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ORIGINAL PAPER

An optimization model for construction project scheduling by considering CO_2 emissions with multi-mode resource constraints under interval-valued fuzzy uncertainty

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Abstract

In Iran, the entire energy system relies on fossil fuels, which imposes significant greenhouse gas emissions. Besides, among different greenhouse gases, carbon dioxide (CO_2) has the most considerable portion, and Iran is known as one of the top ten CO_2 emitting countries, especially in the industry section. In this paper, a new multi-mode resource-constrained project scheduling problem is presented regarding the emitted CO_2 as a greenness index. The proposed mathematical model has four objective functions, which are, minimizing the project completion time, project costs, and emitted CO_2, and the fourth objective function maximizes the project quality. The time lag and reworking are regarded in the mathematical model. Reworking not only causes an increase in the project quality and more CO_2 emissions but also increases the complexity of the problem. Uncertainty is an essential part of any construction project in real situations, so activities duration and cost of non-renewable and renewable resources are under interval-valued fuzzy uncertainty. To solve the mathematical model with uncertainty, a new extended solving method is proposed. Furthermore, a case study in Iran is presented to show the impact of the given model in real projects, and related results along with the analyses are conducted on this case. Additionally, Pareto front solutions are presented to show the trade-off between objectives. The results illustrate that considering CO_2 emissions as a greenness index can reduce project costs and improve quality. On the other hand, this index increases the project completion time. This paper has practical implications for project managers and companies to reach their fundamental goals (i.e., time, cost, and quality) alongside minimizing emitted CO_2 in an uncertain environment.

Keywords Construction project scheduling · Multi-mode resource-constrained project scheduling problem · CO_2 emissions · Rework · Interval-valued fuzzy sets · Mixed-integer linear programming

Introduction

Because a great number of measures and plentiful resources are taken, enhancing the project schedule is considered a complicated problem. In the past few years, the project scheduling implementation has been extended to include industries, e.g., production, engineering, construction, and maintenance. When the resources are scarce, scheduling means assuring priority and proper allocation of resources. Properly allocating the time specified to execute each activity during the planning phase may become lengthier than the anticipated time. Nonetheless, it is an essential job in project management because it affects the makespan (Turner et al. 1999; Zavadskas et al. 2019; Banihashemi et al. 2021). Project scheduling by considering uncertainty is studied as a survey conducted by Herroelen and Leus (2005). Among the literature, one may refer to a number of solution and modeling methods, like multi-stage stochastic optimization (Stork 2000; Li and Womer 2015; Creemers 2015), proactive (also on certain occasions, denoted robust) scheduling, fuzzy optimization (Arik and Toksari 2018; Aramesh et al. 2021a, b; Mohagheghi et al. 2019; Zolfaghari et al. 2021; Dorfeshan et al. 2021; Davoudabadi et al. 2021), reactive scheduling (Van de Vonder et al. 2007), and simulations in combination with sensitivity analyses (Hall and Posner 2004).

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The activities scheduling under technological and resource limitations with the aim of minimizing the makespan is a standard issue in project scheduling, investigated as the resource-constrained project scheduling problem (RCPSP) (Servranckx and Vanhoucke 2019; Javanmard et al. 2022). Various surveys are conducted on the RCPSP fundamental principles (Brucker et al. 1999; Demeulemeester and Herroelen 2002) and RCPSP approaches (Hartmann and Kolisch 2000; Kolisch and Hartmann 2006; Weglarz et al. 2011; Weglarz 2012). The RCPSP is categorized as NP-hard (Blazewicz et al. 1983). A basic RCPSP assumption is that continued activities are non-preemptable. The preemptive resource-constrained project scheduling problem (PRCPSP) simplifies the same assumption, and allows the activities to be interrupted. The preemptive resource-constrained project scheduling problem was first studied by Słowinski (1980).

Each mode in a multi-mode resource-constrained project scheduling problem (MRCPSP) is depicted as a combination of resources, time, and costs. A solution of MRCPSP involves selecting a single mode per activity, resources allocation, and determining the start time of the activity for minimizing the project completion time by considering budget and precedence constraints (Ghasemi et al. 2020). In the MRCPSP, activities might be implemented in a number of scenarios corresponding to special time/resource profiles of activities. Weglarz et al. (2011) have conducted a comprehensive survey on the MRCPSP.

Zadeh (1968) introduced the fuzzy sets theory, which brought up new promising solutions to a variety of scientific fields, like project scheduling (Atli and Kahraman 2012). Considering the uniqueness of some activities in the projects and the loss of historical information regarding the duration of activities, a project manager may not properly characterize random variables (Aramesh et al. 2021a, b; Dodin 2006). Consequently, fuzzy set-based schemes are brought up for managing the projects that many unpredicted occurrences may occur (Long and Ohsato 2008). Guinness (1976) remarked that displaying linguistic expressions as fuzzy sets do not suffice. Due to the same weakness, we employed IVF sets, which is a particular form of fuzzy numbers with crisp interval-based membership values. RCPSP with the IVF numbers was studied in Huang et al. (2016) such that the duration of activities and resource requirement was IVF numbers.

The scarcity of energy resources and major materials utilized in modern projects in the future have been scrutinized (Mansouri et al. 2016). The same challenge requires efficient engineering of resources because shifting from a linear economy to a circular one has already been initiated (Sun 2013). Low-carbon economy and inventive resource-efficient solutions are required to maximize project materials' recovery, conserve resources, recycle, reuse and also, to minimize wastes for responding to pro-actively preparation for immense technological challenges faced in sustainable scheduling. Today, facing projects with low gas emissions for most of the industries is a critical issue. The industrial sector is currently responsible for one-half of global energy usage, nearly doubled within the last sixty years (US Energy Information Administration (EIA), 2010). For example, in China, the average industrial gross domestic product (GDP) ratio (40.1%) is realized by the consumption of 67.9% of total national energy and emission of 83.1% of the total national CO_2 emissions since 1978 (Chen 2009). Emission reduction and energy saving have been increasingly focused on by scholars and governments in the last few years (Wu and Sun 2018). Energy demand of projects and firms is a vital requirement for the realization of sustainable development since energy supply and consumption result in adverse environmental influences (for example, extensive land use, emissions of greenhouse gas, and acidification). Nevertheless, energy is an element with no substitutable alternative. As a result, decreasing energy demands is partly constrained and influenced by the sought-after production outputs (Gahm et al. 2016).

Given that the current oil prices reflect abundant energy resources, the increased energy consumption and losses along with the increased population have led the world to face with an energy crisis in the next few years (Reuters 2015). Thus, project corporates are forced to not only attempt to decrease their environmental influences but to take into account the potential energy deficiencies in their operations proactively as well. A possible solution is employing the most effective methods for reducing the emitted energy pollution (Duflou et al. 2012).

Global warming is becoming one of the most vital global concerns in dire need of being considered by the whole countries all around the globe (Mousavi et al. 2017). Many scholars have discussed that recent global warming is primarily attributable to increasing CO_2 level emitted due to fossil fuels consumption (Pachauri et al. 2014). As International Energy Agency (IEA) has reported, the annually global CO_2 emission released from fossil fuels has risen from nearly 23.6 gigatonnes of carbon dioxide ($GtCO_2$) in the 1990s to about 32.4 $GtCO_2$ in 2014. In the absence of more aspiring climate mitigation policies than the ones applied today, an increase by 50% in emissions is expectable to occur in 2050 leading to a higher global average temperature of 3.2–4 °C than the ones estimated for the preindustrial levels (Pachauri et al. 2014). To reduce or stop CO_2 emissions, this study presents a new RCPSP model, while one of the objective functions aims to minimize the emitted CO_2. Manzoor and Aryanpur (2017) explained the potential advantages of loyalty to energy planning in Iran in the long run. They have demonstrated that the power sector developments have primarily been the outcome of short-term plans, whilst the obligation to long-term energy planning would have decreased costs of power systems by \$0.7 up to \$3.0 billion annually. Besides, long-term planning could have guaranteed a reduction of 15–33% in total CO_2 emitted through the past thirteen years.

One of the regular energy indicators employed in any region is energy intensity (Faridzad et al. 2020). As IEA (2018) has reported, the same index in Iran is equal to 0.51, which is 10 and 15 times higher than that for European Union (EU) and Japan, respectively, because Iran pays higher subsidies on the energy supply (Yazdan et al. 2012). Among the environmental risks, as statistical reports remark, CO_2 is of more intense effects on global warming compared to other greenhouse gases (Shabani and Shahnazi 2019). During the 1990–2015 period, the CO_2 intensity was reduced − 1.4% annually at the global scale; it is noteworthy that CO_2 intensity has decreased in the whole countries except for those within the Middle East since 1990 (Global Energy Statistical Yearbook 2017). Iran emitted 603.9 million tons of CO_2 in 2016, and CO_2 emissions were ascended by 3.5% during the 2005–2015 period in Iran (BP 2017). In spite of the global CO_2 intensity in 2016, its intensity in Iran was 60% more than that of global levels. Consequently, Iran has been ranked as the 8th highest CO_2 emitter globally (Global Energy Statistical Yearbook 2017), as given in Fig. 1. In this figure, countries with the highest amount of emitted CO_2 are compared, where their numbers are based on $GtCO_2$.

During 2000–2016, energy intensity decreased by − 1.6% on average, annually. Compared to the global average, Iran has had higher energy consumption intensity. Given Iran's high CO_2 emissions and high intensity of energy consumption, it seems essential to recognize some approaches to reduce CO_2 emissions and energy consumption with no adverse effects on economic growth.

In this paper, a new MRCPSP model is presented by considering CO_2 emission as a greenness index. The proposed mathematical model has four objectives. The first object seeks for minimizing the time required for project completion; the second one aims to minimize the project costs; the third objective minimizes the average emitted CO_2 from the project activities, and the fourth object maximizes the project quality. The rework and time lag are considered, so by reworking the quality of activities and the emitted CO_2 increase. To show the application of the presented mathematical model in the real world, a case study in Iran is proposed. To face the real-world uncertainty, activities duration and cost of resources (both renewable and non-renewable) are IVF numbers. To solve the mathematical model, a new extended interval-valued fuzzy-Selim and Ozkarahan (IVF-SO) method is presented. Finally, to find out the effect of the greenness index, some related sensitivity analyses are presented.

The rest of this paper has been structured as follows. Some elementary definitions are presented in Sect. 2. Section 3 describes the problem. The solving method is developed in Sect. 4. The case study is described in Sect. 5. After that, the computational experiments are presented in Sect. 6. Finally, Sect. 7 concludes the results.

Preliminary

Generalized fuzzy numbers

As per Zadeh (1968) and Zadeh (1976), one can describe a fuzzy set as an object class with a membership grade continuum, in which the membership grade is 0–1. One can describe the fuzzy set A as a universal set X by a membership function mapping each element x in X to a real number [0,1]. A fuzzy number is described as a fuzzy set in such a way that $M = \{x, \mu_M(x), x \in R\}$ where $\mu_M(x)$ is a continuous mapping of the closed interval [0,1].

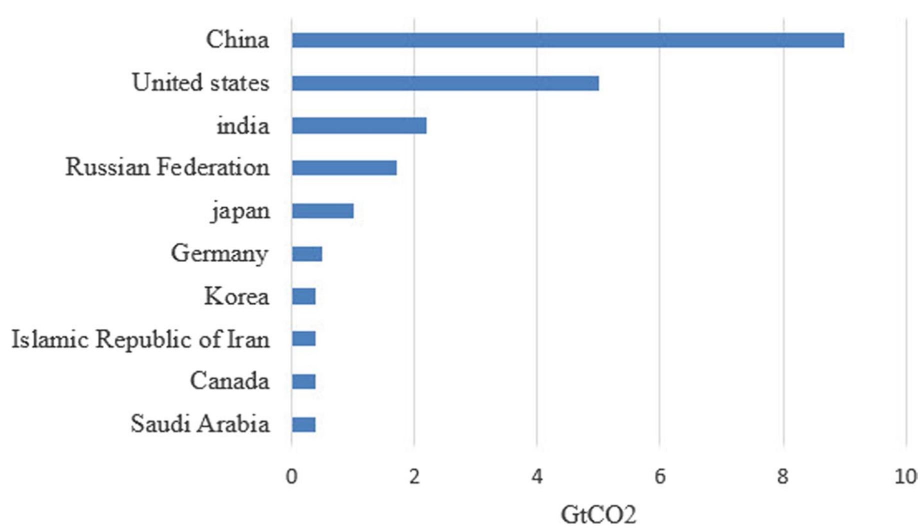

Fig. 1 Top ten countries with the most amount of emitted CO2 (Source: IEA 2017)

A generalized fuzzy number $\widetilde{Z} = (z_1, z_2, z_3, z_4; v)$, $0 \le z_1 \le z_2 \le z_3 \le z_4 \le 1$ and $0 \le v \le 1$ is a fuzzy subset of the universe of discourse V with the membership function $\mu_{\widetilde{z}}(x)$ meeting the conditions below (Chen and Chen 2003):

- $\mu_{\widetilde{z}}(x)$ is a continuous mapping from the universe of discourse X to the closed interval $[0, v]$.
- $\mu_{\widetilde{z}}(x) = 0$ considering $-\infty \le x \le z_1$.
- $\mu_{\widetilde{z}}(x)$ is uniformly increasing in the range of $[z_1, z_2]$.
- $\mu_{\widetilde{z}}(x) = v$ for all $z_2 \le x \le z_3$, where x is constant and $v \in [0, 1]$.
- $\mu_{\widetilde{z}}(x)$ is uniformly decreasing in the following range $[z_3, z_4]$.
- $\mu_{\widetilde{z}}(x) = 0$ considering $z_4 \le x \le +\infty$.

Suppose that $\mu_{\widetilde{z}}(x)$ being linear both in intervals $[z_1, z_2]$ and $[z_3, z_4]$, so the formed generalized fuzzy number is named as a generalized trapezoidal fuzzy number. Having $v = 1$ and $z_2 = z_3$, the generalized trapezoidal fuzzy number becomes a generalized triangular fuzzy number.

Taking into account all types of fuzzy numbers, trapezoidal and triangular fuzzy numbers are the most significant. Triangular fuzzy numbers (TFNs) are often hired in practical applications to describe inaccurate, ambiguous, and non-transparent data. The triangular fuzzy number $\widetilde{Z}$ is proposed by a triangular $\widetilde{Z} = (z_1, z_2, z_3)$ and a membership function as the following $\mu_z(x)$.

$$\mu_Z(y) = \begin{cases} 0 & \text{otherwise} \\ \frac{x-z_1}{z_2-z_1} & x_1 \le x \le x_2 \\ \frac{z_3-x}{z_3-z_2} & x_2 \le x \le x_3 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

Interval-valued fuzzy sets

According to the study proposed by Gorzalczany (1987), as illustrated in Fig. 2, an IVF set is defined on $(-\infty, +\infty)$ as:

$$\tilde{B} = \left\{ \left(x, \left[\mu_B^L(x), \mu_B^U(x)\right]\right) \right\}$$
$$\text{where } \mu_B^L, \mu_B^U : X \to [0,1] \forall x \in X, \mu_B^L \le \mu_B^U$$

where, if $\overline{\mu}_{\widetilde{B}}(x) = [\mu_B^L(x), \mu_B^U(x)]$ then $\widetilde{B} = \left\{x, \overline{\mu}_{\widetilde{B}}(x)\right\}$, $x \in (-\infty, +\infty)$.

As illustrated, μ_B^U and μ_B^L are the upper and lower limits of the membership degrees, respectively. The membership degree at x^* related to the IVF set $\widetilde{B}$ is associated with the interval $[\mu_B^L(x^*), \mu_B^U(x^*)]$, representing $\mu_B^U(x^*)$ and $\mu_B^L(x^*)$ as the maximum and minimum membership degrees (Gorzałczany 1987).

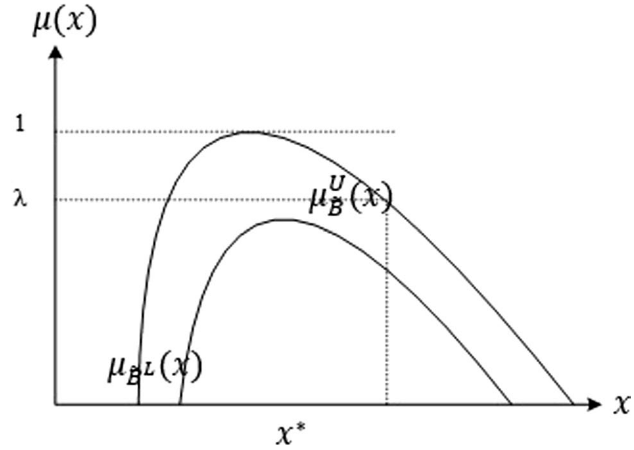

Fig. 2 Interval-Valued Fuzzy Set

Triangular interval-valued fuzzy numbers (TIVFNs)

Noteworthy, to get a more reliable and exact solution, a very convenient approach has to be applied for solving the presented model. The method regarded in this paper employs a normalized triangular interval-valued fuzzy represented as NTIVF. There are two main reasons for using the interval-valued fuzzy; first, it is of a high degree of flexibility that exists in IVF. The other reason is the existence of doubt and ambiguity in the actual values.

The IVF numbers are considered a certain form of generalized fuzzy numbers. Like generalized fuzzy numbers, IVF numbers can be triangle or trapezoidal. According to the study conducted by Yao and Lin (2002), triangular IVF numbers can be denoted as the following: $\widetilde{C} = \left[\widetilde{C}^L, \widetilde{C}^U\right] = \left[\left[c_1^L, c_2^L, c_3^L; \widetilde{v}_{\widetilde{C}}^L\right], \left[c_1^U, c_1^U, c_1^U; \widetilde{v}_{\widetilde{C}}^U\right]\right]$ (Fig. 3), where $\widetilde{C}^L, \widetilde{C}^U \to \widetilde{C}^L \subset \widetilde{C}^U$ denote the lower and upper triangular IVF numbers, respectively; considering $\mu_{\widetilde{C}}(x)$ as the membership function, depicting the degree to an event which might be a part of $\widetilde{C}$, $\mu_{\widetilde{C}}^L(x) = \widetilde{v}_{\widetilde{C}}^L$ and $\mu_{\widetilde{C}}^U(x) = \widetilde{v}_{\widetilde{C}}^U$ are the lower and the upper membership functions, respectively.

According to what was denoted above, the following relations hold:

- If $c_1^L = c_1^U = c_2^L = c_2^U = c_3^L = c_3^U$ and $v_{\widetilde{C}}^L = v_{\widetilde{C}}^U$, then the triangular IVF number $\widetilde{C}$ is considered as a crisp value.
- If $v_{\widetilde{C}}^L = v_{\widetilde{C}}^U$ and $c_2^L = c_2^U = c_2$, then the NTIVF number demonstrated in Fig. 4 can be denoted as: $\widetilde{C} = \left[\widetilde{C}^L, \widetilde{C}^U\right] = \left[\left(c_1^L, c_1^U\right), \left(c_2^L = c_2^U\right), (c_3^L, c_3^U)\right]$ $= [\left(c_1^L, c_1^U\right), c_2, (c_3^L, c_3^U)]$

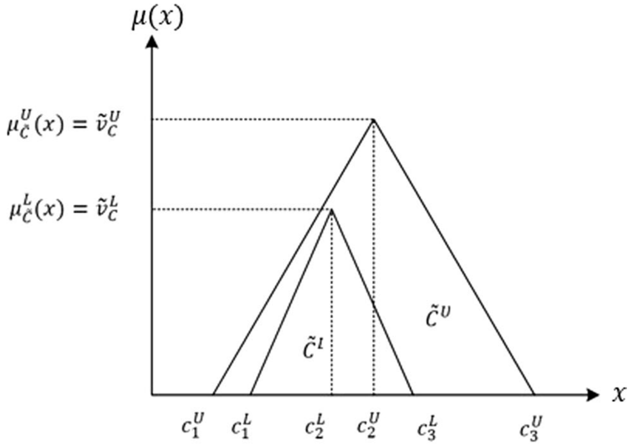

Fig. 3 Triangular IVF number

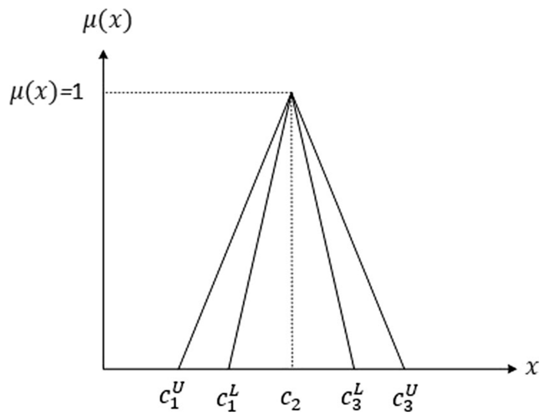

Fig. 4 Normalized triangular IVF number

Materials and methods

In the MRCPSP, there are multiple execution modes of the activities, and exactly one of these modes has to be chosen (Ghasemi et al. 2020). The schedule quality is based on four objective functions. The first objective function minimizes the project makespan. The second one minimizes project costs. The third objective function minimizes the emitted CO_2, and finally, the fourth one maximizes the project quality. In the fourth and third objective functions, the emitted CO_2 and quality of activities could be increased by reworking.

A project consists of $j = 1, 2, \ldots, J + 1$ activities, and each activity has $m = 1, 2, \ldots, M$ execution modes while this activity in mode m has the duration of $d_{j,m}$. The non-renewable and renewable resources requirements are (r_{jmk}), and (β_{jml}), respectively, where $k = 1, 2. \ldots, K$ is the set of renewable resources and $l = 1, 2. \ldots, L$ is the set of non-renewable resources. The total availability of these resources are (R_k^t) for renewable resources, and (N_l) for non-renewable resources. The mathematical model determines the value of R_k^t and N_l based on their cost and the second objective function. The cost of renewable resources is C_k and the cost of non-renewable resources is C_l.

Quality amount of each activity is q_{jm}, and by reworking the quality of activities increases qr_{jm} unit. The maximum acceptable rework for each activity is MR_{jm}. The greenness index of the project is calculated based on the emitted CO_2, which is shown as g_{jm}. During the reworking, more CO_2 emits and this extra emitted CO_2 is denoted by gr_{jm}, which depends on the rework value of each activity in the certain execution mode denoted by Re_{jm}. Activities are finished between their earliest finish time (EF_j) and latest finish time (LF_j). Besides, x_{jmt} is a binary variable that shows the activity j operated in mode m is finished at period t where $t = 1, 2. \ldots, T$ is a set of time periods. Furthermore, between finish time of activity i and start of activity j there is a time lag which is shown by lag_{ij}.

The proposed mathematical model is presented with the aim of minimizing time, cost, and emitted CO_2 and maximizing the quality level as follows:

$$Min\ Z_1 = \sum_{m=1}^{M} \sum_{t=EF_{j+1}}^{LF_{j+1}} t x_{j+1,m,t} \tag{2}$$

$$Min\ Z_2 = \sum_{k=1}^{K} \sum_{t=1}^{T} \widetilde{C_k} R_k^t + \sum_{l=1}^{L} \widetilde{C}_l N_l \tag{3}$$

$$Min\ Z_3 = \frac{\sum_{j=1}^{N} \sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} x_{jmt} g_{jm} + \sum_{j=1}^{N} \sum_{m=1}^{M} gr_{jm} Re_{jm}}{N} \tag{4}$$

$$Max\ Z_4 = \frac{\sum_{j=1}^{N} \sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} x_{jmt} q_{jm} + \sum_{j=1}^{N} \sum_{m=1}^{M} qr_{jm} Re_{jm}}{N} \tag{5}$$

Subject to:

$$\sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} x_{jmt} = 1 \qquad ; \forall j \tag{6}$$

$$\sum_{m=1}^{M} \sum_{t=EF_i}^{LF_i} t x_{imt} \le \sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} (t - \widetilde{d}_{jm}) x_{jmt} \qquad ; \forall (i.j) \in P \tag{7}$$

$$\sum_{m=1}^{M} \sum_{t=EF_i}^{LF_i} t x_{imt} + lag_{ij} + Re_{im} \le \sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} (t - \widetilde{d}_{jm}) x_{jmt} \qquad ; \forall (i.j) \in P, \forall (i.j) \in A \tag{8}$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{b=\max\{t,EF_j\}}^{\min\{t+\widetilde{d}_{jm}-1,LF_j\}} r_{jmk}x_{jmb} \le R_k^t \qquad ;\forall k \in K, \forall t \in T \quad (9)$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{b=\max\{t,EF_j\}}^{LF_j} \beta_{jml}x_{jmb} \le N_l \qquad ;\forall l \in L \quad (10)$$

$$\sum_{j=1}^{N}\sum_{m=1}^{M}\sum_{t=EF_j}^{LF_j} x_{jmt}g_{jm} + \sum_{j=1}^{N}\sum_{m=1}^{M} gr_{jm}Re_{jm} \le NG \quad (11)$$

$$y_{jm} = \sum_{t=EF_j}^{LF_j} x_{jmt} \qquad ;\forall j \in A, \forall m \in M \quad (12)$$

$$Re_{jm} \le MR_{jm}y_{jm} \qquad ;\forall j \in A, \forall m \in M \quad (13)$$

$$\begin{aligned}&x_{jmt}, y_{jm} \in \{0,1\}, R_k^t, N_l, Re_{jm} \in int^+;\\ &\forall j \in A, \forall m \in M, \forall k \in K, \forall l \in L, \forall t \in T\end{aligned} \quad (14)$$

The first objective function minimizes the project makespan. The second objective function minimizes the cost of both renewable and non-renewable resources. The third objective function minimizes the average emitted CO_2 of all activities. The fourth objective function maximizes the quality level of the project. Constraint (6) shows that each activity is executed only once. Constraint (7) represents the precedence relationship between project activities. Constraint (8) confirms the rework and time lag in the precedence relationship. It means that the rework time and the time lag should be added to the precedence constraint. Constraint (9) ensures renewable resource availability, and constraint (10) guarantees the availability of non-renewable resources. Constraint (11) shows the green index of the project. According to this constraint, the average emitted CO_2 should be fewer than the least acceptable green index which is denoted by NG. Constraint (12) indicates that each activity is executed only in one mode. Constraint (13) guarantees that the rework of each activity should not exceed the maximum possible rework of the activity. Finally, constraint (14) indicates the domain of the variables.

Proposed new extended IVF-SO solution method

According to the uncertainties of the proposed problem and the IVF parameters as well as the multi-objective mathematical model, in this paper a hybrid approach is proposed to deal with the fuzzy multi-objective linear programming (FMOLP) problem. In the first step of the presented method based on Jiménez et al. (2007), a crisp model is derived. After defuzzification, a multi-objective crisp model is obtained, which is solved by using SO procedure (Selim and Ozkarahan 2008).

Let C be a triangular fuzzy number, and its membership function is defined as follows:

$$\mu_{\tilde{c}}(x) = \begin{cases} f_c(x) = \frac{x-c^p}{c^m-c^p} & \text{if } c^p \le x \le c^m \\ 1 & \text{if } x = c^m \\ g_c(x) = \frac{c^o-x}{c^o-c^m} & \text{if } c^m x \le c^o \\ 0 & \text{if } x < c^p \quad \text{or} \quad x > c^o \end{cases} \quad (15)$$

Given careful consideration to the fuzzy mathematical model is below where all the parameters are IVF numbers:

$$\begin{aligned}&\min\ z = \tilde{c}^{tL}x\\ &\text{s.t.}\\ &\tilde{a}_i^L x \ge \tilde{b}_i^L \quad \forall (i = 1,2,\dots,l)\\ &\tilde{a}_i^L x = \tilde{b}_i^L \ \forall (i = l+1, l+2,\dots,m)\\ &x \ge 0\end{aligned} \quad (16)$$

$$\begin{aligned}&\min\ z = \tilde{c}^{tU}x\\ &\text{s.t.}\\ &\tilde{a}_i^U x \ge \tilde{b}_i^U \quad \forall (i = 1,2,\dots,l)\\ &\tilde{a}_i^U x = \tilde{b}_i^U \ \forall (i = l+1, l+2,\dots,m)\\ &x \ge 0\end{aligned} \quad (17)$$

The equivalent model corresponding to the above model can be replaced by an α-parametric model, which is as follows:

$$
\begin{aligned}
&\min z = EV(\tilde{c}^L)x \\
&\text{s.t.} \\
&[(1-\alpha)E_2^{a_i^L} + \alpha E_1^{a_i^L}]x \ge \alpha E_2^{a_i^L} + (1-\alpha)E_1^{b_i^L} \quad \forall (i = 1,2,\ldots,l) \\
&[(1-\frac{\alpha}{2})E_2^{a_i^L} + \frac{\alpha}{2}E_1^{a_i^L}]x \ge \frac{\alpha}{2}E_2^{a_i^L} + (1-\frac{\alpha}{2})E_1^{b_i^L} \quad \forall (i = l+1,\ldots,m) \\
&[\frac{\alpha}{2}E_2^{a_i^L} + (1-\frac{\alpha}{2})E_1^{a_i^L}]x \le (1-\frac{\alpha}{2})E_2^{a_i^L} + \frac{\alpha}{2}E_1^{b_i^L} \quad \forall (i = l+1,\ldots,m) \\
&x \ge 0
\end{aligned}
\tag{18}
$$

where

$$
EV(\tilde{c}^L) = \frac{c^{p^L} + 2c^{m^L} + c^{o^L}}{4},\ E_1^{a^L} = \frac{1}{2}(a^{p^L} + a^{m^L}),\ E_1^{b^L} = \frac{1}{2}(b^{p^L} + b^{m^L}),
$$
$$
E_2^{a^L} = \frac{1}{2}(a^{m^L} + a^{o^L}),\ E_2^{b^L} = \frac{1}{2}(b^{m^L} + b^{o^L})
$$

And for the upper bound of the membership degree:

$$
\begin{aligned}
&\min z = EV(\tilde{c}^U)x \\
&\text{s.t.} \\
&\left[(1-\alpha)E_2^{a_i^U} + \alpha E_1^{a_i^U}\right]x \ge \alpha E_2^{a_i^U} + (1-\alpha)E_1^{b_i^U} \quad \forall (i = 1,2,\ldots,l) \\
&\left[\left(1-\frac{\alpha}{2}\right)E_2^{a_i^U} + \frac{\alpha}{2}E_1^{a_i^U}\right]x \ge \frac{\alpha}{2}E_2^{a_i^U} + \left(1-\frac{\alpha}{2}\right)E_1^{b_i^U} \quad \forall (i = l+1,\ldots,m) \\
&\left[\frac{\alpha}{2}E_2^{a_i^U} + \left(1-\frac{\alpha}{2}\right)E_1^{a_i^U}\right]x \le \left(1-\frac{\alpha}{2}\right)E_2^{a_i^U} + \frac{\alpha}{2}E_1^{b_i^U} \quad \forall (i = l+1,\ldots,m) \\
&x \ge 0
\end{aligned}
\tag{19}
$$

where

$$
EV(\tilde{c}^U) = \frac{c^{p^U} + 2c^{m^U} + c^{o^U}}{4},\ E_1^{a^U} = \frac{1}{2}(a^{p^U} + a^{m^U}),\ E_1^{b^U} = \frac{1}{2}(b^{p^U} + b^{m^U}),
$$
$$
E_2^{a^U} = \frac{1}{2}(a^{m^U} + a^{o^U}),\ E_2^{b^U} = \frac{1}{2}(b^{m^U} + b^{o^U})
$$

According to the aforementioned procedure, the equivalent mathematical model for the upper bound of the membership degree is as follows:

$$
\text{Min } Z_1{}^U = \sum_{m=1}^{M} \sum_{t=EF_{j+1}}^{LF_{j+1}} tx_{j+1,m,t} \tag{20}
$$

$$
\text{Min } Z_2{}^U = \sum_{k=1}^{K} \sum_{t=1}^{T} \left(\frac{C_k^{pU} + 2C_k^{mU} + C_k^{oU}}{4}\right)R_k^t + \sum_{l=1}^{L} \left(\frac{C_l^{pU} + 2C_l^{mU} + C_l^{oU}}{4}\right)N_l \tag{21}
$$

$$
\text{Min } Z_3 = \frac{\sum_{j=1}^{N} \sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} x_{jmt} g_{jm} + \sum_{j=1}^{N} \sum_{m=1}^{M} gr_{jm} Re_{jm}}{N} \tag{22}
$$

$$
\text{Max } Z_4 = \frac{\sum_{j=1}^{N} \sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} x_{jmt} q_{jm} + \sum_{j=1}^{N} \sum_{m=1}^{M} qr_{jm} Re_{jm}}{N} \tag{23}
$$

Subject to:

$$
\sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} x_{jmt} = 1 \quad ;\forall j \tag{24}
$$

$$
\sum_{m=1}^{M} \sum_{t=EF_i}^{LF_i} tx_{imt} \le \sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} \left(t - ((1-\alpha)E_2^{d_{jm}{}^U} + \alpha E_1^{d_{jm}{}^U}\right)x_{jmt} \quad ;\forall (i,j) \in P \tag{25}
$$

$$
\sum_{m=1}^{M} \sum_{t=EF_i}^{LF_i} tx_{imt} + lag_{ij} + Re_{im} \le \sum_{m=1}^{M} \sum_{t=EF_j}^{LF_j} \left(t - ((1-\alpha)E_2^{d_{jm}{}^U} + \alpha E_1^{d_{jm}{}^U})\right)x_{jmt}; \quad \forall (i,j) \in P, \forall (i,j) \in A \tag{26}
$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{b=\max\{t,EF_j\}}^{\min\{t+(\frac{d_{jm}^{p\ U}+2d_{jm}^{m\ U}+d_{jm}^{o\ U}}{4})-1,LF_j\}} r_{jmk}x_{jmb} \le R_k^t \qquad ;\forall k \in K, \forall t \in T \tag{27}$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{b=\max\{t,EF_j\}}^{LF_j} \beta_{jml}x_{jmb} \le N_l \qquad ;\forall l \in L \tag{28}$$

$$\sum_{j=1}^{N}\sum_{m=1}^{M}\sum_{t=EF_j}^{LF_j} x_{jmt}g_{jm} + \sum_{j=1}^{N}\sum_{m=1}^{M} gr_{jm}Re_{jm} \le NG \tag{29}$$

$$y_{jm} = \sum_{t=EF_j}^{LF_j} x_{jmt} \qquad ;\forall j \in A, \forall m \in M \tag{30}$$

$$Re_{jm} \le MR_{jm}y_{jm} \qquad ;\forall j \in A, \forall m \in M \tag{31}$$

$$Z_1^U \le Z_1^U \tag{32}$$

$$Z_2^U \le Z_2^U \tag{33}$$

$$x_{jmt}, y_{jm} \in \{0,1\}, R_k^t, N_l, \mathrm{Re}_{jm} \in \mathrm{int}^+ \quad ; \forall j \in A,\ \forall m \in M,\ \forall k \in K,\ \forall l \in L,\ \forall t \in T \tag{34}$$

The equivalent crisp model for the lower bound of the membership function is obtained as follows:

$$\text{Min } Z_1{}^L = \sum_{m=1}^{M}\sum_{t=EF_{j+1}}^{LF_{j+1}} tx_{j+1,m,t} \tag{35}$$

$$\text{Min } Z_2{}^L = \sum_{k=1}^{K}\sum_{t=1}^{T}\left(\frac{C_k^{pL}+2C_k^{mL}+C_k^{oL}}{4}\right)R_k^t + \sum_{l=1}^{L}\left(\frac{C_l^{pL}+2C_l^{mL}+C_l^{oL}}{4}\right)N_l \tag{36}$$

(22), (23)
Subject to:
(24), (28)–(31), and (34)

$$\sum_{m=1}^{M}\sum_{t=EF_i}^{LF_i} tx_{imt} \le \sum_{m=1}^{M}\sum_{t=EF_j}^{LF_j} (t-((1-\alpha)E_2^{d_{jm}{}^L} + \alpha E_1^{d_{jm}{}^L})x_{jmt} \qquad ;\forall (i,j) \in P \tag{37}$$

$$\sum_{m=1}^{M}\sum_{t=EF_i}^{LF_i} tx_{imt} + lag_{ij} + Re_{im} \le \sum_{m=1}^{M}\sum_{t=EF_j}^{LF_j} (t-((1-\alpha)E_2^{d_{jm}{}^L} + \alpha E_1^{d_{jm}{}^L}))x_{jmt} \quad ;\forall (i.j) \in P, \forall (i.j) \in A \tag{38}$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{b=\max\{t,EF_j\}}^{\min\{t+(\frac{d_{jm}^{p\ L}+2d_{jm}^{m\ L}+d_{jm}^{o\ L}}{4})-1,LF_j\}} r_{jmk}x_{jmb} \le R_k^t \qquad ;\forall k \in K, \forall t \in T \tag{39}$$

Case study

For a better understanding of the presented mathematical model results and particularly influences of the emitted CO_2 on the real projects, in this section, a case study is described in Iran. The corporate under the name of "Rah Ahan Sang" had been set up since 1993, and later the name of the corporate has changed to Ballast Manufacturing and Infrastructure, as shifting the central office. At first, activities of the corporate entail ballast manufacturing, later by achieving grade from management & planning organization, activities, e.g., bridge construction, infrastructure and railway superstructure, added to services of the corporate. Besides, several new duties, e.g., renovation, reconstruction, building maintenance, and wagon transportation, have been added to this company's activities. In 2004, the company changed to public stock.

Ballast company is a project implementation and management company active in the field of railway infrastructure and superstructure, railway renovation and reconstructions, slab track construction, tunnel and bridge construction, landscaping, and road superstructure and infrastructures. The company is also active in manufacturing sleepers, pretension slabs, and ballast stones. Ballast company is aware that cooperating with scientific research centers, benefiting from efficient manpower experiences, and the use of modern technology can represent its capabilities. Thus, the company attempts to satisfy its clients' and employers' needs. The company's board of directors is committed to manage and implement projects in the same manner in accordance with

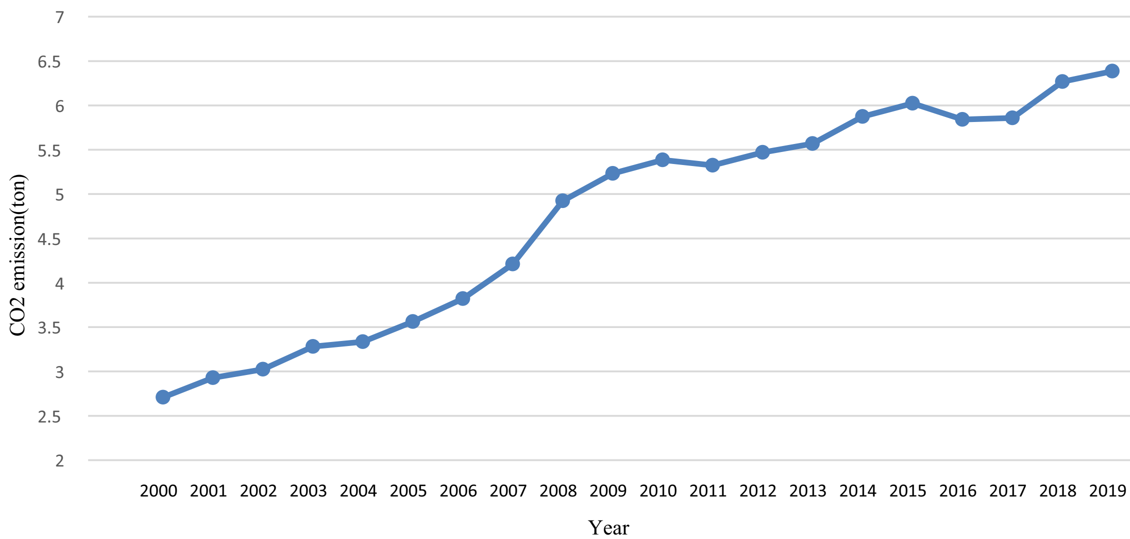

Fig. 5 The amount of emitted greenhouse gases in Iran between 2000 and 2019

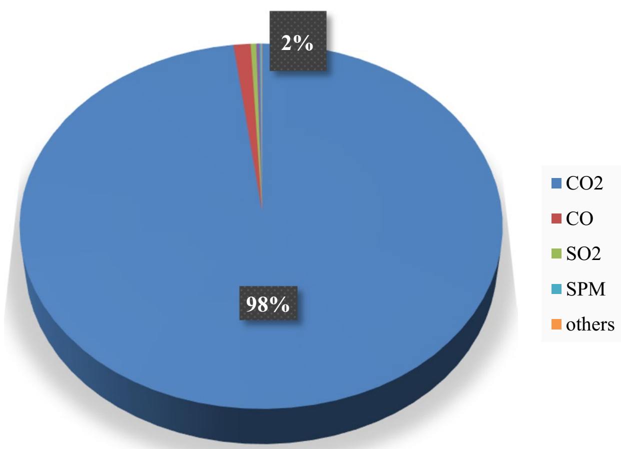

Fig. 6 Comparing the emitted pollution by different gases in Iran

international standards. One of these important standards is the environmental effect. The increasing trend of the emitted greenhouse gases in the whole energy section of Iran is shown in Fig. 5.

Figure 5 shows the increasing amount of emitted greenhouse gases in Iran. Among the different greenhouse gases, CO_2 has the biggest portion in Iran, about 98%, which is shown in Fig. 6. Other gases' effect is negligible; thus, this paper focuses on the impact of the emitted CO_2 in the Ballast company projects.

The effect of emitted CO_2 in the industries section in Iran is shown in Fig. 7. Note that this figure is based on the emitted CO_2 by burning fuels.

The trend of CO_2 emission in the industries section shows an increase in the emitted CO_2 in Iran. Note that the real

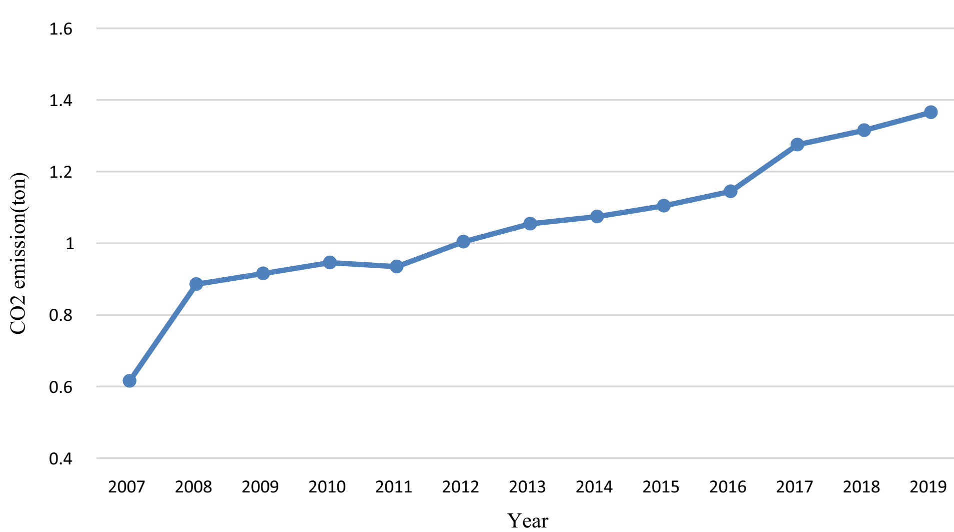

Fig. 7 Amount of the CO_2 emission from the burning fuels in the industries section

Table 1 Details of the case study activities including names and modes

Activity	Activity name	Duration	
		Mode 1	Mode 2
1	Equip	30	35
2	Excavation	210	200
3	Embanktion	192	190
4	Construction of aqueducts	120	124
5	Wall construction	156	150
6	Drilling a tunnel	170	178
7	Lining	85	82
8	Installation of facilities	57	50
9	Pile execution	54	52
10	Foundation	53	52
11	Culées execution	83	88
12	Deck execution	21	25
13	Additional works	24	21
14	Overbridge	115	117
15	Under-ballast	40	44
16	Base and subbase	52	50
17	Others	26	20
18	Temporary delivery and dismantling of the workshop	15	17

emitted CO_2 is more than what Fig. 7 illustrates. Thus, due to the huge amount of the emitted CO_2, the study of controlling the CO_2 emission is a critical issue in Iran.

To sum it up, the emitted CO_2 plays the most critical role in Iran's pollution. The Ballast company is regarded as a case study, and the corresponding details of this company in the mathematical model are represented in Table 1. As Table 1 shows, the case study has 18 activities, which can be performed in two execution modes.

Besides the duration of project activities, which is provided in Table 1, Ballast Company has 9 renewable resources and 4 non-renewable resources.

Table 2 The results of objective functions by solving the model with $\alpha = 0.5$

Objective functions	Value of objective functions
Z_1(minimize completion time of project)	1197
Z_2(minimize total cost of resources)	$1.321E+11$
Z_3(minimize the project emitted CO_2)	26.833
Z_4(maximize quality of all project activities)	0.885

Results and discussion

In this section, various sensitivity analyses are conducted on the real case study to validate the presented model. Notably, the MILP formulation presented for multi-objective MRCPSP is coded in GAMS 25.1.2 software and is solved by CPLEX solver. The whole computations are conducted on a Laptop (Intel Core i7 4500U 1.80 GHz CPU and 8 GB of RAM). CPU time spent on solving the mathematical model with $\alpha = 0.5$ is 494.208 s, and the value of the objectives is summarized in Table 2.

The details of project activities in the solved model are provided in Table 3. Sensitivity analysis helps to better understand the model's behavior in different situations. The first sensitivity analysis is about the trade-off between the greenness index and project quality, which is presented in Fig. 8 and Table 4.

According to Fig. 8, the green and quality objective functions have a direct effect on each other. It means that by an increase in the average quality of the project, the emitted CO_2 increases.

This happens because the increase in quality level stems from reworking, and more pollution is emitted due to this reworking. Thus, the increase in the project quality has a direct effect on the project greenness index. As it is reported in Table 4, changes in the quality of activities and emitted CO_2 are so close to each other (25.51% increases for quality and 25% for green increases). To sum it up, the reworking is

Table 3 Execution mode and finish time of activities in the solved model

Act No	Modes		Finish time
	1	2	
1	✓		34
2		✓	311
3		✓	501
4	✓		621
5		✓	978
6	✓		751
7		✓	1061
8		✓	1111
9		✓	559
10		✓	674
11	✓		1053
12	✓		1075
13		✓	1111
14	✓		708
15	✓		1161
16		✓	1161
17		✓	1182
18	✓		1197

Fig. 8 The relation between greenness index and project quality

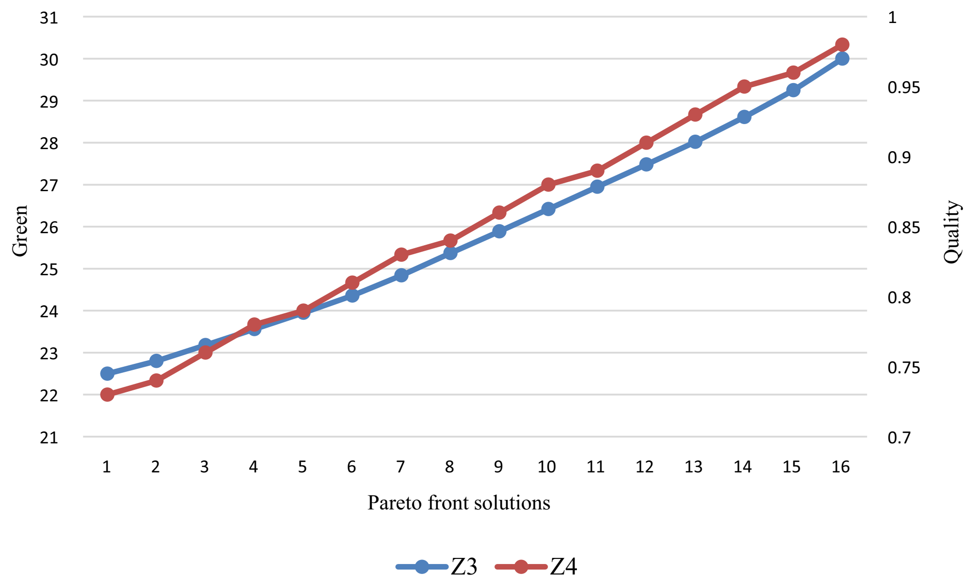

Table 4 The relation between greenness index and project quality

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Green	22.5	22.8	23.18	23.56	23.95	24.36	24.84	25.37	25.89	26.42	26.95	27.48	28.02	28.61	29.25	30
Q uality	0.73	0.74	0.76	0.78	0.79	0.81	0.83	0.84	0.86	0.88	0.89	0.91	0.93	0.95	0.96	0.98

Fig. 9 The relation between the project completion time and the greenness index

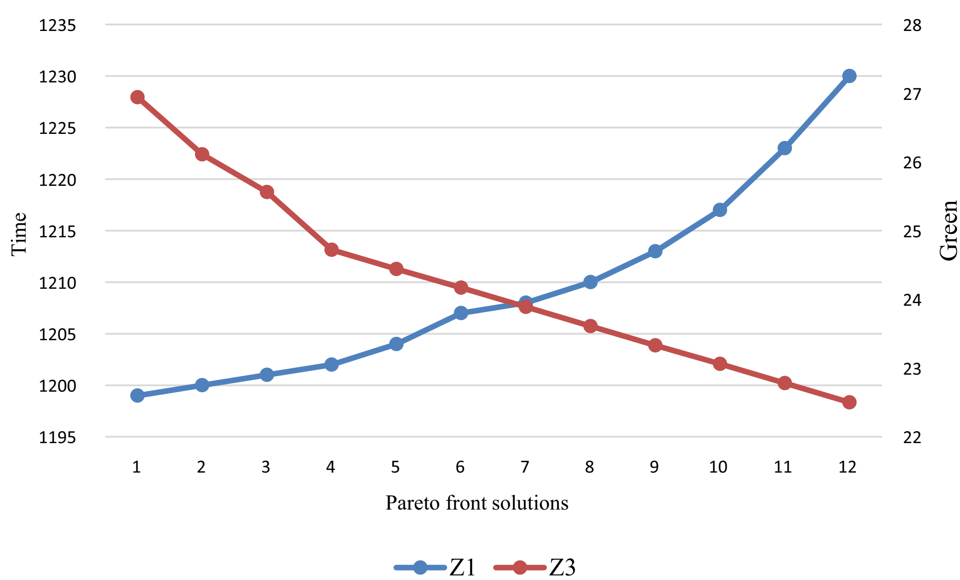

Table 5 Relation between project completion time and greenness index

	1	2	3	4	5	6	7	8	9	10	11	12
Green	26.94	26.11	25.56	24.72	24.44	24.17	23.89	23.61	23.33	23.06	22.78	22.5
Time	1199	1200	1201	1202	1204	1207	1208	1210	1213	1217	1223	1230

the reason that the project greenness and the project quality level are in the same direction.

In the second analysis, the relation is analyzed between the project completion time and the greenness index, which is shown in Fig. 9 and Table 5.

The result of the trade-off between the first and third objective functions shows that longer project makespan produces more pollution. Based on Fig. 9, when project completion time decreases, the use of non-renewable and renewable resources increases. This issue causes more CO_2 emissions. In addition, according to Table 5 and comparing the first and the last greed points, the greenness index decreases 16.48% while the project completion time increases only 2.52%. Thus, the least project completion time is in the highest mitted value of the CO_2 emission. The third analysis is regarding the time quality trade-off, which is shown in Fig. 10 and Table 6.

Figure 10 shows that an increase in the project completion time has a direct effect on the project quality. The longer project completion time means that more reworking is done,

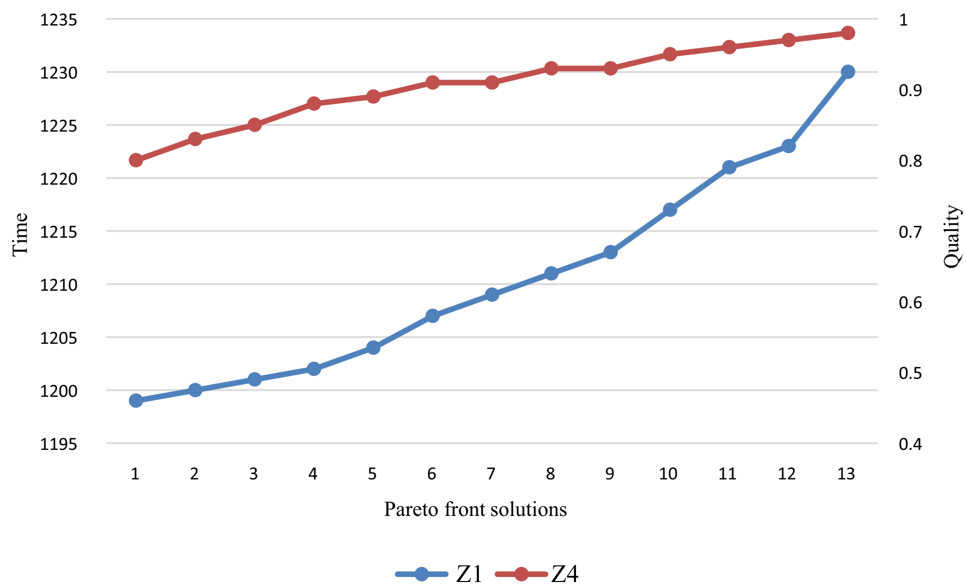

Fig. 10 The relation between project completion time and project quality

Table 6 The relation between project completion time and the project quality

	1	2	3	4	5	6	7	8	9	10	11	12	13
Quality	0.8	0.83	0.85	0.88	0.89	0.91	0.91	0.93	0.93	0.95	0.96	0.97	0.98
Time	1199	1200	1201	1202	1204	1207	1209	1211	1213	1217	1221	1223	1230

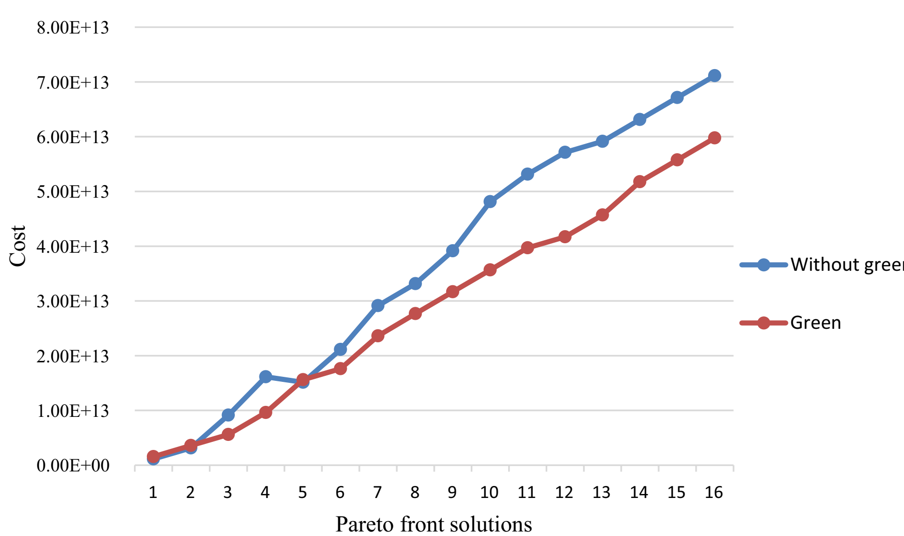

Fig. 11 The effect of considering and ignoring greenness index on the project cost

and more reworking results in a higher quality level. Based on Fig. 3, by an increase in the project makespan, the project quality increases sharply. Thus, the average quality of the project highly depends on the required time for project completion. It is evident that when there is no time pressure, the project quality increases. Moreover, based on Table 6, the project quality increases 18.37%, but the project completion time increases only 2.52%. Hence, when the time pressure increases, the project quality decreases, but the longer project makespan results in the higher project's quality level.

The cost and greenness relation is another issue, which is illustrated in Fig. 11. Based on Fig. 11, in the constant Pareto solution the project costs without the greenness index are more than the project costs with the greenness index. The reason is that the company has to pay a large amount of penalty if it is indifferent to environmental impacts. In some greed points (1, 2, and 5), the project costs by considering emitted CO_2 are higher than the project costs without the greenness index. The reason is that the penalty cost in these points is fewer than the cost of considering the greenness index. The cost of greenness index can be for example the cost of newer machines. To conclude, the project costs by considering the emitted CO_2 as an object decrease due to the environmental penalty costs elimination. Finally, Fig. 12 presents the effect of α value on project completion time.

According to Fig. 12, for any value of the α, the project completion time with the lower value is longer than the upper value. This issue is true, and generally, the upper value of the IVF numbers can produce better results than the lower value. Another point in Fig. 5 is that by an increase in the value of α, project makespan decreases. The closest makespan is observed in $= [0.4, 0.6]$, and the biggest gap is observed in $\alpha = 0.1$ and $\alpha = 0.9$. Hence, the project completion time with the upper value of the IVF number has better results than the lower value.

To sum up and compare the previous articles with this study, a comparative analysis is conducted in Table 7.

Conclusion

The environmental effect of the industries section is an essential issue that is neglected in many developing countries. In Iran, approximately the entire energy system relies on fossil fuels, which impose significant greenhouse gases emission on the country. On the other hand, among the different greenhouse gases, CO_2 has the most considerable section, and Iran is a country with lots of CO_2 emissions, especially in the industry section. In this paper, a new MRCPSP is presented by considering CO_2 emission minimization as an objective function. The mathematical model, besides minimizing emitted CO_2, has three other objective functions, which are minimizing project completion time, minimizing the project costs, and maximizing the project quality. To show the effect of the proposed mathematical model on real-world situations, the case study in Iran is proposed. In real projects, uncertainty is an inseparable part of the project, so the mathematical model is presented and solved by considering fuzzy uncertainty. To solve the multi-objective model with the IVF numbers, a new extended solving method is presented.

The evaluated result shows the effect of the CO_2 emission on the other objective functions. The greenness index and project quality have a direct impact on each other due to the reworking. By reworking on the activities, their quality and the greenhouse gas emission increase. The other important issue is the increase in the CO_2 emission in the projects

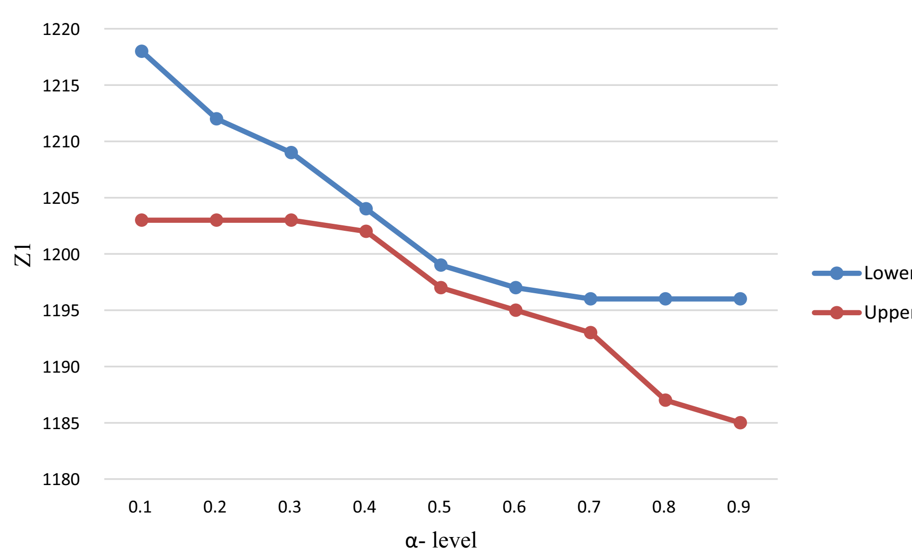

Fig. 12 The effect of α value on the project completion time

Table 7 Comparative analyses between the proposed model and previous studies

Element of comparisons	The result of comparisons
General framework	In this paper, a new MRCPSP model by considering the greenness index is presented in an uncertain environment where activity crashing is allowed. Some previous papers focused on green scheduling in job shop scheduling environments, e.g., Wu and Sun (2018) and Mansouri et al. (2016). Other papers, like Elloumi et al. (2021), only investigated RCPSP and considering CO2 emission in construction projects in an uncertain environment is neglected.
CO2 emission	Previous papers, e.g., Shabani and Shahnazi (2019), only discussed the importance of reducing CO_2 emissions in Iran. But presenting a proper mathematical model for considering emitted CO_2 is neglected, so in this paper, a new mathematical model is introduced for considering CO_2 emission in construction projects
Mathematical model	Although time–cost-quality trade-off is formulated in some papers, such as Luong et al. (2021), considering CO_2 emission as an objective function alongside time–cost-quality trade-off is neglected in an uncertain environment. Besides, in this paper the crashing is formulated which is only considered in a few papers, e.g., Zhang and Zhong (2018), where the environmental effect is not regarded
Uncertainty	Uncertainty is addressed in some previous studies, but formulating MRCPSP by considering CO_2 emission as a greenness index is neglected in a fuzzy environment, particularly IVF set as an extension of fuzzy sets

with the time pressure. This time pressure caused more use of the resources, machines, and act, so as it was shown in the computational experiments, more CO_2 will be emitted. Finally, considering the CO_2 emission as an objective function results in a reduction in the project costs. The other results are about the fuzzy uncertainty that demonstrate the upper value of the IVF numbers with a better result than the lower value. Many companies wish to protect the environment, but their problem is the fact that the profit of the company is on the top of their priority list. Besides, the lack of practical methods to reduce CO_2 is another problem. Thus, in this paper a new mathematical model is extended to help project managers for reducing CO_2 emissions in construction projects alongside their fundamental goals (i.e., time, cost, quality). The presented method can be generalized for applying in other sections, but the special restrictions and constraints of each section should be considered in detail.

Considering the real-world conditions and the possibility of disruption in project implementation, some parameters are strongly affected, and this could be an interesting topic for researchers in future research. In addition, due to the importance of the project and its impact on various aspects of society, sustainable project scheduling would be an interesting subject to be studied. On the other hand, due to the existence of various projects for contractors and project organizations, a successful organization needs to select appropriate projects in its project portfolio. Therefore, the discussion of portfolio selection to increase corporate income for future research is another future direction.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in the study.

Consent for publication This study does not contain any studies with human participants or animals performed by any authors.

Ethical approval The manuscript is original. It has not been published previously by any of the authors and even not under consideration in any other journal at the time of submission.

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