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## ► To cite this version:

Reza Shahabi-Shahmiri, Reza Tavakkoli-Moghaddam, Alexandre Dolgui, Seyed-Ali Mirnezami, Mohammad Ghasemi, et al.. Preemptive and non-preemptive multi-skill multi-mode resource-constrained project scheduling problems considering sustainability and energy consumption: A comprehensive mathematical model. *Journal of Environmental Management*, 2024, 367, pp.121986. 10.1016/j.jenvman.2024.121986 . hal-04925494

**HAL Id: hal-04925494**

**<https://hal.science/hal-04925494v1>**

Submitted on 21 Feb 2025

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## Research article

# Preemptive and non-preemptive multi-skill multi-mode resource-constrained project scheduling problems considering sustainability and energy consumption: A comprehensive mathematical model

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## ARTICLE INFO

## Keywords:

Project scheduling

Sustainability

Energy consumption

Activity preemption and crashing

Robust chance-constrained programming

## ABSTRACT

Modern project managers cope with significant challenges to schedule and control projects considering dynamic environments, frequent uncertainties, strict project deadlines, and stricter sustainable requirements above all. Sustainability taking into account resource utilization has been recently associated with project management. Hence, this paper presents a new mixed-integer linear programming (MILP) model with two objectives for a resource-constrained project scheduling problem (RCPSPP) with multiple skills and multiple modes, assuming preemptive and non-preemptive activities in an uncertain environment. Given the importance of sustainable developments in projects, the considered objectives are to maximize job opportunities and minimize project duration, resource costs, and total energy consumption. To deal with the model, an AUGMECON2VIKOR algorithm is utilized to create Pareto solutions. In this model, project activities can be crashed by allocating extra resources. Furthermore, multi-skill resources are used to perform project activities. This study also investigates the impact of these resources on project scheduling. To deal with uncertain circumstances, a fuzzy chance-constrained programming method is employed to develop a robust possibilistic programming model. With respect to the increasing significance of sustainability in project management, this study pioneers the examination of the impact of sustainable factors on project scheduling. Finally, the proposed formulation is validated using instances from the well-known PSPLIB and MMLIB test sets. Finally, a comparison is drawn between the presented solution method considering AUGMECON2VIKOR and AUGMECON2.

## 1. Introduction

Project management has been investigated in various articles and has been utilized by several companies to date (Herroelen and Leus, 2004; Song et al., 2022). In project management, the project scheduling problem is a significant one and has been investigated broadly in previous studies. The most common variant is the resource-constrained project scheduling problem (RCPSPP), which was tackled by using exact and approximate methods. It consists of scheduling projects with

non-preemptive and inter-dependent activities, requiring limited resources, typically for project makespan minimization (Vanhoucke et al., 2004). Simple methods (e.g., critical path method (CPM)) are unable to consider resource allocation while minimizing project costs and duration at the same time and therefore fail to acquire an optimum solution for the issue (Sonmez et al., 2016). The RCPSPP has been commonly addressed in novel production systems and industrial procedures, like semiconductor wafer fabrication (e.g., Wang et al., 2018), automobile assembly systems (e.g., Bartels and Zimmermann, 2009), and cloud

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<https://doi.org/10.1016/j.jenvman.2024.121986>

Received 28 May 2024; Received in revised form 9 July 2024; Accepted 21 July 2024

Available online 1 August 2024

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workflow scheduling (e.g., [Arabnejad et al., 2017](#)).

The RCPSP and the respective developments have been studied thoroughly in the literature to date. These extensions include the multi-mode RCPSP (MRCPSP) (e.g., [Ghoddousi et al., 2013](#); [Van Peteghem and Vanhoucke, 2014](#)), generalized precedence relations (GPR) (e.g., [Dorndorf et al., 2000](#); [Schnell and Hartl, 2016](#)), multi-objective RCPSP (e.g., [Ballestín and Blanco, 2011](#)), and uncertain environments (e.g., [Zhao et al., 2023](#); [Peng et al., 2023](#)).

In contrast to the problem of the trade-off between expenses and time, in which expenses are supposed to be minimized considering the project deadline, the general RCPSP aims at minimizing the project duration while considering resource restrictions and precedence relations. Project experts are usually concerned about satisfying or mitigating delays and achieve this by compressing the schedule to shorten the project duration. In the last five decades, operational research, project management, and scheduling areas of research have produced a great number of prolific studies.

Considering sustainable development in real-life conditions is one of the recent significant problems ([Habibi et al., 2018](#)). The inclination of corporations to schedule their tasks and have a plan for applying resources while considering the next generations can emphasize their responsibility for taking into account sustainable development ([Habibi et al., 2019](#)). Building technologies in addition to courteous and thoughtful human resource management approaches are required to be taken into account for sustainable development in the construction industry ([Lill, 2008](#)). Despite this fact, there are a few studies in which sustainability in the project scheduling problem has been investigated. Based on the research conducted by ([Harvard Business School, 2020](#)), corporations that pay no attention to sustainability mostly face more production expenses, supply chain risks, and inappropriate financial performance. Furthermore, [Armenia et al. \(2019\)](#) mentioned that although traditional project management methods without taking into account sustainability may bring about short-term gains, they can lead to long-term negative impacts on economic, social, and environmental factors. Corporations that ignore sustainability mostly have reduced project success and inappropriate organizational performance. This study was motivated by some practical case studies, which integrate sustainable developments with project scheduling successfully. For instance, Project Management Institute (PMI) standards have been utilized by Vodafone to include sustainability in their project management. It permitted this company to deliver complicated technology projects with more effectiveness and reduced environmental effects. The combination of sustainability and project scheduling contributed to their success and innovation capacity ([PwC, 2024](#)).

In what follows, it is illustrated that different approaches have been applied to shorten the schedule in previous investigations that consider predetermined relationships between cost and duration. A linear trade-off between expenses and time can be regarded as the most prevalent assumption in the literature; that is, shortening the duration through utilizing extra resources which in turn results in a linear cost increment per unit of time shortened ([Reda and Carr, 1989](#)).

Scheduling activities considering resource restrictions is a highly complicated problem. These problems, i.e., RCPSPs, have been thoroughly reviewed in [Hartmann and Briskorn \(2022\)](#). There are many different aspects of the scheduling problem that have been studied so far by researchers. Various methodologies and solution strategies have been utilized, such as reactive scheduling (e.g., [Van de Vonder et al., 2006](#)), multi-stage stochastic optimization (e.g., [Li and Womer, 2015](#); [Creemers, 2015](#)), fuzzy programming (e.g., [Alipouri et al., 2020](#); [Arik and Toksari, 2018](#)), simulations integrated with sensitivity analyses (e.g., [Hall and Posner, 2004](#)), chance-constrained programming (e.g., [Lamas Vilches and Demeulemeester, 2015](#)), and robust optimization (e.g., [Balouka and Cohen, 2019](#)). The most important and relevant aspects of the literature will be discussed in the following sections.

In spite of the abovementioned explanations, the issues of multi-skilled workforce and uncertain conditions are the challenges in

sustainable project management that have not been appropriately investigated in optimization modeling research. Hence, the main goal of the presented study is to extend a mathematical model for MSRCPSP with sustainability under uncertainty considering non-renewable resources and due date to maximize social dimension and minimize project makespan, cost, and energy consumption. To achieve this aim, the presented study investigates the following research questions.

- What is the effect of considering multi-skilled workforce on project scheduling?
- What is the effect of considering multi-skilled workforce on energy consumption and social dimensions?
- How can increasing level of workforce skills and considering energy consumption maximize social dimensions and minimize the project makespan and cost simultaneously?

The outline of this paper is organized as follows. Section 2 provides a review of recent works on MSRPCP, trade-off problems, preemptive scheduling, sustainability, resources with multiple skills, and robust possibilistic as well as chance-constrained programming in the RCPSP. An elaborate description of the problem and sustainable developments is explained in Section 3. The notations and mathematical formulation are presented in Section 4. Section 5 describes the proposed solution approach. Computational results, scenario analysis, and sensitivity analysis are presented in Sections 6, 7, and 8, respectively. Managerial implications and limitations as well as future developments are presented in Section 9.

## 2. Literature review

Project scheduling platforms interest many scholars in studying project scheduling issues and extending the respective approaches to improve the performance of the project scheduling platforms. In this regard, the extensions of project scheduling, like the RCPSP, MRCPSP, trade-off problems, preemptive scheduling, and robust possibilistic and chance-constrained programming in the RCPSP, have been investigated in previous research. Because the domains of the presented paper are chiefly associated with the MRCPSP under uncertainty, trade-off problems, and preemptive activities, they are investigated in more detail in the following subsections.

### 2.1. MRCPSP

The multi-mode RCPSP (MRCPSP) is a famous extension of the classic RCPSP. Activities can be related to different modes, namely, various ways to implement these activities. It facilitates, for instance, employing various types of resources or employing more resources to reduce the completion time ([Hartmann and Briskorn, 2022](#)). The quantity and type of required resources in addition to the interactions among activities, which are a result of the shared resources utilization, have a considerable effect on activities' duration in MRCPSPs ([Zapata et al., 2008](#)). These problems have received remarkable attention from scholars due to their great significance in real-life projects ([Ghasemi et al., 2023](#); [Mirnezami et al., 2023](#)).

To deal with the MRCPSP considering renewable and non-renewable resources, [Chakraborty et al. \(2016\)](#) utilized a modified heuristic algorithm to find a near-optimal solution. Aiming at minimizing project completion time and considering existing uncertainties, [Balouka and Cohen \(2019\)](#) applied a robust technique to tackle the MRCPSP. An improved version of the genetic algorithm (GA) has been presented by [Afshar et al. \(2022\)](#) for solving the MRCPSP. Minimizing project makespan and resource costs are two aims of research conducted by [Liu et al. \(2022\)](#) in the MRCPSP. The combination of the GA and particle swarm optimization (PSO) was proposed to cope with the problem. [Chu et al. \(2023\)](#) utilized an adaptive meta-heuristic recommendation model (MRM) for the MRCPSP.

## 2.2. Trade-off problems

Due to the critical importance of duration and expenditures of activities in RCPSPs, previous studies have presented different methods concerning these problems for the trade-off between expenses and time. Li et al. (2020) investigated the issue of scheduling to appraise the trade-off among duration, expenses, and robustness considering different modes for activity implementation in an uncertain environment. The proposed mathematical model in their work, which is aimed at maximizing robustness and minimizing project makespan and cost, is solved using a genetic algorithm. A three-objective nonlinear mixed integer-constrained programming model was developed by Chen et al. (2024) considering staff skill increments, team diversity, and R&D cycle in the multi-skilled staff scheduling problem and team configuration. The trade-off among environmental effects, activities duration, expenditure, and quality was addressed by Banihashemi and Khalilzadeh (2021) by analyzing the efficiency of activities in various implementation modes and choosing the most appropriate mode using a data envelopment analysis (DEA) method. The discrete time-cost trade-off problem (DTCTP) considering limited resources was studied by Zou and Zhou (2021) taking into account resource transfer and flexible resource constraints (FRC). The trade-off between resources considering the combination of building information modeling (BIM), multi-objective optimization (MOO), and multi-criteria decision-making (MCDM) was represented by Nguyen et al. (2022). Hashemi and Shahbandarzadeh (2024) proposed a fuzzy model for time-cost-quality trade-off in construction projects considering sustainability. Sharma and Trivedi (2022) formulated a time-cost-quality-safety trade-off model for the MRCPSP. A time-cost-quality-energy trade-off was represented by Lotfi et al. (2022a) in the applicable blockchain technology in project management. A time-cost trade-off was extended by Li et al. (2022) for the MS-RCPSP. Banihashemi and Khalilzadeh (2023) extended a time-cost-environmental effect trade-off considering construction project scheduling problems.

## 2.3. Preemptive scheduling

To date, several studies have been conducted concerning the extensions of the RCPSP (Hartmann and Briskorn, 2022). In both multi-mode and single-mode RCPSPs, the assumption is that once activities are started, they are not permitted to stop/pause during their execution and continue until completed. In contrast to the aforementioned assumption, the preemptive MRCPSP, allows activities to preempt and start again during execution. Consequently, in real-world situations, scheduling a project can be conducted considering preemptive and non-preemptive activities (Biażewicz et al., 2007). Saeidi et al. (2020) presented a methodology to tackle the issue of scheduling projects considering resource restrictions and activity preemption considering the optimization of both project delivery time and human resources under uncertainty. For the net present value (NPV) maximization, Delgoshaei et al. (2019) introduced an approach for the MRCPSP assuming preemptive scheduling of resources and using a genetic algorithm. To minimize the expenditures, Maghsoudlou et al. (2019) addressed an RCPSP taking both preemption of activities and multiple skills for resources into account using an ant colony-based method. Various models were presented by Artigues et al. (2021) for minimization of the completion time while scheduling a project considering preemption and different skills for the utilized resources. A serial greedy algorithm was improved by Polo-Mejía et al. (2021) for the MS-RCPSP considering partial preemption. A practical study conducted by Peng et al. (2023) studied a preemptive MS-RCPSP model to minimize maintenance time and improve the maintenance efficiency in large ships. An integer programming model was formulated by Ma et al. (2022) for proactive RCPSP to analyze the trade-off between the merits of activity preemption and the disadvantages of more resource transfer times.

## 2.4. Sustainability

There is a lack of approaches for the issue of project scheduling that assists experts with planning projects in an optimal way taking into account social sustainability measures, which might be useful for both workers and project managers in addition to owners (Florez et al., 2013). RezaHoseini et al. (2020) presented a linear formulation with multiple objectives for maximizing total benefits in addition to the value of utility for projects and minimizing the amount of interruption in implementing adopted projects for sustainable project portfolio selection considering project splitting. A decision-making method considering multiple criteria was utilized in their investigation to rank, score, and compute the sustainable utility of projects. A mixed-integer programming (MIP) model was developed by Tabrizi (2018) for project scheduling and material procurement simultaneously, aiming at minimizing project costs and environmental effects. The trade-off between resource-leveling, duration, and greenhouse gas emissions was considered in a mathematical formulation with multiple objectives presented by Hussain and Hussain (2023) for sustainable construction projects. Sustainable construction projects have also been investigated by Martinez et al. (2022) and Zhang et al. (2023). This problem was also considered in Banihashemi and Khalilzadeh (2023) by developing a project scheduling formulation considering restricted resources as well as multiple modes and objectives. In their investigation, environmental influences of construction projects in addition to the objectives of cost, time, and quality were considered. To minimize the project's delay, Askarifard et al. (2021) presented a formulation with multiple objectives aiming to minimize cost, risk, and socio-environmental effects. To cope with the multi-objective model under uncertainty, robust programming and the  $\epsilon$ -constraint method were utilized in their study. A combination of project management with innovation and sustainability was investigated by Calderon-Tellez et al. (2024). In the study conducted by Yang et al. (2023), optimizing energy consumption, CO<sub>2</sub> emissions, and production cost have been considered. Time, expenses, energy consumption, and CO<sub>2</sub> emissions were considered by Razi and Ansari (2024) in a prediction-based formulation for the optimization of construction programs. Sustainable developments in other types of projects (e.g., forestation and mining projects) have been addressed in Rollan et al. (2018) and Li et al. (2023), respectively.

## 2.5. Resources with multiple skills

In the MS-RCPSP, resources have more than one skill required for executing an activity. A group of skills is taken into account, and resources have at least one of them. In addition, resources with determined skills are required in each task. Determining a beginning time and suitable resources for activities to minimize the project completion time is the goal. The MS-RCPSP has been dealt with in Almeida et al. (2018), and Almeida et al. (2019). Multi-skill issues, in which resources have skills at various levels and resources that have skills at least at a determined level, are needed for activities were studied by Lin et al. (2020) and Zheng et al. (2017). The weighted MS-RCPSP has been addressed by Akbar et al. (2024) to minimize software project makespan. A scheduling method, namely greedy and parallel scheduling (GPS), was proposed in this study to cope with the underutilization of workforces owing to different activity durations.

A similar setting considering both time and expense minimization was investigated by Wang and Zheng (2018). In the current year, multi-skill renewable resources were taken into account in the MRCPSP with preemptive project tasks by Zarei et al. (2024), Mirnezami et al. (2023). Ghasemi et al. (2024) discussed the impact of this realistic assumption on project scheduling.



## 2.6. Robust possibilistic and chance-constrained programming in the RCPSP

According to the investigations identified in Scopus, the number of papers on robust optimization has risen from 2010 to 2023. In 2020, over three thousand articles have been published, that is, roughly speaking, similar to the number of articles published in 2010. Davari and Demeulemeester (2019) presented a model to tackle the chance-constrained RCPSP and applied a branch-and-bound method. Sallam et al. (2021) utilized a reinforcement learning approach to cope with a stochastic RCPSP. Furthermore, a chance-constrained-based method was taken into account in their investigation to tackle uncertainties. A chance-constrained method was employed by Bianco et al. (2019) for a scheduling issue taking into account precedence dependencies and no restriction for resources in an uncertain environment. Robust nonlinear programming was utilized by Lotfi et al. (2022b) for RCPSP with sustainable considerations. Yanting and Zhengwen (2023) presented a robust schedule considering the MRCPSP in Emergence Rescue. Fuzzy-robust-stochastic (FRS) optimization techniques were presented by Ramedani et al. (2024) for conflicting criteria including sustainability, time, budget, and resource constraints in the project portfolio selection and scheduling.

Table 1 shows some of the most relevant studies conducted from 2014 to 2024. As can be observed in this table, preceding studies have not adequately investigated crashing and preemptive in MRCPSPs. Despite dealing with uncertainties in different research, as of yet, no research has utilized a robust chance-constrained programming method with the AUGMECON2VIKOR approach for MRCPSPs that takes both activity crashing and preemption into account. The main dimensions of sustainability (i.e., cost, social, green) have not been considered simultaneously in MRCPSPs. Despite the importance of social aspects in modern organizations, only Askarifard et al. (2021) considered it as an objective in mathematical formulation. All of the previous research presented sustainability for scheduling problems, assuming that project tasks cannot be preempted and crashed during the project execution.

There is a notable absence of scholarly work on the investigation of how sustainable factors influence project scheduling. In addition to sustainability, multi-skill resources have not been investigated by researchers concurrently. Multi-skill resources and preemptive project activities in the MRCPSP have only been studied by Mirnezami et al. (2023) and Ghasemi et al. (2024). However, in their work, activities cannot be crashed and the sustainable dimensions have not been considered. Regarding the research gap in project scheduling, in the presented article, a novel extended mixed-integer linear programming (MILP) model with multiple objectives is proposed in the MRCPSP considering preemptive and crashable project activities under uncertainty. The aims are to minimize project makespan and total project cost. Furthermore, the impacts of sustainable dimensions including environmental, social, and economic, as well as resources with multiple skills in project scheduling are analyzed. To cope with the uncertain environment and the multi-objective optimization formulation, a robust chance-constrained programming with the AUGMECON2VIKOR method is utilized for the first time.

According to the above-mentioned explanations and Table 1, the principal novelties of the current investigation are highlighted as follows.

- Extending a new multi-objective MILP model aiming at maximizing social dimension and minimizing makespan, total project cost, and energy consumption in the MRCPSP with multiple skills.
- Taking into account sustainable development as a substantial and updated issue in MRCPSP with multiple skills and its impacts on project scheduling for the first time.
- Investigating the impacts of multi-skill resources on reducing energy consumption in project scheduling problems for the first time.

- Assuming preemptable and crashable multi-mode project activities in MS-RCPSP with sustainable developments considering the lack of resources in project scheduling problems.
- Utilizing the AUGMECON2VIKOR method for tackling the multi-objective mathematical formulation in MS-RCPSP with multiple modes for the first time.
- Integrating a robust chance-constrained programming with the AUGMECON2VIKOR method for solving the introduced mathematical formulation to cope with uncertainty in real-world conditions.

## 3. Problem definition

The purpose of the presented model is to deal with the MRCPSP. Project makespan and cost minimization are the objectives considered in this article. Additionally, activity crashing will be supported, since it is a usual technique used in real-life projects to reduce the project completion time. Also, the proposed formulation will allow preemption of activities, something that can occur for diverse reasons, such as temporary resource unavailability. In other words, project activities can be preempted at various planning stages during their execution stage. Finally, we assume that the setup times of tasks and the duration for resource allocation are zero.

In the presented problem, project tasks are numbered topologically, with 0 and  $N + 1$  denoting dummy start and finish tasks, respectively. Additional expenses incurred due to additional resource requirements for crashing activities are taken into account.  $CT_{im}$  represents the duration of crashable task  $i$  executed through mode  $m$ .  $ES_i$  and  $LF_i$  indicate earliest starting in addition to the latest finish time of task  $i$ , respectively. Actual task starting time can be bounded using them.  $KA_{rt}$  indicates the available quantity of renewable resource  $r$  in each time period  $t$ .  $k_{imr}$  represents the needed renewable resource  $r$  to perform task  $i$  through mode  $m$ .  $k'_{imr}$  denotes the additional quantity of resource  $i$  required for crashing task  $i$  while implementing through mode  $m$ . Similarly,  $non_{imn}$  and  $non'_{imn}$  represent the corresponding quantities for non-renewable resources. Each project activity  $i \in I$  needs a skill  $s \in S$  considering a certain kind at a minimum level. Each renewable resource  $r \in R$  can implement the task  $i \in I$  on condition that the resource learns the needed skill and familiarity level is not lower than the minimum level. Furthermore, at most one activity at a time can be performed by each resource, and each activity is required to be performed once.

### 3.1. Effects of sustainable dimensions on project scheduling

Project scheduling is crucial for the successful completion of various tasks, and it goes beyond just managing time. Nowadays, sustainability factors, which include environmental, social, and economic aspects, are becoming more important in project planning and execution. Several studies (RezaHoseini et al., 2020; Tabrizi, 2018) have emphasized the integration of sustainability into project scheduling. This section discusses the various ways in which these sustainability factors affect project scheduling.

#### 3.1.1. Environmental considerations

Incorporating sustainability into project scheduling requires a deep understanding of environmental aspects. Examining these environmental dimensions entails evaluating how a project might affect air quality and noise levels. These considerations significantly shape the scheduling process, influencing choices like equipment selection, construction timelines, and the project's overall environmental impact. The difficulty lies in aligning project schedules with environmental objectives to minimize negative environmental effects (Carvalho and Rabechini Junior, 2015; Habibi et al., 2019).

#### 3.1.2. Social impacts

The social dimension encompasses a broad spectrum of factors,

**Table 1**  
Overview of the related articles.

Article	Year	Objective function(s)		Resources		Type of objective(s)					Problem Characteristic(s)					Uncertain environment	Solution approach	
		Single	Multi	Renewable	Non-renewable	Time	Cost	Social	Green	Others	Sustainability	Multi-skill	Multi-mode	Preemptive	Crashing			Time windows
Kopanos et al.	2014	✓		✓		✓										✓	No	MILP models and CPLEX solver
Zheng and Wang	2015	✓		✓		✓											Interval numbers	TLBO algorithm
Elloumi et al.	2017		✓	✓	✓	✓				✓							Yes	MOEA + Novel reactive multi-objective heuristic
Muritiba et al.	2018	✓		✓	✓	✓											No	Path-Relinking (PR) algorithm
Tabrizi	2018		✓	✓			✓		✓		✓						No	NSGA-II and MOMBO meta-heuristic algorithms
Van Den Eeckhout et al.	2019	✓		✓			✓								✓	✓	No	Iterated local search procedure
Afshar et al.	2022	✓		✓	✓	✓											No	Genetic algorithm (GA)
Maghsoudlou et al.	2019	✓		✓			✓				✓						No	Ant colony-based metaheuristic
Subulan	2020		✓	✓	✓	✓	✓										Interval numbers	Chance-constrained Programming (CCP)
Sharma and Trivedi	2022		✓	✓	✓	✓	✓			✓							No	NSGA III
Chaleshtarti et al.	2020	✓		✓	✓												No	Lagrangian relaxation with GA
Askarifard et al.	2021		✓	✓		✓		✓	✓	✓	✓					✓	Yes	Robust programming method + ε-constraint
Artigues et al.	2021	✓		✓		✓						✓		✓			No	Mixed-Integer/Linear Programming and Constraint Programming
Liu et al.	2022		✓	✓	✓	✓	✓										Fuzzy + Stochastic	particle swarm optimization (PSO) and GA algorithms
Aramesh et al.	2022		✓	✓	✓	✓	✓		✓	✓	✓					✓	Triangular IVF numbers	IVF-SO solution method
Banihashemi and Khalilzadeh	2023		✓	✓		✓	✓		✓		✓						Fuzzy numbers	Fuzzy BWM method
Hussain and Hussain	2023		✓	✓	✓	✓			✓	✓	✓					✓	No	MGWO and NSGGA-II algorithms
Mirnezami et al.	2023		✓	✓	✓	✓	✓			✓	✓		✓			✓	Stochastic	Stochastic chance-constrained Model
Ghasemi et al.	2024	✓		✓	✓	✓					✓	✓	✓			✓	Interval type-2 fuzzy parameters	Chance-constrained programming method with credibility Measure prediction-based model
Razi and Ansari	2024		✓	✓		✓	✓		✓		✓						No	NSGA-II
Chen et al.	2024		✓	✓		✓	✓		✓	✓	✓						No	NSGA-II
Current study			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Trapezoidal fuzzy numbers	Robust chance-constrained programming + AUGMECON2VIKOR approach

**Note:** Teaching-learning-based optimization (TLBO), multi-objective evolutionary algorithm (MOEA), multi-objective migrating birds optimization (MOMBO), non-dominated sorting genetic algorithm (NSGA-II), Multi-objective grey wolf optimization (MGWO), Interval-valued fuzzy (IVF), Best worth method (BWM).

including employment and public well-being. The impact of social factors on project scheduling is substantial. For instance, high unemployment rates can lead to project delays and disruptions due to social unrest. Factors affecting public comfort, like noise pollution and inconveniences, can impact community relations and, subsequently, project advancement. Moreover, changes in labor availability due to construction-related migration patterns can directly influence scheduling decisions. (Singh et al., 2012; Ika et al., 2012).

### 3.1.3. Economic factors

These factors have a vital role in project scheduling, encompassing resource allocation, workforce engagement, employment prospects, and overall expenses. Efficiently using resources and labor can impact project timelines, while generating job opportunities both within and beyond the project’s scope. Furthermore, financial aspects, including construction expenses, equipment costs, and maintenance outlays, significantly influence decisions regarding project scheduling. Striking a balance between economic objectives and project timelines presents a complex challenge in the realm of sustainable project scheduling (Wang et al., 2014; Jones et al., 2013).

Given the previously discussed information, Table 2 offers a well-structured framework for assessing the diverse impacts of environmental, social, and economic factors on project planning and implementation. This framework harmonizes project management with sustainability goals, allowing stakeholders to make informed choices

**Table 2**  
Multidimensional assessment framework for environmental, social, and economic impacts.

Dimension	Indicator	Explanation
Environmental	1. Air pollution	Evaluation of the creation of air pollutants and greenhouse gas emissions.
	2. Noise pollution	Analysis of the production of noise and vibrations.
Social	1. Employment	Investigation into the psychological and societal consequences of unemployment, encompassing effects such as immigration, addiction, and depression.
	2. Public comfort	Appraisal of the effects on community well-being and convenience, including issues such as noise pollution, light pollution, the generation of unpleasant odors, and dust.
Economic	1. Direct job opportunities	Analysis of the employment opportunities generated by the project, encompassing a range of roles including labor, professionals, and engineers.
	2. Indirect job opportunities	Evaluation of employment opportunities created through upstream and downstream industries.
	3. Cost of construction	A comprehensive evaluation of construction costs, encompassing expenses such as materials, water, energy, transport, labor, professional fees, and compensation for environmental destruction.
	4. Cost of equipment and their installation	Assessment of costs associated with procuring and installing various equipment and facilities, including items like factory equipment, cranes, elevators, air conditioning systems, transportation, installation, and employee training.
	5. Cost of operation and maintenance	Evaluation of the expenses related to facility maintenance and upkeep, including costs for repair, general utilities (e.g., water, electricity, and gas), resources, employee training, and other expenditures during the operational and maintenance phases.

aimed at minimizing negative effects and reinforcing project resilience. Through the integration of these aspects into the scheduling process, project managers can adeptly navigate the complex interplay between sustainability concerns and project timelines, ultimately promoting more responsible and effective project management practices. This table establishes a cornerstone for the subsequent analyses and discussions within this paper, shedding light on the intricate connections between sustainability and project scheduling.

## 4. Problem formulation

The nomenclatures for the proposed MILP model, which is similar to Shahabi-Shahmiri et al. (2023), are presented below.

### 4.1. Notations

Indices/sets:	
$i \in I$	Project activities
$m \in M$	Implementation modes
$t \in T$	Time periods
$r \in R$	Renewable resources
$n \in NR$	Non-renewable resources
$s \in S$	Skills
$\lambda \in \Lambda$	Crash unit
Subsets:	
$I_c$	Crashable activities, $I_c \subset I$
$I_p$	preemptive activities, $I_p \subset I$
$I_{cp}$	Both preemptive and crashable activities, $I_{cp} = I_p \cap I_c, I_{cp} \subset I$
$I_{ncp}$	Non-crashable and non-preemptive activities, $I_{ncp} = I \setminus (I_p \cup I_c), I_{ncp} \subset I$
$I_{pr}$	Activity precedence relationships $(i, j) \in I_{pr}$
Parameters:	
$T$	Time horizon
$\overline{NAV}_n$	Available quantity of non-renewable resource $n$
$nor_{imn}$	Quantity of non-renewable resource $n$ needed for activity $i$ when implemented through mode $m$
$nor'_{imn}$	Quantity of extra non-renewable resource $n$ needed for crashable activity $i$ when implemented through mode $m$
$ES_i$	Earliest beginning time of task $i$
$LF_i$	Latest completion time of task $i$
$NT_{im}$	Normal time of task $i$ in mode $m$
$CT_{im}$	Crash time of task $i$ in mode $m$
$\widetilde{C}_r$	Total expense of renewable resource $r$
$\widetilde{C}'_r$	Total expense of utilizing the additional renewable resource $r$ for crashing activities
$\widetilde{C}^n_r$	Total expense of non-renewable resource $n$
$\widetilde{C}^n_r$	Total expense of utilizing the additional non-renewable resource $r$ for crashing activities
$G_r$	Energy consumption of renewable resource $r$
$G'_r$	Energy consumption of additional renewable resource $r$ for crashing activities
$G^n_r$	Energy consumption of non-renewable resource $n$
$G^n_r$	Energy consumption of additional non-renewable resource $n$ for crashing activities
$\widetilde{du}$	Due date of the project
$Q_{rs}$	1 if renewable resource $r$ has skill $s$ ; 0, otherwise
$Q'_{rs}$	1 if additional renewable resource type $r$ has skill $s$ ; 0, otherwise
$I_{ims}$	1 if skill $s$ is needed to implement task $i$ in mode $m$ ; 0, otherwise
$I'_{ims,\lambda}$	1 if skill $s$ is needed to implement crashable activity $i$ through mode $m$ in crash unit $\lambda$ ; 0, otherwise
$AG$	Average allowable emission
Continuous variables:	
$ST_i$	Beginning time of task $i$
$FT_i$	Completion time of task $i$
$p_{im}$	Duration of task $i$ through mode $m$
$z_{im}$	Quantity of crash duration of task $i$ through mode $m$
$\xi_t$	Number of workforces in time period $t$
$\omega_t$	Number of hired workforces in time period $t$
$EGreen$	Amount of energy consumption less than the average allowable emission
$TGreen$	Excess energy consumption beyond the average
Binary variables:	
$y_{im}$	1 if task $i$ is performed through mode $m$ ; 0, otherwise
$x_{imt}$	1 if task $i$ is implemented through mode $m$ in time period $t$ ; 0, otherwise
$h_t$	1 if the workforce is hired in time period $t$ ; 0, otherwise
$e_t$	1 if the workforce is fired in time period $t$ ; 0, otherwise

(continued on next page)

(continued)

$\gamma_{im\lambda}$	1 if crashable activity $i$ is performed through mode $m$ in crash unit $\lambda$ ; 0, otherwise
$\phi_{imrt}$	1 if task $i$ is implemented in mode $m$ utilizing renewable resource $r$ in time period $t$ ; 0, otherwise
$\psi_{imrt}$	1 if crashable activity $i$ is implemented in mode $m$ utilizing additional renewable resource $r$ in time period $t$ ; 0, otherwise
$\phi$	1 if energy consumption is less than the average allowable emission
$\zeta$	1 if energy consumption exceeds the average allowable emission
Auxiliary variable:	
$Q_{im\lambda}$	Binary auxiliary variable for linearization of the model

#### 4.1. Mathematical model

The first and second objectives minimize project makespan in addition to total project expenses, respectively. The second objective includes both standard resource costs and additional expenses incurred by utilizing extra resources for crashing activities. The total energy emitted by renewable and non-renewable resources for both non-crashable and crashable tasks is minimized by the third objective function (OF). Finally, job opportunities are maximized by the fourth OF.

$$\text{Min } Z1 = F_{N+1} \tag{1}$$

$$\begin{aligned} \text{Min } Z2 = & \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m \tilde{C}_r \cdot \phi_{imrt} + \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m \tilde{C}'_r \cdot \psi_{imrt} \right) + \left( \sum_{n=1}^{NR} \right. \right. \\ & \times \left. \sum_{i=1}^N \sum_{m=1}^m \tilde{C}''_n \cdot \text{non}_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \sum_{m=1}^m \tilde{C}'''_n \cdot \text{non}'_{imn} \cdot z_{im} \right) \Big) + TGreen \cdot \alpha \\ & - EGreen \cdot \beta \end{aligned} \tag{2}$$

$$\begin{aligned} \text{Min } Z3 = & \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \phi_{imrt} + \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G'_r \cdot \psi_{imrt} \right) + \left( \sum_{n=1}^{NR} \right. \right. \\ & \times \left. \sum_{i=1}^N \sum_{m=1}^m G''_n \cdot \text{non}_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \sum_{m=1}^m G'''_n \cdot \text{non}'_{imn} \cdot z_{im} \right) \Big) \end{aligned} \tag{3}$$

$$\text{Max } Z4 = \sum_{t=1}^T \omega_t \tag{4}$$

s.t.

$$\sum_{m=1}^M y_{im} = 1 \quad \forall i \tag{5}$$

$$\sum_{t=ES_i}^{LF_i} x_{imt} = p_{im} \quad \forall i \in I_c, m \tag{6}$$

$$\sum_{t=ES_i}^{LF_i} x_{imt} = NT_{im} y_{im} \quad \forall i \in I - I_c, m \tag{7}$$

$$ST_i + \sum_{m=1}^M NT_{im} y_{im} = FT_i + 1 \quad \forall i \in I_{ncp} \tag{8}$$

$$t \bullet x_{imt} \leq FT_i \quad \forall i \in I - I_{ncp}, m, t \in \{ES_i, \dots, LF_i\} \tag{9}$$

$$t \bullet x_{imt} + T(1 - x_{imt}) \geq ST_i \quad \forall i \in I - I_{ncp}, m, t \in \{ES_i, \dots, LF_i\} \tag{10}$$

$$FT_i \leq ST_j - 1 \quad \forall (i, j) \in I_{pr} \tag{11}$$

$$\sum_{\lambda=1}^{\lambda} \lambda \cdot \gamma_{im\lambda} = z_{im} \quad \forall i \in I_c, m \tag{12}$$

$$\sum_{\lambda=1}^{\lambda} \gamma_{im\lambda} \leq y_{im} \quad \forall i \in I_c, m \tag{13}$$

$$\sum_{r=1}^R \phi_{imrt} \cdot Q_{rs} \geq I_{ims} \cdot x_{imt} \quad \forall i, m, s, t \tag{14}$$

$$\sum_{r=1}^R \psi_{imrt} \cdot Q'_{rs} \geq \sum_{\lambda=1}^{\lambda} I'_{ims\lambda} \cdot \gamma_{im\lambda} \cdot x_{imt} \quad \forall i \in I_c, m, s, t \tag{15}$$

$$\sum_{r=1}^R \phi_{imrt} \leq M \cdot x_{imt} \quad \forall i \in I_c, m, t \tag{16}$$

$$\sum_{r=1}^R \psi_{imrt} \leq M \cdot x_{imt} \quad \forall i, m, t \tag{17}$$

$$\sum_{i=1}^N \sum_{m=1}^M \phi_{imrt} + \sum_{i=1}^N \sum_{m=1}^M \psi_{imrt} \leq 1 \quad \forall r, t \tag{18}$$

$$\sum_{t=1}^T \sum_{i=1}^N \sum_{m=1}^M \text{non}_{imn} x_{imt} + \sum_{i=1}^N \sum_{m=1}^M \text{non}'_{imn} z_{im} \leq \widetilde{NAV}_n \quad \forall n \tag{19}$$

$$F_{N+1} \leq \widetilde{du} \tag{20}$$

$$CT_{im} y_{im} \leq p_{im} \quad \forall i \in I_c, m \tag{21}$$

$$p_{im} \leq NT_{im} y_{im} \quad \forall i \in I_c, m \tag{22}$$

$$NT_{im} y_{im} - p_{im} \leq z_{im} \quad \forall i \in I_c, m \tag{23}$$

$$z_{im} \leq (NT_{im} - CT_{im}) y_{im} \quad \forall i \in I_c, m \tag{24}$$

$$\xi_t = \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^M (\phi_{imrt} + \psi_{imrt}) \quad \forall t \tag{25}$$

$$\omega_t \leq \xi_t - \xi_{t-1} + M(1 - h_t) \quad \forall t \tag{26}$$

$$\omega_t \geq \xi_t - \xi_{t-1} - M(1 - h_t) \quad \forall t \tag{27}$$

$$M \cdot h_t \geq \xi_t - \xi_{t-1} \quad \forall t \tag{28}$$

$$M \cdot e_t \leq \xi_{t-1} - \xi_t \quad \forall t \tag{29}$$

$$h_t + e_t \leq 1 \quad \forall t \tag{30}$$

$$\begin{aligned} & -M(1 - \zeta) + \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \phi_{imrt} + \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G'_r \cdot \psi_{imrt} \right) + \left( \sum_{n=1}^{NR} \right. \right. \\ & \times \left. \sum_{i=1}^N \sum_{m=1}^m G''_n \cdot \text{non}_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \sum_{m=1}^m G'''_n \cdot \text{non}'_{imn} \cdot z_{im} \right) \Big) - AG \\ & \leq TGreen \end{aligned} \tag{31}$$

$$\begin{aligned} & M(1 - \zeta) + \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \phi_{imrt} + \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G'_r \cdot \psi_{imrt} \right) + \left( \sum_{n=1}^{NR} \right. \right. \\ & \times \left. \sum_{i=1}^N \sum_{m=1}^m G''_n \cdot \text{non}_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \sum_{m=1}^m G'''_n \cdot \text{non}'_{imn} \cdot z_{im} \right) \Big) - AG \\ & \geq TGreen \end{aligned} \tag{32}$$



$$\begin{aligned}
 & -M(1 - \phi) + AG - \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \phi_{imrt} + \sum_{r=1}^R \sum_{i=1}^N \right. \right. \\
 & \quad \times \left. \sum_{m=1}^m G'_r \cdot \psi_{imrt} \right) + \left( \sum_{n=1}^{NR} \sum_{i=1}^N \sum_{m=1}^m G''_n \cdot \text{non}_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \right. \\
 & \quad \times \left. \sum_{m=1}^m G'''_n \cdot \text{non}'_{imn} \cdot z_{im} \right) \\
 & \leq EG_{Green} \tag{33}
 \end{aligned}$$

$$\begin{aligned}
 & M(1 - \phi) + AG - \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \phi_{imrt} + \sum_{r=1}^R \sum_{i=1}^N \right. \right. \\
 & \quad \times \left. \sum_{m=1}^m G'_r \cdot \psi_{imrt} \right) + \left( \sum_{n=1}^{NR} \sum_{i=1}^N \sum_{m=1}^m G''_n \cdot \text{non}_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \right. \\
 & \quad \times \left. \sum_{m=1}^m G'''_n \cdot \text{non}'_{imn} \cdot z_{im} \right) \\
 & \geq EG_{Green} \tag{34}
 \end{aligned}$$

$$\begin{aligned}
 & \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \phi_{imrt} + \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G'_r \cdot \psi_{imrt} \right) + \left( \sum_{n=1}^{NR} \sum_{i=1}^N \right. \right. \\
 & \quad \times \left. \sum_{m=1}^m G''_n \cdot \text{non}_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \sum_{m=1}^m G'''_n \cdot \text{non}'_{imn} \cdot z_{im} \right) - AG \\
 & \leq M \cdot \zeta \tag{35}
 \end{aligned}$$

$$\begin{aligned}
 & AG - \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \phi_{imrt} + \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G'_r \cdot \psi_{imrt} \right) + \left( \sum_{n=1}^{NR} \sum_{i=1}^N \right. \right. \\
 & \quad \times \left. \sum_{m=1}^m G''_n \cdot \text{non}_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \sum_{m=1}^m G'''_n \cdot \text{non}'_{imn} \cdot z_{im} \right) \\
 & \leq M \cdot \phi \tag{36}
 \end{aligned}$$

$$\phi + \zeta \leq 1 \tag{37}$$

$$ST_i, FT_i, p_{im}, z_{im}, \xi_t, \omega_t, EG_{Green}, TG_{Green} \in \text{int}^+ \forall i, m, t \tag{38}$$

$$y_{im}, x_{imt}, h_t, e_t, \gamma_{im\lambda}, \phi_{imrt}, \psi_{imrt}, \phi, \zeta \in \{0, 1\} \forall i, m, r, t, \lambda \tag{39}$$

$$\gamma_{im\lambda} \cdot x_{imt} = Q_{im\lambda} \forall i, m, \lambda, t \tag{40}$$

$$Q_{im\lambda} \leq \gamma_{im\lambda} \forall i, m, \lambda, t \tag{41}$$

$$Q_{im\lambda} \leq x_{imt} \forall i, m, \lambda, t \tag{42}$$

$$Q_{im\lambda} \geq \gamma_{im\lambda} + x_{imt} - 1 \forall i, m, \lambda, t \tag{43}$$

Constraint (5) forces activities to be implemented in exactly one mode. Exactly one execution of each crashable activity is ensured in Constraint (6). More so, this constraint guarantees that task  $i \in I_c$  in mode  $m$  will be executed for several periods equal to its duration in a specific mode. Non-crashable activities are required to be carried out in a time period equal to the related normal time in Constraint (7). The finishing time for all non-crashable and non-preemptive activities  $i \in I_{ncp}$  can be determined by Constraint (8). Constraints (9) and (10) calculate the finishing and starting times, respectively, for activities that are crashable, preemptive, or both  $i \in I - I_{ncp}$ . Constraint (11) implies FS (finish-to-start) relations between the project tasks. Constraint (12) determines the number of crash units in the crashable project activities. Constraint (13) forces each activity to have at most one crash unit.

In Constraints (14) and (15), concerning the needed renewable resources for each normal and crashable activity, only renewable resources and additional renewable resources with skills associated with

normal activities and crashable activities are assigned to them. Constraint (16) states that resources are assigned to an activity only when it begins to be performed in the desired mode. Constraint (17) implies that additional resources are assigned to a crashable activity only when it is crashed. Constraint (18) indicates that each renewable resource can be assigned to at most one normal or crashable activity. Constraint (19) forces the amount of utilized non-renewable resources besides needed additional non-renewable resources to be smaller than the quantity of available non-renewable resources. Constraint (20) ensures the deadline feasibility. The required duration for carrying out activity  $i \in I_c$  in respective mode is forced for being between the related normal and crash time in Constraints (21) and (22). The number of time periods task  $i \in I_c$  crashed is determined in Constraints (23) and (24). Constraint (25) calculates the number of human resources in each time period. The number of hired human resources in each time period is determined in Constraints (26)–(28). Number of fired workforces at each time period is calculated in Constraint (29).

Constraint (30) ensures that either hiring or firing occurs in each period. The amount of excess energy consumption in the whole project is calculated by Constraints (31) and (32). Furthermore, the amount of energy consumption that is less than the average allowable emission in the whole project is calculated by Constraints (33) and (34). Constraints (35) and (36) represent that the project incurs a penalty for exceeding the average allowable emission or receives a reward for emitting less than the average allowable emission level. Constraint (37) ensures that the project can only be less than or exceed the allowable emission. Ultimately, Constraints (38) and (39) define the domains of the decision variables.

It is worth noting that the presented formulation is MINLP because Constraint (40) is non-linear owing to the multiplication of two binary variables  $x_{imt}$  and  $\gamma_{im\lambda}$ . To make the issue less complex, linearization approaches (Govindan et al., 2020) are considered. Hence, determining a novel integer auxiliary variable that comprises the mentioned binary variables is required.

Utilizing the determined auxiliary variable, Constraints (41)–(43) are considered in the proposed formulation. Therefore, considering the above-mentioned procedure, the presented formulation can be transformed equivalently to corresponding linear forms considering Constraints (40)–(43).

## 5. Proposed solution approach

In this section, to tackle uncertainty efficiently, a possibilistic programming method, namely robust possibilistic programming (RPP-II), which was represented in Shahabi-Shahmiri et al. (2023), is utilized based on its performance. Furthermore, to solve the multi-objective mathematical model, a hybrid algorithm is utilized in combination with AUGMECON2 and VIKOR methods to find appropriate Pareto solutions.

### 5.1. Robust possibilistic programming

To meet the limitations related to resource capacity, the needed renewable and non-renewable resources are mostly considered to be high. Owing to crashable activities, additional resources are needed to be used to decrease the typical durations. The respective expenses of the RCPSP are grown through using extra resources. It should be noted that these parameters are mostly uncertain in real circumstances. To tackle this complication, a robust possibilistic method, which is by Pishvae et al. (2012), is employed.

According to the introduced theory of possibility by Zadeh (1978), many methods have been developed until now to deal with the existing uncertainties in OFs and constraints. In the presented study, among the other proposed methods (Günay et al., 2021), the fuzzy chance-constrained programming based on necessity measure has been utilized for robust possibilistic programming approaches. Because

employing the necessity measure is more meaningful for satisfying chance limitations, the necessity measure has been used to deal with the chance constraints.

Both triangular and trapezoidal fuzzy numbers can be considered through the chance-constrained programming approach (Men et al., 2019). The trapezoidal fuzzy number has been taken into account as the most commonly applied fuzzy number in real conditions and different issues like project planning (Sajadi et al., 2017) and risk evaluation (Wang et al., 2018). Thus, a trapezoidal fuzzy number that has been depicted in Fig. 1 has been utilized in the presented study.

Considering  $\tilde{\zeta}$  and  $r$  as a fuzzy variable with membership function and a real number, respectively, based on Liu (2002), necessity (Nec) and credibility (Cr) measures, can be defined as follows:

$$Nec(\tilde{\zeta} \leq r) = 1 - \sup_{x>r} \mu(x) \tag{44}$$

$$Cr(\tilde{\zeta} \leq r) = \frac{1}{2} \left( \sup_{x \geq r} \mu(x) + 1 - \sup_{x>r} \mu(x) \right) \tag{45}$$

It should be noted that since  $Pos(\tilde{\zeta} \leq r) = \sup_{x \leq r} \mu(x)$ , the necessity measure can be also considered as follows:

$$Nec(\tilde{\zeta} \leq r) = 2Cr(\tilde{\zeta} \leq r) - Pos(\tilde{\zeta} \leq r) \tag{46}$$

Consider that  $\tilde{\zeta}$  is a trapezoidal fuzzy number that can be determined through a quadruplet  $(\zeta_1, \zeta_2, \zeta_3, \zeta_4)$  of crisp numbers with  $\zeta_1 \leq \zeta_2 \leq \zeta_3 \leq \zeta_4$ , and its membership function is defined as follows:

$$\mu_{\tilde{\zeta}}(x) = \begin{cases} \frac{x - \zeta_1}{\zeta_2 - \zeta_1}, & \zeta_1 \leq x \leq \zeta_2 \\ 1, & \zeta_2 \leq x \leq \zeta_3 \\ \frac{x - \zeta_4}{\zeta_3 - \zeta_4}, & \zeta_3 \leq x \leq \zeta_4 \\ 0, & \text{otherwise} \end{cases}$$

Moreover, according to Pishvae et al. (2012), the expected value of  $\tilde{\zeta}$  is  $\left( \frac{\zeta_1 + \zeta_2 + \zeta_3 + \zeta_4}{4} \right)$  and the related necessity measures are as follows:

$$Nec\{\tilde{\zeta} \leq r\} = \begin{cases} 1, & \zeta_4 \leq r \\ \frac{r - \zeta_3}{\zeta_4 - \zeta_3}, & \zeta_3 \leq r \leq \zeta_4 \\ 0, & r \leq \zeta_3 \end{cases} \tag{47}$$

$$Nec\{\tilde{\zeta} \geq r\} = \begin{cases} 1, & r \leq \zeta_1 \\ \frac{\zeta_2 - r}{\zeta_2 - \zeta_1}, & \zeta_1 \leq r \leq \zeta_2 \\ 0, & r \geq \zeta_2 \end{cases} \tag{48}$$

Consequently, based on Eqs. (47) and (48), it can be represented that on condition that  $\alpha \geq 0.5$ :

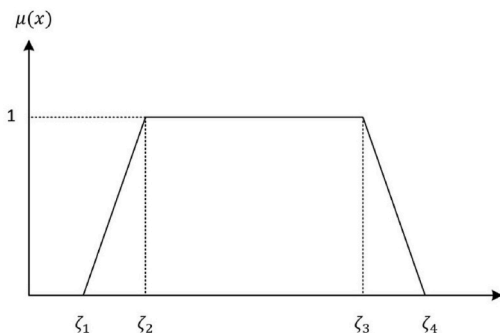


Fig. 1. Trapezoidal fuzzy parameter  $\tilde{\zeta}$ .

$$Nec(\tilde{\zeta} \leq r) \geq \alpha \iff r \geq (1 - \alpha)\zeta_3 + \alpha\zeta_4 \tag{49}$$

$$Nec(\tilde{\zeta} \geq r) \geq \alpha \iff r \leq (1 - \alpha)\zeta_2 + \alpha\zeta_1 \tag{50}$$

Based on Pishvae et al. (2012), the minimization of maximum deviation over and under the expected optimal value has been conducted through  $(z_{max} - z_{min})$  in the objective function of RPP formulation. Nonetheless, the aforementioned deviations are not always significant for decision-makers. In the presented study, the deviation of resource expenses under the expected optimal value, namely  $E(z)$ , might not have great importance for decision-makers. Instead, gaining fewer resource expenses in comparison with the expected optimal value for any realization is desirable for the experts. In these circumstances, the utilized model (RPP-II) is as follows:

$$\begin{aligned} \text{Min } E[z] + \rho(z_{max} - E(z)) + \pi(c_4 - (1 - \alpha)c_3 - \alpha c_4) + \vartheta(\beta d_1 + (1 - \beta)d_2 - d_1) \end{aligned} \tag{51}$$

s.t.  
 $x, y, \alpha, \beta \in F$

The sensitivity of simply to deviations over expected optimal value, without considering any limitation on deviations under expected optimal value, is ensured through  $(z_{max} - E(z))$ . Minimizing the expected value and  $(z_{max} - E(z))$ , which can be controlled by  $\rho$ , can be greatly compensated through the RPP-II. In the proposed MILP model, coefficients of the second OF, namely resource expenses, and Constraints (19) and (20) are subject to uncertainty. The confidence level for Constraint (19) is denoted as  $\beta$ , while for Constraint (20), it is represented as  $\alpha$ . Equivalent Constraints (19) and (20) are computed as Constraints (56) and (57), respectively. Therefore, the RPP-II formulation of MRCPSP is summarized below.

$$\text{Min } Z1 = F_{N+1} \tag{52}$$

$$\begin{aligned} \text{Min } E[Z2] + \rho(Z2_{max} - E[Z2]) + \vartheta_1(\beta NAV_n^{(1)} + (1 - \beta)NAV_n^{(2)} - NAV_n^{(1)}) \\ + \vartheta_2(\alpha du^{(1)} + (1 - \alpha)du^{(2)} - du^{(1)}) \end{aligned} \tag{53}$$

$$\begin{aligned} \text{Min } Z3 = \sum_{t=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \phi_{imr} + \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m G_r \cdot \psi_{imr} \right) + \left( \sum_{n=1}^{NR} \right. \right. \\ \left. \left. \times \sum_{i=1}^N \sum_{m=1}^m G''_n \cdot non_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{j=1}^N \sum_{m=1}^m G''_n \cdot non'_{imn} \cdot z_{im} \right) \right) \end{aligned} \tag{54}$$

$$\text{Max } Z4 = \sum_{t=1}^T \varpi_t \tag{55}$$

s.t.

$$\begin{aligned} \sum_{t=1}^T \sum_{i=1}^N \sum_{m=1}^m non_{jmn} x_{jmt} + \sum_{i=1}^N \\ \times \sum_{m=1}^m non'_{imn} z_{im} \leq (\beta NAV_n^{(1)} + (1 - \beta)NAV_n^{(2)}); \forall l \end{aligned} \tag{56}$$

$$F_{N+1} \leq (\alpha du^{(1)} + (1 - \alpha)du^{(2)}) \tag{57}$$

Constraints (5)–(18), and (21)–(43). Where  $E[Z2]$  has been determined as follows:

$$\begin{aligned}
 E[Z2] = & \sum_{r=1}^T \left( \left( \sum_{r=1}^R \sum_{i=1}^N \sum_{m=1}^m \left( \frac{C_r^{(1)} + C_r^{(2)} + C_r^{(3)} + C_r^{(4)}}{4} \right) \cdot K_{imr} \cdot x_{imt} + \sum_{r=1}^R \right. \right. \\
 & \times \sum_{i=1}^N \sum_{m=1}^m \left( \frac{C_r^{(1)} + C_r^{(2)} + C_r^{(3)} + C_r^{(4)}}{4} \right) \cdot K'_{imr} \cdot z_{im} \left. \right) + \left( \sum_{n=1}^{NR} \sum_{i=1}^N \right. \\
 & \times \sum_{m=1}^m \left( \frac{C_n^{(1)} + C_n^{(2)} + C_n^{(3)} + C_n^{(4)}}{4} \right) \cdot non_{imn} \cdot x_{imt} + \sum_{n=1}^{NR} \sum_{i=1}^N \\
 & \left. \left. \times \sum_{m=1}^m \left( \frac{C_n^{(1)} + C_n^{(2)} + C_n^{(3)} + C_n^{(4)}}{4} \right) \cdot non'_{imn} \cdot z_{im} \right) \right) \quad (58)
 \end{aligned}$$

In the introduced methodology, compared to the preceding one (i.e., RPP-I, which was presented by Pishvae et al. (2012), merely the second OF is converted and the equivalent limitations are shown similar to the RPP-I model (Shahabi-Shahmiri et al., 2023).

### 5.2. AUGMECON2VIKOR

A mathematical model through which more than one objective is supposed to be optimized considering a set of variables is a multi-objective optimization problem (MOP). These issues mostly arise in engineering, management, and healthcare (Ehrgott and Ruzika, 2008). Previously several solution approaches have been proposed to deal with MOPs. Such approaches can be classified into interactive, decision-aided, meta-heuristic, scalar, and fuzzy approaches. To cope with the four-objective MILP model, development of the augmented  $\epsilon$ -constraint (AUGMECON) approach, which is AUGMECON2 that was first presented by Mavrotas and Florios (2013), will be combined with VIKOR (Vlse Kriterijumska Optimizacija I Kompromisno Resenje in Serbia) approach, which has been presented in Opricovic (1998), to achieve more appropriate outcomes. The appropriate solutions gained using AUGMECON2 are desirable merely in conditions that the uniqueness of optimal values is guaranteed. Mavrotas and Florios (2013) presented an extended form of AUGMECON, namely AUGMECON2, in which slack/surplus variables data in each iteration is employed and the factor of bypass coefficient in the method is added for removing superfluous iterations. Furthermore, it was represented that this method is greatly effective for issues with discrete spatial variables and integer programming issues with multiple objectives, in which the Pareto set is restricted and countable. The formulation of the method has been presented as follows.

$$\begin{aligned}
 & \text{Max} \left( f_1(x) + eps \times \left( \frac{S_2}{r_2} + 10^{-1} \frac{S_3}{r_3} + \dots + 10^{-(p-2)} \frac{S_p}{r_p} \right) \right) \\
 & \text{s.t.} \\
 & f_2(x) - S_2 = e_2 \\
 & f_3(x) - S_3 = e_3 \\
 & f_p(x) - S_p = e_p \\
 & x \in S \text{ and } S_i \in R^+ \quad (59)
 \end{aligned}$$

Shahabi-Shahmiri et al. (2021) developed the AUGMECON2-VIKOR method for scheduling in cross-docking networks. VIKOR is an approach to dealing with multi-criteria decision-making (MCDM) issues considering various units and conflicting criteria. The best solution among different alternatives is ranked and adopted using this approach according to a compromise mechanism, especially to tackle issues considering conflicting criteria (Opricovic and Tzeng, 2004, 2007). In this paper, VIKOR and AUGMECON2 are utilized for ranking and adopting, respectively. The VIKOR approach consists of different steps for ranking. These steps have been shown in previous research (e.g., Zhang and Wei, 2013; Heydari et al., 2010). While utilizing the VIKOR

approach for ranking with multiple criteria, an LP approach can be extended as an aggregating function in a compromise programming approach (Yu, 1973; Zeleny and Cochrane, 1982). Because a hybrid approach is utilized, including VIKOR and AUGMECON2, merely some steps of the VIKOR approach, which have been used in AUGMECON2, are presented.

It is supposed that options are appraised according to a single criterion, and ranking can be performed by drawing a comparison with the ideal option. Various  $M$  options have been denoted by  $A_1, A_2, \dots, A_m$ . The rank of the  $j$ -th dimension has been represented as  $f_{ij}$  for option  $A_i$ . For instance, the value of the  $j$ -th criterion function for alternative  $A_i$  is indicated by  $f_{ij}$  and  $N$  represents the number of criteria. The first stage for the extension of the hybrid AUGMECON2VIKOR method is according to an LP metric:

$$L_{pi} = \left\{ \sum_{j=1}^n \left[ \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right] \right\}^{\frac{1}{p}} \quad 1 \leq p \leq \infty, i = 1, 2, \dots, m \quad (60)$$

In the VIKOR approach, values of  $L_1$  and  $L_\infty$  are considered as  $S_i$  and  $R_i$  in ranking formulation. Solutions gained through  $\min S_i$  and  $\min R_i$  are maximum group utility (i.e., majority rule) and minimum individual regret of the opponent, respectively. The ranking method includes the following steps:

Step 1 The best  $f_j^*$  and the worst  $f_j^-$  can be represented using all criterion functions ( $j = 1, 2, \dots, n$ ). On condition that the  $j$ -th function indicates the benefit, then:

$$f_j^* = \max_i f_{ij} \quad f_j^- = \min_i f_{ij} \quad (61)$$

Step 2 Benefit values of  $S_i$  and expenses  $R_i$  for the options ( $i = 1, 2, \dots, m$ ) have been determined as follows:

$$S_i = \sum_{j=1}^n w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \quad (62)$$

$$R_i = \max_j w_j \frac{(f_j^* - f_{ij})}{(f_j^* - f_j^-)} \quad (63)$$

where  $W_j$  indicates the weight of the criteria and shows the respective significance. After computing  $S_i$  and  $R_i$ , they can be considered in the AUGMECON2 method as the OFs and transferred to the adoption stage. The flowchart of the AUGMECON2VIKOR method is represented in Fig. 2.

Furthermore, Fig. 3 represents the pseudo-code of the presented method. The presented hybrid method integrates the preceding proposed approaches.

The principal idea of the method can be determined as follows. The method begins using a payoff table according to the MILP formulation. Afterward,  $f_j^*$  and  $f_j^-$  are obtained through Eq. (61). Then, consider the preferences of decision-makers ( $W_j$ ),  $S_i$  and  $R_i$ . In the third stage, by preferring the augmented  $\epsilon$ -constraint approach, the bi-objective VIKOR-based formulation can be solved.

## 6. Computational results

The most broadly utilized RCPSP instances can be achieved considering PSPLIB (<http://www.om-db.wi.tum.de/psplib/>), which has been provided by ProGen (Kolisch and Sprecher, 1997). Because merely a subset of parameters of the presented model is in the aforementioned dataset and the OF consists of time and expenses, these instances were

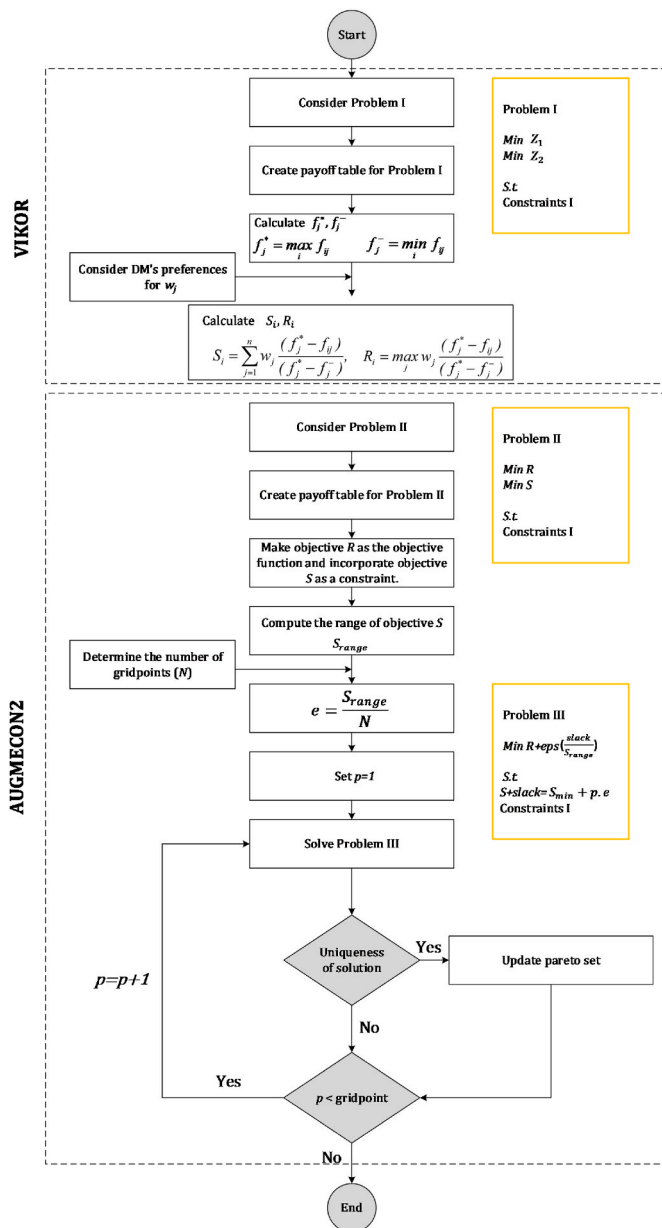


Fig. 2. Flowchart of the proposed AUGMECON2VIKOR approach.

adapted and other parameters were added. More so, new benchmark problem sets considering MMLIB (<http://www.projectmanagement.ugent.be>) created by Van Peteghem and Vanhoucke (2014) were utilized for evaluation of the introduced approach in more complex networks.

To deal with the proposed MILP model and obtain Pareto solutions, the problem has been coded in GAMS 24.1.2, on an i7 core computer with a 2.7 GHz CPU and 12 GB of RAM. Owing to the linearity of the model, the CPLEX solver (in GAMS software) has been utilized.

Computational results are compared and summarized based on two algorithms (i.e., AUGMECON2VIKOR and AUGMECON2) for j10, j20, j30, MM50 and MM100 in Table 3. As can be seen in Table 3, amounts of the two OFs including pay-off tables accompanying the CPU time are reported. Shahabi-Shahmiri et al. (2021) concluded that AUGMECON2VIKOR can search for a broader solution space with the appropriate division of each objective and efficient ranking in the first phase. Through an accurate search on each division, in the second phase, AUGMECON2VIKOR can improve the number and the quality of solutions. As mentioned, after running problem instances with two

algorithms, project makespan and total cost achieved by AUGMECON2VIKOR are lower than AUGMECON2. For instance, using AUGMECON2VIKOR, j20 was performed in 29 and 34 days, with 2.64 E+09 (~7.75%) and 1.08 E+09 (~3.95%) units' improvement in project cost compared to AUGMECON2. Going through large problem instances such as MM100, the proposed algorithm's performance is highlighted even more. As can be observed in Table 3, MM50 was executed four and three days earlier with costs of 8.25 E+09 (~7.74%) and 5.32 E+09 (~5.30%) units less than AUGMECON2. As expected, the performance of AUGMECON2VIKOR is better shown in MM100. Therefore, the mentioned figures were two days, ~11%, and ~8.85% for MM100. Furthermore, the CPU time of AUGMECON2VIKOR in all problem instances is lower than that of the previous algorithm.

Based on Table 4, AUGMECON2VIKOR provides one more grid point in comparison with AUGMECON2. In grid points one to four, utilizing AUGMECON2VIKOR, set j20 completed one day, and in grid point 5, three days earlier than AUGMECON2. Enhancement of the proposed algorithm is shown in the second objective function in all grid points. The differences between the two algorithms considering the project makespan and project cost are 0.7 days and 1.60 E+09 units, respectively. To better understand the performance of the AUGMECON2VIKOR, the trade-off between the first and second OFs is shown in Fig. 4.

According to Table 5, both first and second OFs have been significantly improved in two  $\alpha$ - levels (i.e.,  $\alpha = 0.6, 0.9$ ) in most cases using the AUGMECON2VIKOR compared to the AUGMECON2. For instance, the average percentages of improvements of the first and second OFs in the problem set j20 are nearly 3.08% and 3.44%, respectively. Furthermore, its CPU time is less than AUGMECON2 in most instances. For instance, average CPU running times in j10 and j30 are 1.318 and 130.223 s, whereas they are 1.702 and 148.918 s in the AUGMECON2.

According to Tables 3–5, AUGMECON2VIKOR shows a far better performance compared with the AUGMECON2 method in the RPP-II model. To analyze AUGMECON2VIKOR, Table 6 provides comparison results for different problem instances under  $\alpha = 0.6$  considering three OFs weight categories (i.e.,  $W_1 = W_2 = 0.5$ ,  $W_1, W_2 = 0.3, 0.7$ , and  $W_1, W_2 = 0.7, 0.3$ ) in the RPP-II model. As shown in this table, higher weight values are expected to achieve better OF values. Based on this expectation, j20 with  $W_1 = 0.7$  was performed in 29 and 34 days, one and three days earlier than  $W_2 = 0.7$ . In this problem instance, considering  $W_2 = 0.7$ , the total project costs were 3.127046 E+10 and 2.616491 E+10 units, which are significantly less than  $W_1 = 0.7$  (approximately 1.1% and 1.2%, respectively).

### 7. Scenario analysis

In this section, the proposed model is compared with the benchmark model in Shahabi-Shahmiri et al. (2023) taking into account three conditions.

- Without considering energy consumption and social dimension
- With only energy consumption
- With both energy consumption and social dimension

For all the above-mentioned conditions, set j20 is considered to calculate the project makespan, equal conditions are selected and the Gantt charts for the mentioned scenarios are depicted to show the performance of the proposed model. Table 7 summarizes the data of this problem set, including the successors and duration of each activity.

In these four Gantt charts, blue activities have been performed without any crashing or preemption. While yellow represents activities that are crashed and preempted simultaneously, only preempted and crashed activities are shown in red and grey, respectively. As shown in Fig. 5, which is based on the represented figure in Shahabi-Shahmiri et al. (2023), according to scenario 1, the project has been executed in 30 days. Considering scenario 2 in Fig. 6, activities 4, 16, 17, 19, and 21 have been only crashed. Activities 9, 12, and 18 have been both crashed

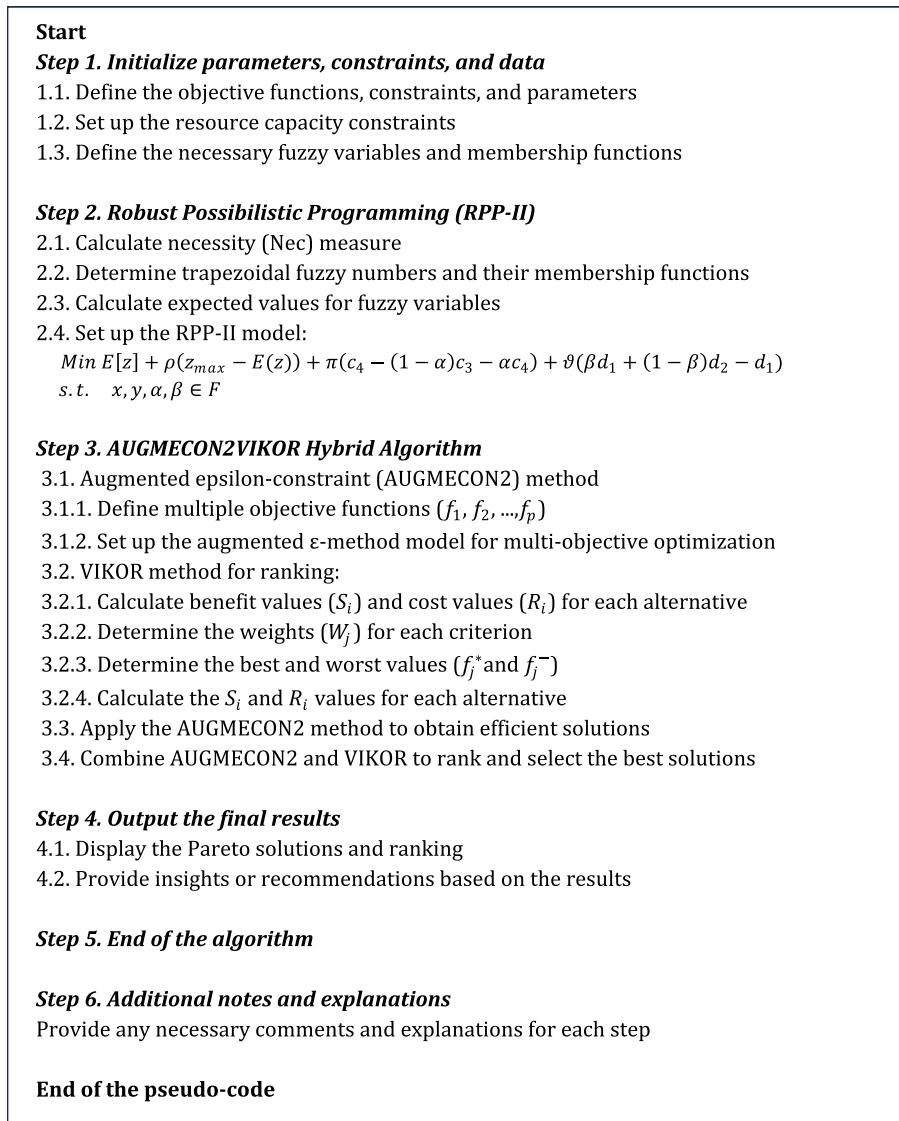


Fig. 3. Pseudo code for the proposed solution approach.

**Table 3**  
Computational results of the RPP-II model for PSPLIB and MMLIB problem sets.

Set	AUGMECON2			AUGMECON2VIKOR		
	Z1 (makespan)	Z2(Cost)	CPU time (s)	Z1 (makespan)	Z2(Cost)	CPU time (s)
j10	17.00	7.5634997 E+9	0.476	17.00	7.5536890E + 9	0.429
	20.00	7.4627728 E+9	2.884	19.00	7.3003181E + 9	2.120
j20	30.00	3.403909 E+10	53.875	29.00	3.140128E + 10	49.673
	35.00	2.736581 E+10	179.459	34.00	2.628452E + 10	171.603
j30	52.00	5.500838 E+10	27.140	49.00	5.450628E + 10	19.160
	54.00	5.051272 E+10	240.493	54.00	4.763914E + 10	212.199
MM50	42.00	1.06614 E+11	1108.491	38.00	9.83658E + 10	864.102
	44.00	1.00355 E+11	2486.73	41.00	9.50391E + 10	1541.88
MM100	31.00	1.84966 E+11	3554.459	29.00	1. 64613E + 11	2376.58
	34.00	1.53129 E+11	4065.865	32.00	1. 39579E + 11	3221.93

and preempted, and activities 5, 10, and 13 have been only preempted. The project has been completed two days earlier, in 29 days. According to scenario 3 in the Gantt chart shown in Fig. 7, considering job dimension and energy consumption simultaneously had a positive impact on project scheduling, and it was completed in 27 days. As shown in Fig. 8, utilizing skills consideration led to a one-day decrease in project makespan. It should be noted that the first mode of most

activities has been selected due to the use of expert workforces. Based on Table 7, activity durations in mode 1 are less than other modes. Moreover, as expected, only activity 16 has been crashed, and activity 17 has been preempted.

Table 8 summarizes the OF values in different scenarios. Based on scenario 1, only makespan and total cost are considered as OFs. It is expected that without considering energy consumption and social



**Table 4**  
Computational results of the OFs in the set j20.

Grid points	AUGMECON2		AUGMECON2VIKOR	
	Z1 (Time)	Z2 (Cost)	Z1 (Time)	Z2 (Cost)
1	30.00	3.403909 E+10	29.00	3.140128E + 10
2	31.00	3.278061 E+10	30.00	3.072070E + 10
3	32.00	3.025004 E+10	31.00	2.969834E + 10
4	33.00	2.836928 E+10	32.00	2.829371E + 10
5	35.00	2.757194 E+10	33.00	2.736581E + 10
6	-	-	34.00	2.628452 E+10
Average	32.20	3.06 E+10	31.50	2.90E + 10

dimensions, the project makespan will be longer than other scenarios. According to Scenario 2, when the third OF is added, better resources to consume less energy will be utilized to perform the project. Therefore, it is reasonable to anticipate that the project will be executed earlier than Scenario 1 at a lower cost. Implementing Scenario 3, which considers energy consumption and social dimension, due to the increasing number of resources, it is reasonable to anticipate that the project will be performed earlier than the two other scenarios, but with more expenses. Moreover, in comparison with Scenario 2, considering social dimensions in Scenario 3 can have positive impacts on energy consumption due to utilizing more human resources rather than machines. As expected, concerning Table 8, the project makespan in Scenario 3 is 29.5, which is 1 and 2.5 days earlier than Scenarios 2 and 1, respectively. The total project cost in Scenario 2 is approximately 4.18% and 1.79% lower than Scenarios 1 and 3, respectively. Finally, in scenario 3, ~20.87% less energy is consumed compared to the scenario 2.

To evaluate the impacts of skill consideration in this survey, Table 9 provides the OFs values in six grid points. Considering skills in resources ensures that the project can be executed earlier than the conditions in which resource skills are not considered. Utilizing expert human resources leads to the employment of fewer workforces. Therefore, total project cost and energy consumption will be much less than the conditions in which resource skills are not considered. As it was reported in Table 9, compared to the conditions in which resource skills are not considered, with skill consideration, the project was executed one day earlier with  $5.00 + E08$  less cost. Considering skills in the proposed model, whereas the third objective function (i.e., energy consumption) has been improved, 23.43% approximately on average, job opportunities decreased by ~25.15%. These results validate the introduced

formulation and the utilized solution approach.

**8. Sensitivity analysis**

Due to the importance of skill consideration in project scheduling, the impacts of changing the number of skills are analyzed in this section. This analysis is classified into three categories, (1) Normal skill, (2) Half skill, and (3) Full skill. The first classification is the normal condition of the project. The number of utilized human resource skills is decreased by 50% and increased by 100% in the second and third classifications, respectively. As mentioned, by increasing the number of skills, it is expected that the project can be executed earlier with fewer resources, less project cost, and less energy consumption. It has been represented in Table 10 considering the three aforementioned classifications. Average results show that set j20 was implemented one day earlier utilizing double skills. With a 50% decrease in the number of skills, most workforces are employed in projects in comparison with two other classifications (i.e., 36.33 on average). Compared to case 1 (i.e., normal skill) and Case 2 (i.e., half skill), the average percentage of improvements in total project cost and energy consumption considering double skills (Case 3) is nearly 17.44%, 17.07%, 16.55%, and 3.73%, respectively. As mentioned in this section, the positive impacts of considering skills are studied in the problem instance j20. Assuming that the problem size increases or a real-case study is employed, these positive impacts on project scheduling and energy consumption are strengthened.

According to the analysis, Fig. 9 shows Pareto solutions for the objective functions considering these three classifications and the conditions in which skills are not taken into account. In each part of this figure, the trade-off between three OFs is considered.

**9. Discussion and conclusion**

*9.1. Managerial implications*

Scheduling multi-mode, preemptive, and non-preemptive project activities, and crashing with multi-skill resources was addressed in this study. In the existing literature, there is no study to consider multi-skill resources in RCPSP with the aforementioned activity characteristics. According to several real companies (e. g., Patagonia, Danone, and Vodafone), which have achieved significant improvements in their performance by considering sustainability in project management, this

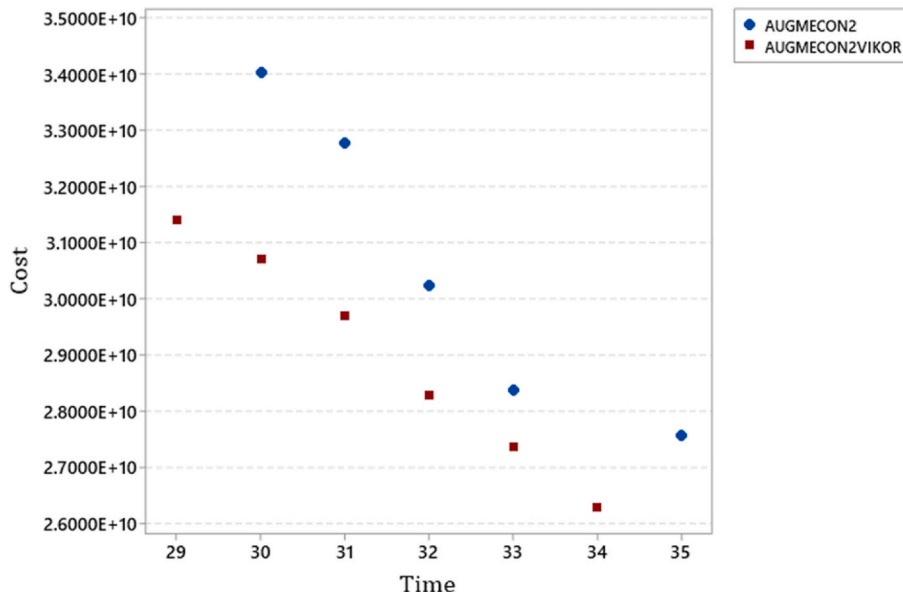


Fig. 4. Time-cost trade-off using the AUGMECON2 and AUGMECON2VIKOR algorithms.

**Table 5**  
Computational comparison results for the PSPLIB and MMLIB problem sets under  $\alpha = 0.6$  and  $\alpha = 0.9$  in the RPP-II model.

Set	$\alpha$ – level	Algorithms	Z1	Z2	CPU time (s)
j10	$\alpha = 0.6$	AUGMECON2	17.00	7.5634997 E+9	0.476
			20.00	7.4627728 E+9	2.884
		AUGMECON2VIKOR	17.00	<b>7.5536890E + 9</b>	0.429
	$\alpha = 0.9$	AUGMECON2	17.00	7.5634997 E+9	0.539
			20.00	7.4627728 E+9	2.911
		AUGMECON2VIKOR	17.00	<b>7.5597183E + 9</b>	0.557
j20	$\alpha = 0.6$	AUGMECON2	30.00	3.403909 E+10	53.875
			35.00	2.757194 E+10	179.459
		AUGMECON2VIKOR	<b>29.00</b>	<b>3.140128E + 10</b>	49.673
	$\alpha = 0.9$	AUGMECON2	30.00	No feasible solution	–
			35.00	2.93947 E+10	184.182
		AUGMECON2VIKOR	<b>29.00</b>	<b>3.260330E + 10</b>	56.263
j30	$\alpha = 0.6$	AUGMECON2	52.00	5.68279 E+10	27.140
			54.00	5.05127 E+10	240.493
		AUGMECON2VIKOR	<b>49.00</b>	<b>5.450628E + 10</b>	19.160
	$\alpha = 0.9$	AUGMECON2	52.00	5.77555 E+10	34.829
			54.00	5.05127 E+10	293.209
		AUGMECON2VIKOR	<b>49.00</b>	<b>5.532090E + 10</b>	26.050
MM50	$\alpha = 0.6$	AUGMECON2	42.00	1.06614 E+11	1108.491
			44.00	1.00355 E+11	2486.73
		AUGMECON2VIKOR	<b>38.00</b>	<b>9.83658E + 10</b>	864.102
	$\alpha = 0.9$	AUGMECON2	No feasible solution	No feasible solution	–
			AUGMECON2VIKOR	<b>37.00</b>	9.26596 E+10
		AUGMECON2VIKOR	41.00	9.60616 E+10	1937.1
MM100	$\alpha = 0.6$	AUGMECON2	31.00	1.84966 E+11	3554.459
			34.00	1.53129 E+11	4065.865
		AUGMECON2VIKOR	<b>29.00</b>	<b>1.64613E + 11</b>	<b>2376.58</b>
			<b>32.00</b>	<b>1.39579E + 11</b>	<b>3221.93</b>

**Table 5 (continued)**

Set	$\alpha$ – level	Algorithms	Z1	Z2	CPU time (s)
	$\alpha = 0.9$	AUGMECON2	No feasible solution	No feasible solution	–
		AUGMECON2VIKOR	<b>28.00</b>	<b>1.59832E + 11</b>	<b>2580.29</b>
			<b>32.00</b>	<b>1.34680E + 11</b>	<b>3975.13</b>

**Table 6**  
Computational comparison results for the PSPLIB and MMLIB problem sets under  $\alpha = 0.6$  considering three OFs weight categories.

Set	(W <sub>1</sub> , W <sub>2</sub> )	Z1	Z2
j10	(0.5, 0.5)	17.00	7.5536890 E+9
		<b>19.00</b>	7.3003181 E+9
	(0.7, 0.3)	17.00	7.5536890 E+9
j20	(0.3, 0.7)	<b>19.00</b>	7.3003181 E+9
		17.00	<b>7.5400935E + 9</b>
	(0.5, 0.5)	<b>20.00</b>	<b>7.2859716E + 9</b>
j30	(0.5, 0.5)	<b>29.00</b>	3.140128 E+10
		34.00	2.628452 E+10
	(0.7, 0.3)	<b>29.00</b>	3.160596 E+10
MM50	(0.3, 0.7)	34.00	2.649021 E+10
		<b>30.00</b>	<b>3.127046E + 10</b>
	(0.5, 0.5)	<b>37.00</b>	<b>2.616491E + 10</b>
MM100	(0.5, 0.5)	<b>49.00</b>	<b>5.450628E + 10</b>
		54.00	<b>4.763914E + 10</b>
	(0.7, 0.3)	49.00	5.524497 E+10
MM50	(0.3, 0.7)	<b>53.00</b>	4.831821E+10
		<b>51.00</b>	<b>5.304063E + 10</b>
	(0.5, 0.5)	<b>56.00</b>	<b>4.697781E + 10</b>
MM100	(0.7, 0.3)	38.00	<b>9.83658E + 10</b>
		<b>40.00</b>	<b>9.50391E + 10</b>
	(0.3, 0.7)	<b>39.00</b>	<b>9.9784E + 10</b>
MM100		<b>44.00</b>	<b>9.67181E + 10</b>
		<b>44.00</b>	<b>9.26357E + 10</b>
		<b>44.00</b>	<b>9.44915E + 10</b>
MM100	(0.5, 0.5)	<b>29.00</b>	<b>1.64613E + 11</b>
		<b>32.00</b>	<b>1.39579E + 11</b>
	(0.7, 0.3)	<b>29.00</b>	<b>1.74137E + 11</b>
MM100		<b>31.00</b>	<b>1.45430E + 11</b>
		<b>33.00</b>	<b>1.37886E + 11</b>
		<b>37.00</b>	<b>1.10642E + 11</b>

paper aimed to maximize social dimensions and minimize project makespan, total project cost, and energy consumption. Thus, a new MILP formulation with multiple objectives was introduced to cope with this problem. Constructing a new MILP formulation with multiple objectives, taking into account sustainable developments, investigating impacts of multi-skill resources on objective functions, considering the uncertainty of non-renewable resource availability and the project’s due date, and utilizing RPP-II with the AUGMECON2VIKOR approach to cope with uncertainty and multi-objective optimization were the main contributions of this survey. Owing to the complication of real cases, insufficient data, and unavailability of some parameters, a possibilistic programming method was utilized, and the proposed method by Pishvaee et al. (2012) was employed to achieve an equivalent model.

The mentioned novelties of this investigation can help companies to make appropriate scheduling of different types of activities considering multiple skill resources. Several different problem instances from PSPLIB and MMLIB were considered to show the performance of the introduced formulation and the solution method. Using data from these problem instances, the considered problem was solved and the outcomes were reported. The completion time of the project considering set j20 was 31.50 days with 2.90 E+10 units project cost. The performance of the AUGMECON2VIKOR was compared to the previous version (i.e., AUGMECON2). Utilizing AUGMECON2VIKOR, the project set j20 was

**Table 7**  
Project activities duration in the set j20.

Activities	Successors	Duration		
		Mode1	Mode2	Mode3
1	2,3,4	-	-	-
2	6,9,14	2	8	10
3	5,8,11	1	5	7
4	12,16,20	4	6	10
5	9,17	2	3	5
6	7,12,18	1	6	7
7	8,17	1	6	10
8	15,16	1	2	3
9	10,13,16	5	7	10
10	12,20	2	3	3
11	14,15,19	3	5	6
12	19,21	3	5	6
13	15	2	6	10
14	18	3	7	8
15	21	1	3	4
16	21	4	8	8
17	19	5	9	10
18	20	10	10	10
19	22	4	6	10
20	22	1	7	9
21	22	2	8	9
22	-	-	-	-

performed 0.7 days earlier with 1.60 E+09 cost less than AUGMNECON2. Computational comparison results were reported considering  $\alpha = 0.6$  and 0.9, to analyze the RPP II parameters and the impacts on project scheduling and total project cost. Moreover, three levels of the first and second objective function weights were considered to evaluate the results obtained by AUGMECON2VIKOR.

To investigate the impacts of considering sustainable developments on MRCPSP, three scenarios were presented. Four Gantt charts were presented to show project scheduling in different scenarios. Results of four OFs were reported in six grid points to investigate the conditions of

both with skill consideration and without skill consideration. As it was expected, the project was implemented one day earlier with 5.00 + E08 less cost with skill consideration in comparison with conditions in which skills are not considered. Considering skills in the proposed model, the third objective function (i.e., energy consumption) was improved by 23.43% approximately, whereas job opportunities decreased by ~25.15%. In addition to the above-mentioned results, a sensitivity analysis was conducted to evaluate the impacts of several skills on time and sustainable development. Although with an increase in the number of skills, project makespan, project cost, and energy consumption decreased, job opportunities decreased due to employing expert workforces.

9.2. Limitations and future development

Three managerial limitations can be taken into account. Initially, in the presented research, it was not pointed out that renewable resources such as machines can be traditional or modern. It is important to note that considering technology can be helpful for energy consumption, project makespan, and social dimensions. Secondly, even though one of the most common problems in the real world is changing activity mode after preemption, it was not taken into account in the presented study. In the real world, companies enhance their workforce skills through on-the-job training programs that lead to encouragement to perform projects more quickly. In addition to the managerial limitations, there are two limitations for methodology and one for results. Initially, due to the high complexity of the problem, utilizing multi-objective metaheuristic algorithms or hybrid algorithms are proposed to solve large size problem instances. Secondly, goal programming is an appropriate method to consider manager preferences and company policies for solving practical multi-objective optimization problems. Furthermore, similar to the study conducted by [Snaauwaert and Vanhoucke \(2023\)](#), no case study has been employed to cope with this problem. Therefore, it is proposed to implement a case study considering the impacts of skill levels of

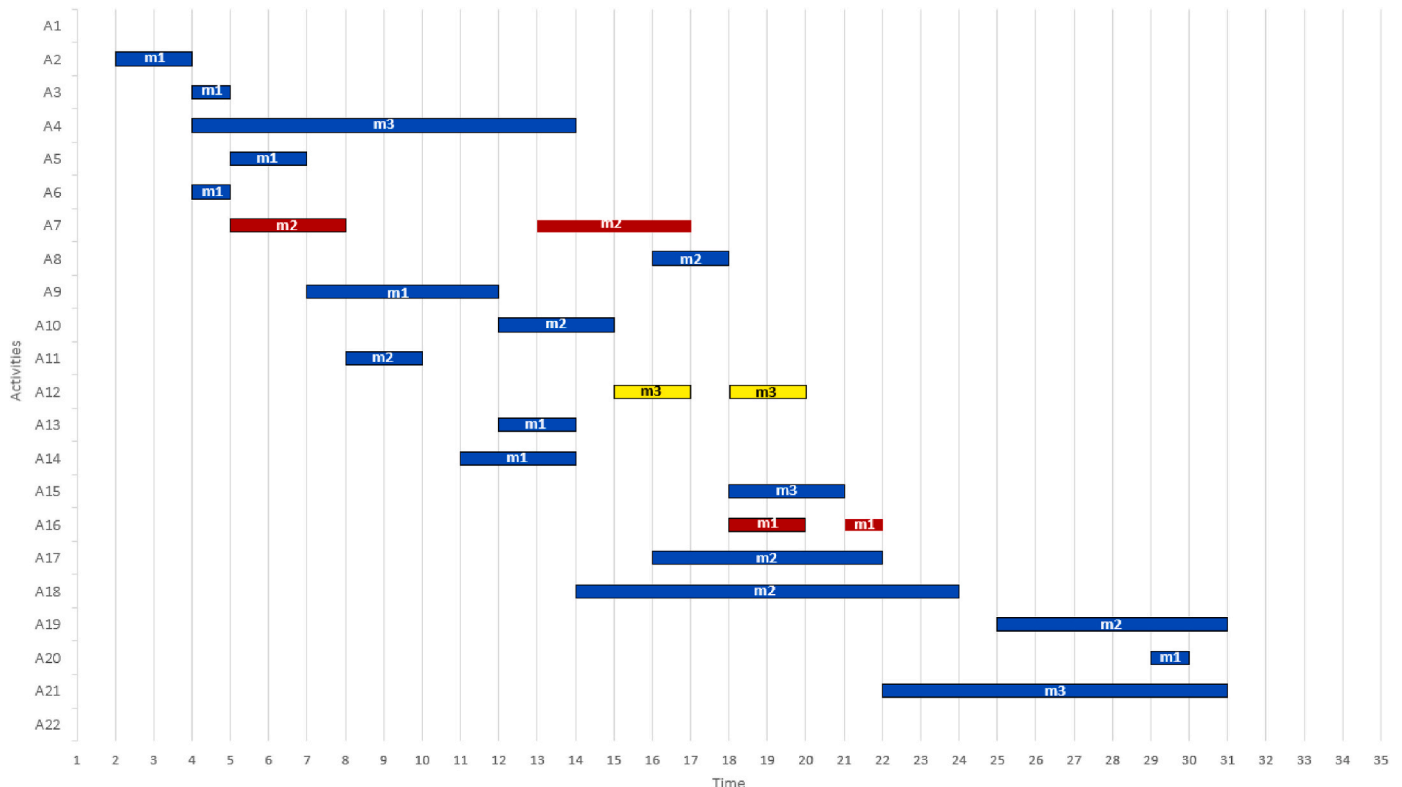


Fig. 5. Gantt chart for Scenario 1.

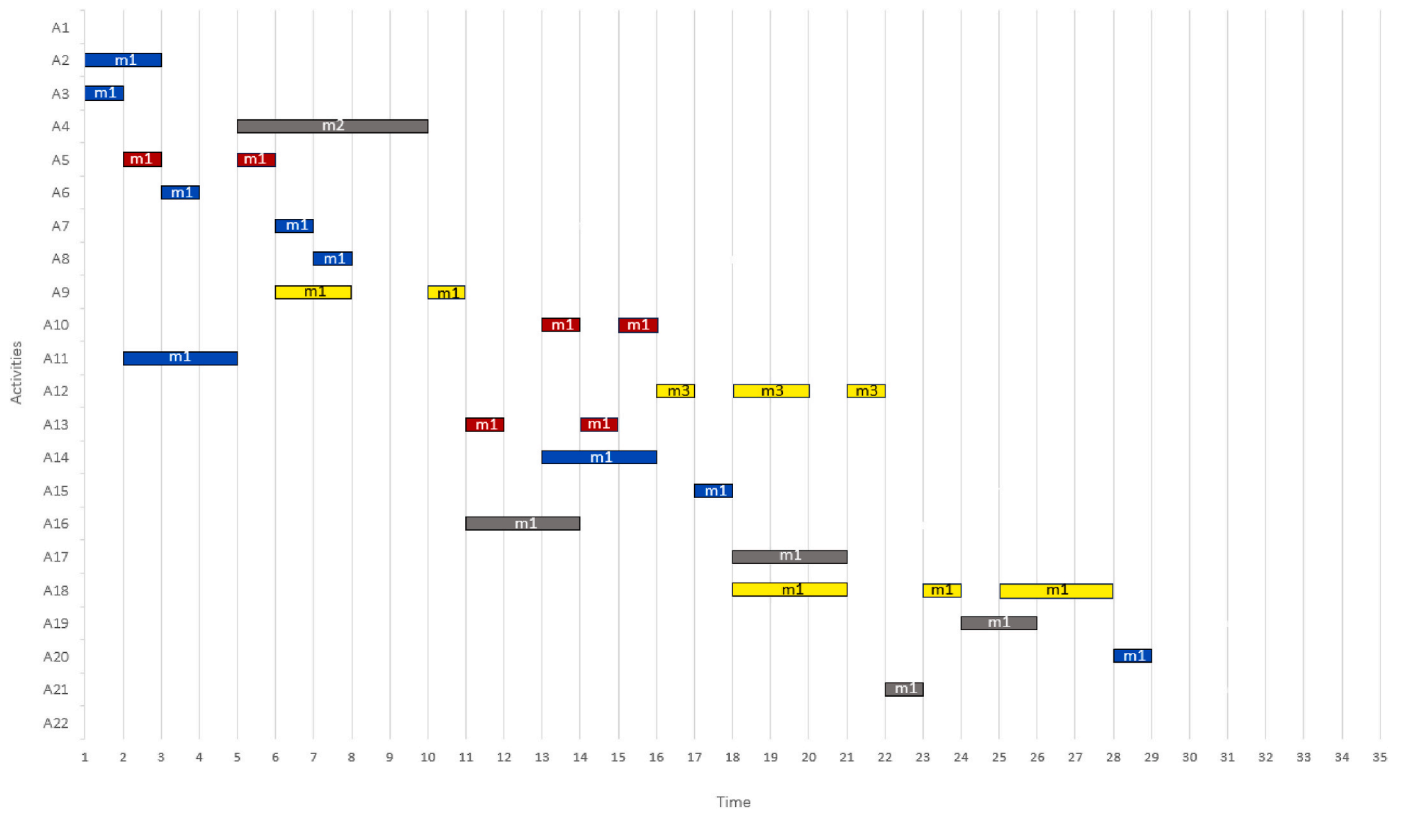


Fig. 6. Gantt chart for Scenario 2.

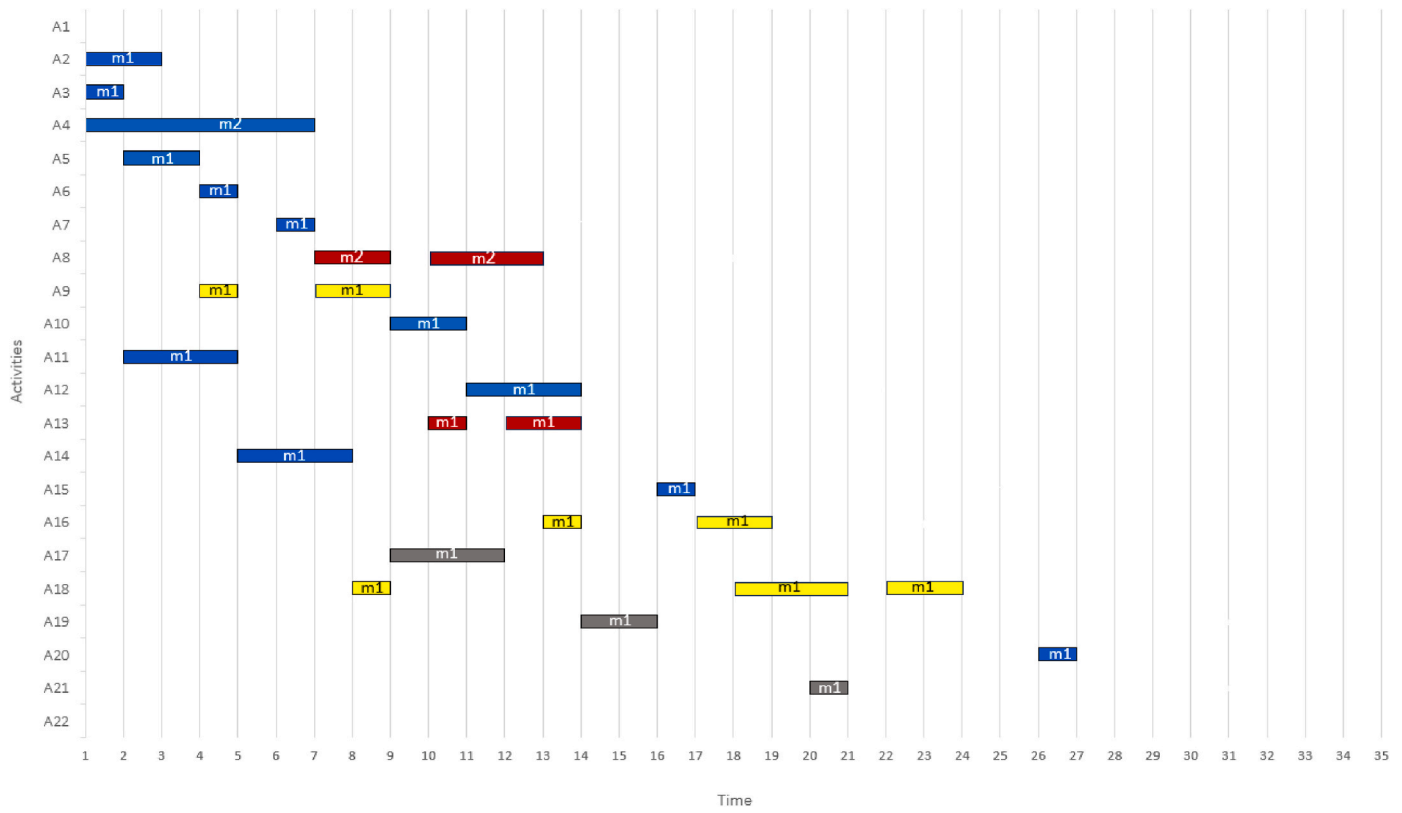


Fig. 7. Gantt chart for Scenario 3.

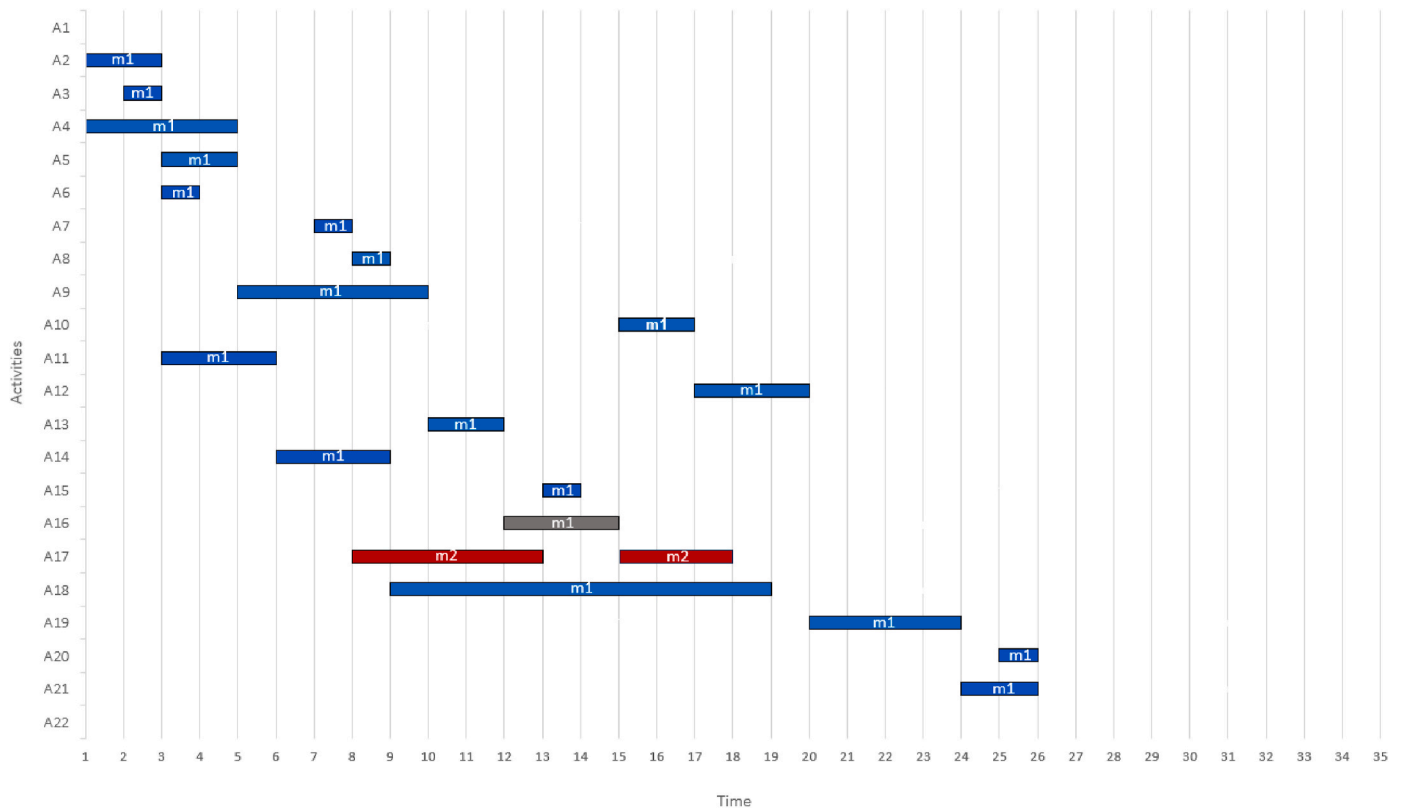


Fig. 8. Gantt chart of Scenario 3 with skill consideration.

Table 8

Experimental results under Scenarios 1 to 3.

Grid points	Scenario 1		Scenario 2			Scenario 3			
	Z1 (Time)	Z2 (Cost) × E+10	Z1 (Time)	Z2 (Cost) × E+10	Z3 (Green)	Z1 (Time)	Z2 (Cost) × E+10	Z3 (Green)	Z4 (job opportunity)
1	29.00	3.14012	28.00	2.85231	13,365	27.00	2.91412	10,616	44.00
2	30.00	3.07207	29.00	2.81492	13,589	28.00	2.88033	10,670	41.00
3	31.00	2.96983	30.00	2.79613	13,640	29.00	2.85268	10,772	39.00
4	32.00	2.83692	31.00	2.76386	13,717	30.00	2.79137	10,824	35.00
5	33.00	2.75719	32.00	2.73201	13,782	31.00	2.77323	10,900	34.00
6	34.00	2.6284	33.00	2.71755	13,811	32.00	2.76896	11,031	32.00
Average	32.00	2.9	30.50	2.78	13,650.67	29.50	2.83	10,802.17	37.50

Table 9

Comparative results with and without skill consideration.

Grid points	Without skill				With multiple skills			
	Z1 (Time)	Z2 (Cost) × E+10	Z3 (green)	Z4 (job opportunity)	Z1 (Time)	Z2 (Cost) × E+10	Z3 (green)	Z4 (job opportunity)
1	27.00	2.914121	10,616	44.00	26.00	2.885711	8822	40.00
2	28.00	2.880338	10,670	41.00	27.00	2.859674	8351	39.00
3	29.00	2.852681	10,772	39.00	28.00	2.816621	8267	37.00
4	30.00	2.791370	10,824	35.00	29.00	2.759166	8114	34.00
5	31.00	2.773234	10,900	34.00	30.00	2.704942	8082	33.00
6	32.00	2.768964	11,031	32.00	31.00	2.680778	7989	31.00
Average	29.50	2.83	10,802.17	37.5	28.50	2.78	8270.833	35.66667

renewable resources on energy consumption. For future research, large problem instances (i.e., more than 100 project activities) can be considered. Taking into account stochastic programming or bi-level stochastic programming is another development that can be considered in future studies for known parameter distribution.

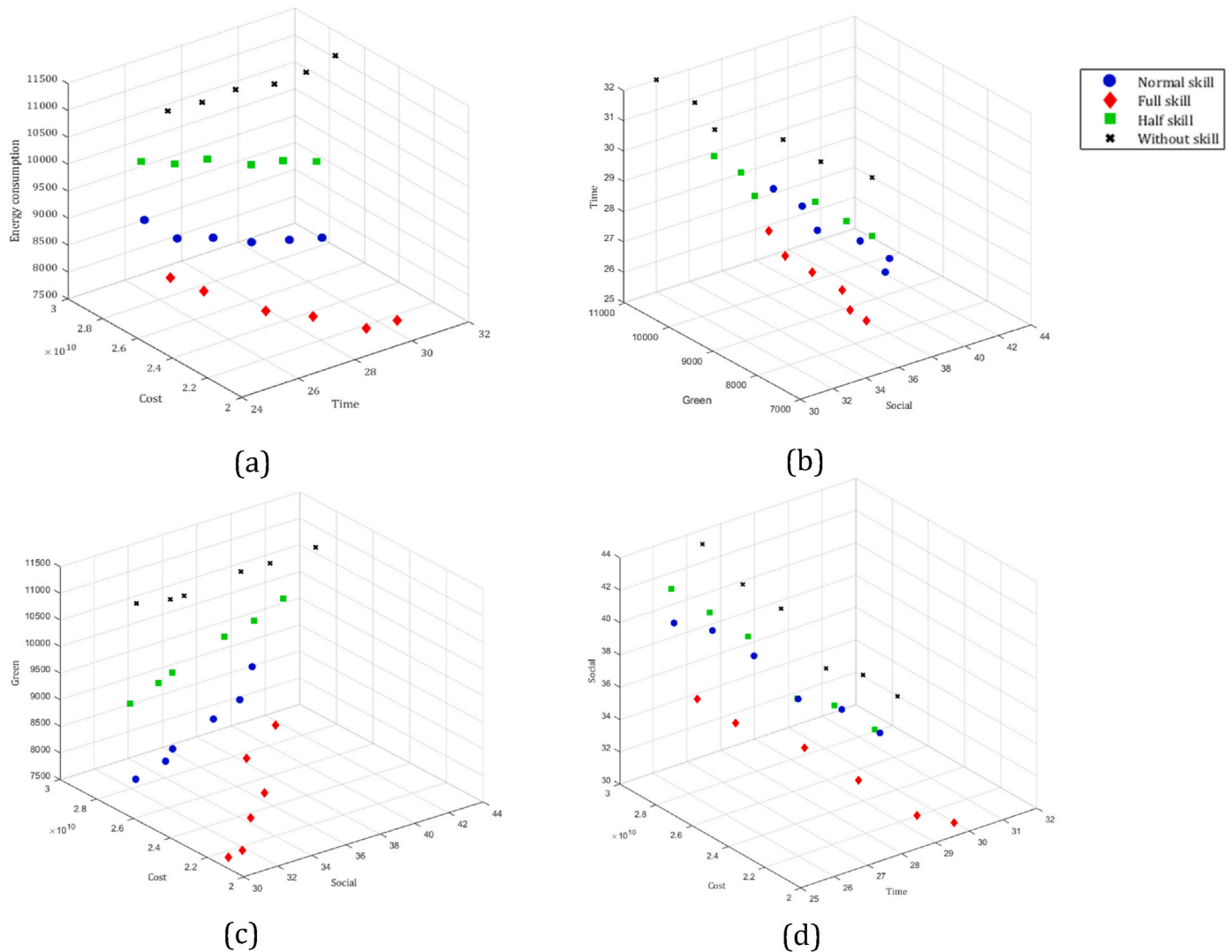
**Ethical approval**

The authors certify that this paper does not contain any studies or involvement with human participants or animals performed by any authors in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this paper.



**Table 10**  
Experimental results under three classes of skill numbers.

Grid points	Normal skill				Half skill				Full skill			
	Z1 (Time)	Z2 (Cost) × E+10	Z3 (green)	Z4 (job opportunity)	Z1 (Time)	Z2 (Cost) × E+10	Z3 (green)	Z4 (job opportunity)	Z1 (Time)	Z2 (Cost) × E+10	Z3 (green)	Z4 (job opportunity)
1	26	2.885711	8822	40.00	26.0	2.90234	9874	42.00	25.0	2.57265	8505	38.00
2	27	2.859674	8351	39.00	27.0	2.87502	9705	40.00	26.0	2.54496	8126	36.00
3	28	2.816621	8267	37.00	28.0	2.84908	9661	38.00	27.0	2.35342	7932	35.00
4	29	2.759166	8114	34.00	29.0	2.76266	9542	34.00	28.0	2.24115	7862	33.00
5	30	2.704942	8082	33.00	30.0	2.74391	9475	33.00	29.0	2.10178	7718	31.00
6	31	2.680778	7989	31.00	31.0	2.71045	9347	31.00	30.0	2.08426	7630	30.00
Average	28.5	2.78	8270.833	35.67	28.5	2.81	9600.67	36.33	27.5	2.32	7962.17	33.83



**Fig. 9.** Trade-off between three objective functions.

**Funding**

This work was partially supported by the Carnot Mines project on Industry of the Future: Responsible Manufacturing.

**CRedit authorship contribution statement**

**Reza Shahabi-Shahmiri:** Writing – original draft, Conceptualization. **Reza Tavakkoli-Moghaddam:** Writing – review & editing, Supervision. **Alexandre Dolgui:** Supervision, Resources, Project

administration. **Seyed-Ali Mirnezami:** Methodology, Investigation. **Mohammad Ghasemi:** Validation, Data curation. **Mahsa Ahmadi:** Visualization.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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