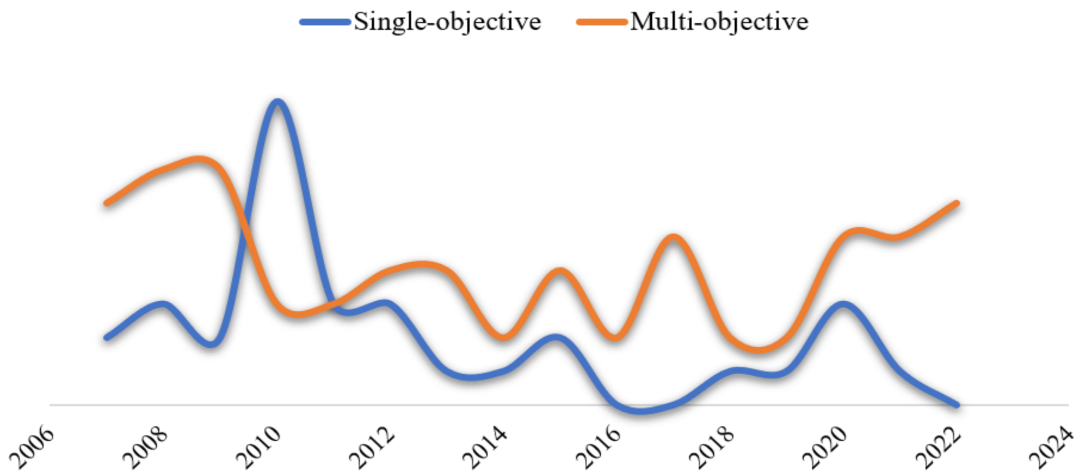

Fig. 7. Distribution of the papers on the types of objective function

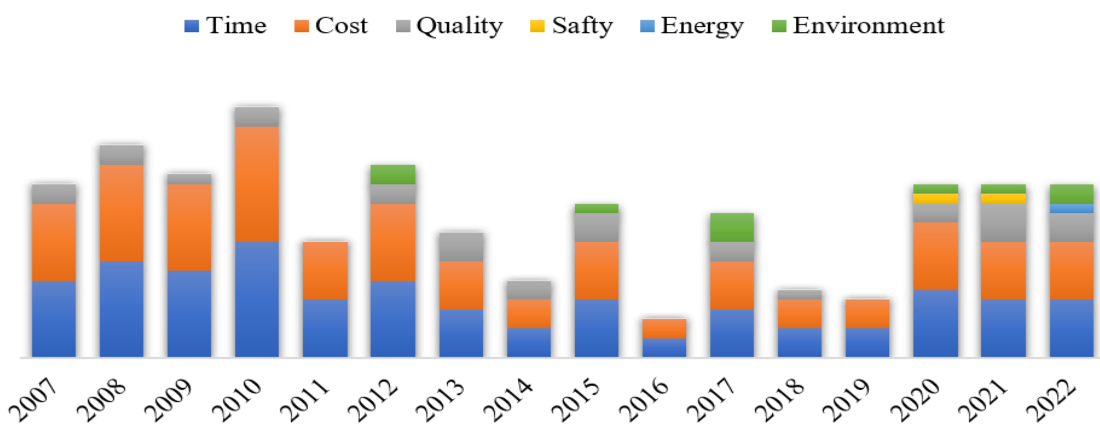

Fig. 8. Distribution of the papers on the parameters in TCTP

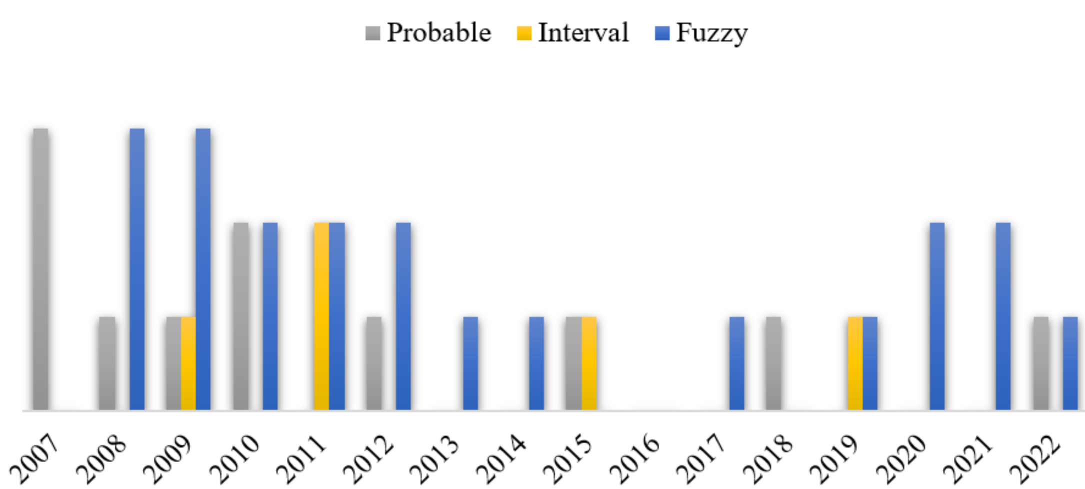

Fig. 9. Distribution of the papers on the types of uncertainty

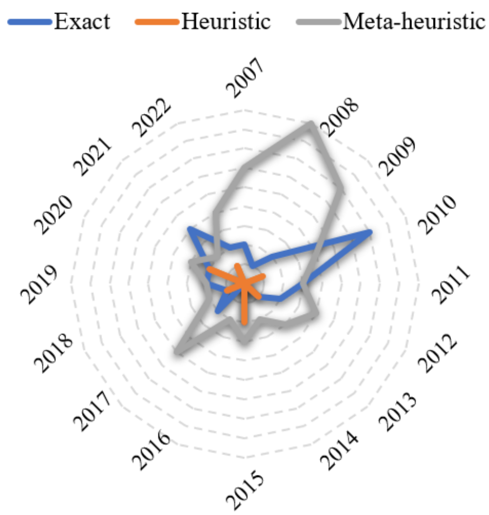

Fig. 10. Distribution of the papers on the solution methods of TCTP

4. Conclusion

The importance of scheduling has increased in many construction projects. Project managers need to schedule their projects efficiently. Our purpose in this study is to investigate the methods employed to solve the problem of time-cost trade-off through the study of recent studies. According to Fig. 7, in recent years, multi-objective methods have increased over the previous years, while single-objective functions are declining. Over time, considering quality as one of the objective functions has grown due to not ignoring the quality of projects (Fig. 8). Also, as global warming and energy consumption have increased in recent years, it has become more common to consider both energy and environmental criteria in time-cost trade-off issues (Fig. 8). To handle uncertainty in a successful manner, fuzzy uncertainty (Kropat & Weber, 2018), interval number (Allahverdi, 2022) and novel robust formulation (Lotfi, et al., 2022) can be considered for all parameters in TCTP. As compared to other uncertainties, fuzzy uncertainties have gained attention over the years, but there has been a decline in the use of probability uncertainty; however, interval uncertainty is rarely used (Figure. 9). Moreover, heuristic 114 and meta-heuristic algorithms (Golab et al., 2022) and other new methods (Golab, et al., 2022; Golab, et al., 2023) are used to solve large-scale TCTP. Based on the radar diagram shown in Figure 10, the use of meta-heuristic methods, to find optimal solutions, in particular for multi-objective problems, is more general than other methods; while TCTPs have rarely been solved by heuristic approaches.

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