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Harmonizing project management and supply chain for sustainable construction: A comprehensive mathematical model and case study

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ABSTRACT

The cornerstone of achieving sustainable project management success lies in the harmonious integration of its multifaceted aspects. The conventional approach of handling different project dimensions in isolation falls short of realizing true success. In this context, sustainability emerges as a central theme, driving our exploration of how "project management" and "supply chain" intersect within the realm of construction projects, with a primary focus on optimizing resource allocation, minimizing environmental impact, and promoting long-term economic stability. Our research endeavors to usher in a paradigm shift, one that aligns "project management" - encompassing considerations of time and cost - with the principles of sustainability. We introduce a comprehensive mathematical model designed to not only maximize project profitability but also enhance its adaptability and environmental conscientiousness. Recognizing the dynamic nature of project financing, we diligently account for the influence of interest rates and housing price fluctuations on revenue and expenses, ensuring that our model reflects real-world conditions. Furthermore, our model delves into the intricate balance between time and cost, particularly in situations where project schedules require acceleration while adhering to the project's original timeline. Through a nuanced analysis, we explore various scenarios, allowing for different strategies. This includes early ordering to mitigate delays at the potential cost of increased maintenance, or an intensified effort to compress activities, which might elevate compressing costs. Our objective functions are designed to identify the most optimal combination, considering both project efficiency and sustainability. In line with our commitment to sustainability, we conduct a thorough examination of environmental, social, and economic factors throughout the project lifecycle. This holistic approach ensures that our model aligns with sustainable practices and promotes eco-friendly construction methods while simultaneously fostering a positive social impact and preserving economic viability. To validate the real-world applicability of our model, we present a case study of its implementation in an actual construction project, demonstrating how sustainability principles can be translated into practical, actionable strategies for the betterment of construction projects and, ultimately, our environment and society.

1. Introduction

Although the design and implementation of all kinds of projects have similar patterns, each one is a temporary, new effort that does not have a quite identical rival and differs, in many aspects, from another. Hence, considering one fixed pattern for all projects is not possible. As Supply Chain (SC) involves fixed processes, they are more common in production flows and rarely seen in projects, especially the construction type.

Since the lack of resources at the right time causes delays in construction projects, researchers tried to enter the SC issue in the construction industry; this was how the Construction Supply Chain (CSC) was born. This chain consists of such processes as customer demand, design, and maintenance, as well as such organizations as the project owner, designer, main contractor, supplier, and so on [1]. Since different sectors were not related properly in the traditional SC, decision centers increased and affected the SC efficiency. This was why the

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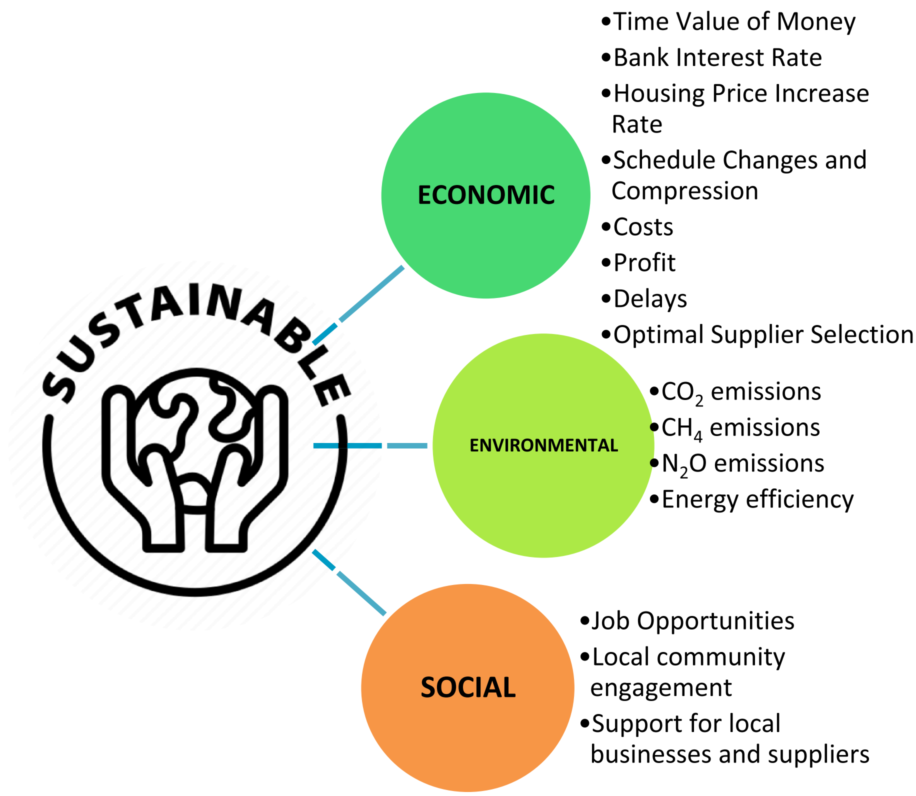

Fig. 1. Sustainable factors considered in this study.

researchers presented the SC integration issue, wherein all the sectors and levels sought to improve the condition of the entire chain; this caused different sectors to relate, increasing the chain's efficiency. In the traditional method, each sector sought to improve its situation and did not care about what it delivered to the project or what happened to the entire SC project. In contrast, both are quite important to improve the SC and the project's logistics because they may face obstacles that should be identified and resolved to reach the desired objectives. Scheduling to provide the project's required items and making it operational still needs serious attention because no proper action has been taken in this regard. Therefore, big steps can be taken to successfully improve the execution of construction projects through efforts made to integrate the SC and its proper management with processes existing in the project management and scheduling.

The project management standards on procurement require decisions on whether it is more cost-effective to perform various works on-site or outsource them to other suppliers/manufacturers. This decision will be expert judgment-based if made based on such factors as: 1) checking the risks on a) production or b) outsourcing, 2) checking the project schedule, 3) estimating the relevant cost and determining the necessary resources (for implementation), 4) checking the project management plan, documents of the requirements, list of stakeholders and environmental factors of the organization and, finally, 5) matching all the conditions with the market situation. Since outsourcing was, in most cases, more economical than production and involves fewer risks, it was used more in different projects.

Therefore, the need emerged to design SCs, where suppliers carry out part of the construction and deliver the final product to the site where the contractor is responsible only for its assemblage. However, timely access to resources is not achieved in some cases because the project and its supporting SC are not coordinated. This causes some executive operations to stop until resources are received, and the duration of some activities extends, which has a chain-like effect on the next activities and, ultimately, the entire project. Delays in the delivery of construction projects have various reasons, one of which is the lack of proper scheduling-SC coordination.

This coordination needs to consider temporary schedules, specify the activities that should be done in different periods, and determine the amount and type of materials they need before each time period, which can be weekly, monthly, quarterly, and so on, depending on different conditions. Then, the optimal demand is determined according to the warehouse capacity, amount of inventory, costs of ordering/maintenance, and other factors/conditions. Finally, the order is performed in such a way that the material shortage may not delay the starting/continuation of the activities, and the customer-agreed time could be achieved. Approaches used by the manufacturing/procurement sectors involve a significant gap. Product planning is based on the product work breakdown structure, where each temporary product, known as the product of one stage, is built by the collaborative efforts of different related teams. Still, product planning follows a traditional approach that does not consider inter-sector relations, which leads to more non-coordination between the planned requirements and their actual availability. Since materials constitute about 60-70 % of the total cost in complex projects, price reduction is widely used as a competitive tool to get orders [2]. Various researchers believe procurement/logistics is both a limitation and an opportunity exploited to improve the overall project performance. This is achievable if some existing management paradigms are used for project procurement management by considering the uncertainties or ambiguities common at the planning level [2,3].

The project SC and logistics issue is a suitable field for research activities due to its novelty, but most efforts made so far to enter the SC issue in construction projects have been conceptual and basic, and have primarily addressed the related infrastructures. Most models presented on the SC and traditional logistics are qualitative or have a production approach and rarely consider the characteristics of a project and its time and resource limitations, or if the model is mathematical, it maximizes the profit of part of the SC locally, which may be limited to an optimal local solution and, hence, causes the entire chain not to behave

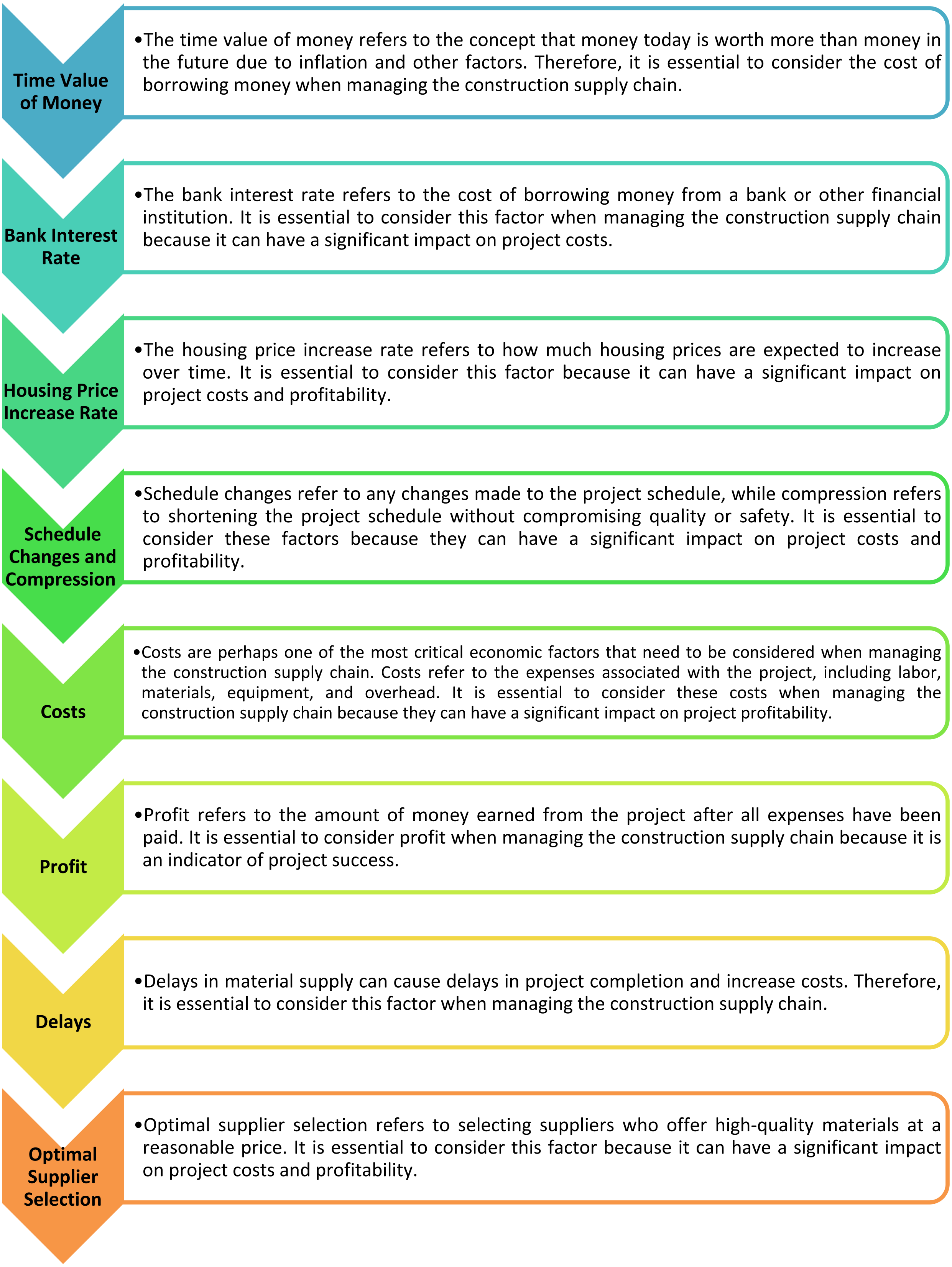

Fig. 2. Economic factors investigated in this study.

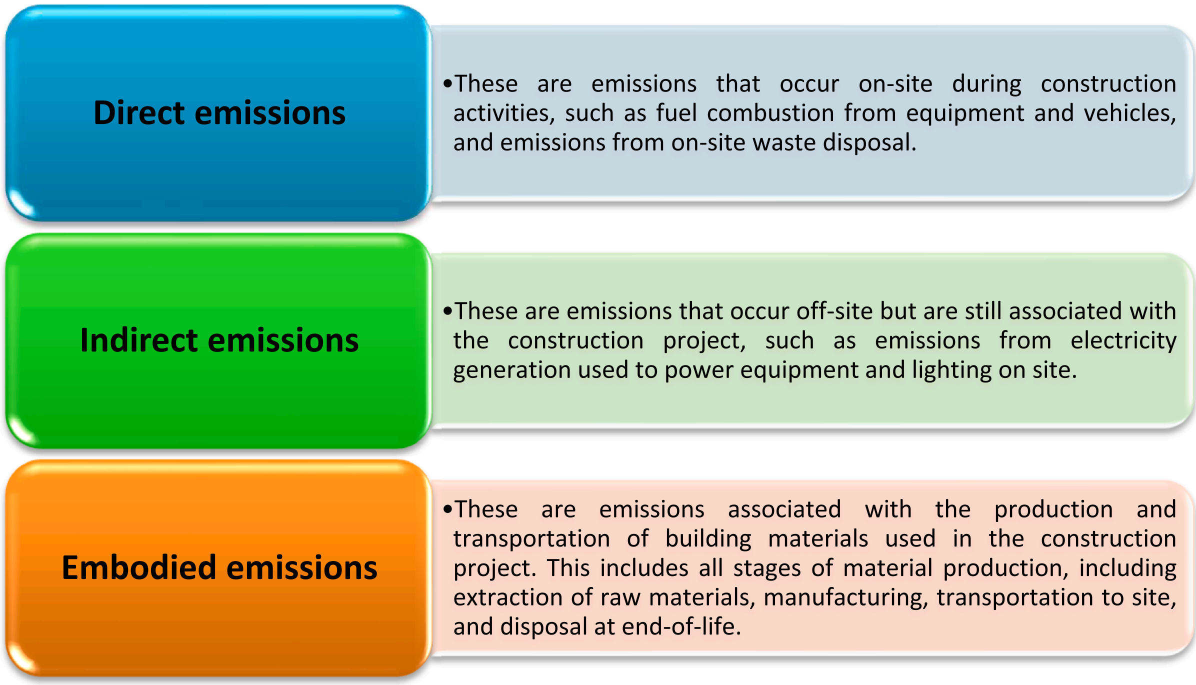

Fig. 3. Main categories of GHG emissions in a construction project.

optimally. But, project SC and logistics present quantitative models that not only address the issues related to the SC and logistics but also consider the characteristics and limitations of a project to identify and remove the existing obstacles to reach the desired objectives in both the project and SC and logistics to optimize the entire integrated SC, minimize the delays caused by orders and supply of project-required materials and make the latest completion time of the last project activity to be as close as possible to the time agreed with the client.

The concept of sustainability in construction supply chain management is gaining momentum due to increasing concerns about climate change and environmental degradation. The construction industry is responsible for significant Green House gas (GHG) emissions and resource depletion. Therefore, there is a need for sustainable practices that reduce carbon emissions and promote resource efficiency [4]. Sustainable supply chain management can help achieve these goals by reducing waste generation, promoting recycling and reuse of materials, using renewable energy sources, and adopting green building practices. Moreover, sustainability in construction supply chain management can have positive social impacts by promoting ethical labor practices and supporting local communities. It can also lead to economic benefits such as cost savings through efficient use of resources and reduced waste generation.

In conclusion, sustainability in construction supply chain management is crucial for achieving sustainable development goals while minimizing negative impacts on the environment, economy, and society. It requires collaboration among all stakeholders involved in the construction supply chain process to adopt sustainable practices that promote resource efficiency, reduce carbon emissions, and support ethical labor practices and local communities while ensuring economic viability. This study investigated all three dimensions of sustainability, which are comprehensively depicted in Fig. 1 and described below:

1.1. Economic aspect

Sustainability in construction supply chain management has become a critical issue in recent years. The construction industry is one of the most significant contributors to global GHG emissions and is responsible for substantial waste and pollution. Therefore, it is essential to consider the economic aspect of sustainability in the construction supply chain management. This paper will discuss various economic factors that must be considered when managing the construction supply chain. The most important application of this research is to provide a platform of scientific calculations for real projects to follow the principles of the project management standards and address all its related areas in an integrated manner. To this end, the effort has been made in the present research to consider all the influencing factors in the real world, including the time value of money, bank interest rate, housing price increase rate, schedule changes, and compression for the timely project completion, costs, profit, delays in the required material supply and optimal supplier selection. Since, in recent years, more models have been proposed for project-oriented SC and logistics, especially construction projects, and most of them try only to maximize profit, this study has examined the related models to identify the areas ignored or paid less attention. In succession, each studied factor is presented briefly (Fig. 2).

1.2. Environmental aspect

GHG emissions in the construction industry significantly contribute to global warming. The entire supply chain of a construction project includes all the activities involved in the production, transportation, and installation of building materials, as well as the operation and maintenance of the building itself [5].

The GHG emissions associated with a construction project can be divided into three main categories (Fig. 3):

The most prevalent GHGs in construction supply chains are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Carbon dioxide is the most prevalent GHG emitted in construction supply chains, accounting for approximately 80 % of all emissions. CO_2 is released during the production of cement, which is a key component in concrete. Concrete production accounts for approximately 5 % of global CO_2 emissions. Methane is another prevalent GHG emitted in construction supply chains, accounting for approximately 10 % of all emissions. Methane is released during the extraction and transportation of natural gas, which is used to power heavy machinery on construction sites. Nitrous oxide is also emitted during the production of cement and accounts for approximately 5 % of all emissions in construction supply chains.

Nitrous oxide is a potent GHG that has a global warming potential 298 times greater than CO_2. Other GHGs that are emitted in smaller quantities include hydrofluorocarbons (HFCs) and sulfur hexafluoride (SF_6). HFCs are used as refrigerants in air conditioning systems, while SF6 is used as an insulating gas in electrical equipment.

In conclusion, carbon dioxide, methane, and nitrous oxide are the most prevalent greenhouse gases emitted throughout the entire supply chain of a construction project. These emissions can be reduced through sustainable practices such as using alternative materials to concrete and reducing reliance on fossil fuels. Minimization of these emissions is considered in the model of this study.

1.3. Social aspect

Social considerations are an important aspect of sustainability in a construction project supply chain. These considerations encompass the social impacts of the project on the local community, workers, and other stakeholders involved in the project. The construction industry has a significant impact on society, and it is essential to ensure that this impact is positive and sustainable [6].

One of the primary social considerations in a construction project supply chain is the welfare of workers. Construction work can be physically demanding and dangerous, and it is crucial to ensure that workers are provided with safe working conditions, fair wages, and benefits such as healthcare. Another crucial social consideration is the impact of the project on local communities. Construction projects can disrupt communities by creating noise pollution, traffic congestion, and other disturbances. It is essential to minimize these impacts by communicating with local residents about the project's timeline and potential disruptions. Additionally, projects should strive to provide benefits to local communities, such as job opportunities or infrastructure improvements. The environmental impact of a construction project can also have social implications. For example, if a project involves deforestation or other environmental damage, it can negatively affect local communities that rely on those resources for their livelihoods. Therefore, it is crucial to consider the environmental impact of a project and take steps to mitigate any adverse effects. Finally, social considerations also include ethical concerns such as human rights violations or exploitation in the supply chain. This includes ensuring that suppliers adhere to ethical labor practices and do not engage in practices such as child labor or forced labor. By prioritizing worker safety and welfare, minimizing disruptions to local communities, considering environmental impacts, and adhering to ethical practices throughout the supply chain, construction projects can have a positive impact on society while also achieving their goals.

This research has been organized as follows: Section 2 represents a deep review of the related literature. In Section 3, a more detailed definition of the problem structure is provided. Also, the assumptions and mathematical modeling are presented. In Section 4, the proposed model-related assumptions are studied based on reality, in which the related data are collected from a case study, a 20-story commercial office building project, then the model is solved by the GAMS software with the CPLEX Solver. In succession, numerical, graphical, and sensitivity analyses are performed and explained, different scenarios regarding the delivery time of the materials are examined, and the results are presented. Finally, the conclusion and some suggestions for future research are presented in Section 5.

2. Literature review

In spite of the fact that estimation and pre-implementation planning of construction projects have received much attention in the construction industry, the logistics of construction materials have tended to be neglected, which is causing delays and increasing costs in the process. Detailed planning that considers all the factors affecting the Construction Logistics (CL) can ensure the project's success.

A wide variety of themes have been explored in the literature about construction supply chains (CSC), including sustainability, optimization techniques, and supply chain integration, among others. In research on sustainability, researchers emphasize the improvement of green supply chain management and reducing greenhouse gas emissions, while in optimization research, researchers focus on methods involving mixed-integer programming and genetic algorithms that can address resource management challenges by addressing them with mathematical models. Several studies have examined how the synergies between project scheduling and supplier management can improve project performance, highlighting the benefits of collaboration between the two disciplines. There are also innovative frameworks like heuristic algorithms for solving complex supply chain problems, as well as hybrid simulations that can be used to solve these problems. The purpose of this organized review is to identify key contributions to CSC research, highlight gaps, and provide a comprehensive understanding of the research, its significance, and its practical application.

2.1. Comprehensive reviews in construction supply chain (CSC)

For a well-rounded literature review, it would be beneficial if we look at review articles in the CSC area. Review articles have investigated CSC from a variety of angles, each one exploring the topic differently.

Liao et al [7] presented a comprehensive literature review on Construction Supply Chain Management (CSCM) and introduced gaps and future research. They scrutinized CSC from three aspects as organization, management, and technology. Specifically speaking, they stated that the organizational structure of CSC should be streamlined, which can be achieved by enhancing the knowledge systems that are relevant to the organization. As a result of their analysis, they suggested that interdisciplinary integration in a wide variety of fields should be an important focus for future studies on CSC, as well. A review conducted by Hussein et al [8] examined articles that dealt with off-site CSC, a state-of-the-art sustainable construction method. The authors concluded that environmental and social aspects of sustainability should be taken into account more by researchers as there have been fewer studies addressing them. Badi and Murtagh [9] studied the Green Supply Chain Management (GSCM) approach in the construction sector.

2.2. Quantitative models and optimization techniques

Salari et al [10] presented a stochastic model for a three-echelon supply chain management for off-site construction. While minimizing total cost and achieving the desired delivery time were their objectives in their investigations, they incorporated the Grasshopper Optimization Algorithm (GOA) and an exact method for solving the presented NP-hard problem. Chen et al [11] presented a mixed-integer linear programming model for a construction supply chain in which supplier selection and material purchasing are scrutinized. They tried to minimize the related lateness while considering uncertainties in the fuzzy scenario-based model. For the simultaneous planning of project timing and material procurement, Tabrizi (2018) [12] presented a mixed integer programming model to facilitate the effective implementation of projects and minimize project costs and environmental effects. Pei-Yuan et al [13] proposed a mathematical model that covered three operational categories (construction, storage, and assembly) and optimized the logistics processes in the new construction trend. As previous studies have stated that delays are the main cause of schedule deviations in construction sites, this research uses the obtained model to see how to adjust the factory production and inventory management to respond to the demand variations in such sites. The two-echelon stochastic programming model, developed to consider all the demand variations in the site, has been evaluated using a residential construction project case study. Liu and Xu [14] developed a non-deterministic multi-objective model that optimized the construction costs and the level of services. They extended the combined GA-fuzzy stochastic method to solve the model and then built and implemented an integrated multi-objective model to plan purchasing and production in a hydropower project in southwest China. Optimization results showed that the integrated activities were critical, and considering uncertainties of the delays and peak of orders was vital for the optimal implementation of the SC of construction projects. Tabrizi and Ghaderi [15] studied a problem with a mixed integer programming mathematical model aiming at minimizing the costs and maximizing the programming robustness. Their model considers uncertainties in both the time and costs of implementing the activities and is solved with the help of the GA and the modified algorithm. Gholizadeh et al [16] focused on the availability of resources and considered a mixed integer programming model that integrated the scheduling of the generalized resource-constraint-involved multi-project problem with SC planning to address the problem of supplying non-renewable resources in the required intervals and defined a construction-transportation schedule for them. It also considered the possibility of renting the additional required amounts to prepare a plan to determine the required amounts of renewable resources.

2.3. Sustainability and green supply chain management

In Shishodia et al [17], 24 factors and subfactors have been identified, which can be referenced from extant literature and expert consultation. They analyzed the factors and subfactors with the objective of promoting supplier resilience. In addition, the authors have proposed a methodology to measure supplier resilience and apply it to the development of new products and construction projects. Du et al [18] investigated the factors that affect carbon emissions in the supply chain of prefabricated buildings. They evaluated four factors: social/governmental, market, technical, and supply chain coordination. Among the factors considered in their study, technical factors have the greatest impact on reducing the carbon emission emitted by the prefabricated buildings supply chain, whereas it is the lowest for supply chain coordination. It was noted by the researchers that "the level of low-carbon design" and "the level of low-carbon awareness of companies" are key factors in reducing carbon emissions in prefabricated building supply chains. In a practical study, Ali et al [19] investigated the green supply chain management practices integrated into the China-Pakistan Economic Corridor (CPEC) construction project. The mentioned project, especially in light of sustainable development, has an important impact on Pakistan's construction sector from a variety of perspectives. Using the green CSM concept, Balasubramanian and Shukla [20] presented a study focusing on the green CSCM approach to understanding the whole life cycle of construction projects. They designed a green CSCM framework to promote the development of green construction practices. Through a multi-objective optimization model, Xu et al [21] studied the environmental aspects of construction materials SC networks. They presented an environmental evaluation method in order to determine a logical balance between environmental effects and economic development. Using a case study from China, they applied the proposed model to a real-life situation. An array of papers can be found scrutinizing CSC case studies, especially in countries [22,23]. Also, various case studies considered sustainability in their investigation [24–27].

2.4. Integration and collaboration in construction supply chain (CSC)

The integration of CSC has been investigated in a wide variety of studies. Rezahosseini et al [28] reviewed the integrated scheduling of suppliers and multi-project activities for green CSC. Through multi-objective linear programming, they investigated the synergy between supplier selection and project scheduling in a green construction supply chain. Shaikh et al [29] studied the role of integration and collaboration in CSC through a quantitative empirical study. They reviewed the role of supply chain collaboration (information sharing, joint decision-making, and risk and reward sharing) and supply chain integration (supplier integration, internal integration, and customer integration) with performance. Using bi-objective linear programming, they considered distance, pollution rate, and road slope. Le et al [30] investigated the integration in CSC through developing a decision-making model. There are two types of purchased materials considered in the model. It helps the main contractor to determine supplier selections, and order quantities, and evaluate third-party logistics usage by considering both types of purchased materials. With a focus on the optimization of on-site production, Magill et al. [31] investigated the integration of 4D building information models within the systems of CSC in the UK using a case study. Fang and Thomas Ng [32] presented a paper that aimed to test the genetic algorithm (GA) potential for the implementation of logistics programs in the processes of production, supply, and consumption of materials.

2.5. Innovative models and frameworks for optimization (time and resource constraints of the project)

A study by Asadujjaman et al [33] is aimed at addressing the Supply Chain Integrated Resource-Constrained Multi-Project Scheduling Problem, where the objective is to optimize the project scheduling and supply chain operations to maximize the net present value of the project. In this study, the authors proposed a mixed integer programming model and introduced a surrogate-based genetic algorithm, both of which were demonstrated to have superior performance when solving complex scheduling problems. To optimize the allocation of shared resources in a project portfolio, Bai et al [34] introduced a hybrid simulation model that combines system dynamics with discrete event simulation in order to optimize decision-making. This model is intended to evaluate the benefits associated with resource allocation both at the project level and the portfolio level, taking into account resource dependence as well as synergy effects. It was demonstrated through numerical examples and sensitivity analysis that the model was both practical and superior compared to traditional discrete event simulation approaches in terms of application and efficiency. The work of Liu et al [35] is focused on the resource-constrained project scheduling problem with transfers, a situation where transferring resources from one activity to another requires additional time. This paper proposes a tree search heuristic that incorporates an improved schedule generation scheme and a novel lower bound in order to enhance both computational efficiency and the quality of the solution. Based on the results of the study, the proposed heuristic displayed superior performance compared to existing algorithms, resulting in a reduction in computing time of 91.30 % on average and a 7.95 % improvement in the quality of solutions. Chen et al [36] conducted a study on how to coordinate supplier selection as well as project scheduling in resource-constrained construction supply chains. They proposed an improved version of a mixed-integer linear programming model in which a common supplier and resource constraints are considered across multiple concurrent projects in order to minimize overall project tardiness. An iterative decomposition-based heuristic has been developed in order to decompose the problem into manageable subproblems that are solved through mathematical programming techniques. As a result of numerical experiments, the proposed heuristic was shown to have a high computational efficiency as well as highlight the significant benefits of integrating supply chain operations into project planning.

The literature review in the previous section concludes that many related papers are qualitative, or if they involve a quantitative model, most of them only minimize the cost or maximize the profit and rarely address such project features as time and resource limitations. Hence, the proposed bi-objective model maximizes schedule flexibility and profit. Compressing the time of activities increases their flotation, enhances schedule flexibility, and helps the project to finish on time or ahead of time. To maximize the profit, the project income is considered as a combination of some cash, some from the sale/presale of the building units, and the daily bank interest in each period, and to

Table 1
A summary of the literature review.

Reference	Case Study	Logistics considerations	Scheduling activities	Compressing time of activities	PM-SCM integration	Uncertainty	Project resource deficit	Income generation	Objective function				Modeling approach	Solution approach	Sustainability
									Single	Multi	Components				
											Max	Min			
Asadujjaman et al [33]	-	✓	✓	-	✓	-	✓	-	✓	-	NPV	-	MIP	SGA	-
Bai et al [34]	-	✓	-	-	✓	✓	-	-	✓	-	Resource Allocation Benefits	-	Hybrid Simulation (SD-DES)	Numerical	-
Liu et al [35]	-	-	✓	-	-	✓	-	-	-	✓	Quality	Time	Tree Search Heuristic		Schedule Generation & Lower Bounds
Chen et al [11]	-	-	-	-	-	✓	✓	-	-	✓	-	Cost, Lateness	MILP	Computational Experiments	-
Salari et al [10]	-	✓	-	-	✓	✓	-	-	-	✓	-	Costs, Route balancing	Stochastic	GOA	-
RezaHoseini et al [28]	-	✓	✓	-	✓	✓	-	-	-	✓	-	Cost, Pollution	MIP	e-constrained	✓
Fang and Thomas Ng [32]		✓	✓	✓	✓	✓	✓	-	✓		-	Cost	Scenario-based	GA	
Tabrizi [12]		✓	✓	-	✓	-	-	-		✓	-	Cost	MIP	Metaheuristic with Taguchi method	✓
Pei-Yuan et al [13]		✓	-	-	-	✓	✓	-		✓	service level during a period	Cost Purchasing, production	Stochastic	GA	
Tamošaitienė et al. [37]		✓	-	-	-	-	-	-	-	-	-	-	AHP	ARAS/	
Tabrizi and Ghaderi [15]		✓	✓	-	✓	✓	✓	-		✓	Robustness	Costs	MIP	Modified GA	
Gholizadeh et al [16]		✓	✓	-	✓	-	✓	-	✓	-	-	Costs	MIP	CPLEX	
Wibowo and Sholeh Moh [38]		✓	-	-	-	-	-	-	-	-	-		SCOR/AHP	OMAX and traffic light	
Liu and Tao [39]		✓	-	-	-	✓	-	-		✓	-	supplier/ contractor/ inventory/ employer cost	MIP	PSO	
Tabrizi and Ghaderi [40]		✓	✓	-	✓	✓	-	✓	✓		Net Profit	-	MIP	Metaheuristic GA with Taguchi method	
Eriksson [41]		✓	-	-	-	✓	-	-	-	-	-	-	Conceptual	-	
Saeed and Al-Raees [42]		✓	✓	-	-	-	-	-	-	✓	-	total logistics cost and	AMCLOS	GA	

(continued on next page)

Table 1 (*continued*)

Reference	Case Study	Logistics considerations	Scheduling activities	Compressing time of activities	PM-SCM integration	Uncertainty	Project resource deficit	Income generation	Objective function				Modeling approach	Solution approach	Sustainability
									Single	Multi	Components				
											Max	Min			
												plan criticality			
Elimam and Dodin [43]		✓	-	-	-	-	-	-	✓	-	-	Total cost	MIP	CPLEX	
Vidalakis et al [44]		✓	-	-	-	✓	-	-	-	-	-		Conceptual simulation model	-	
Cheng et al. [45]		✓	-	-	-	-	-	-	-	-	-		SCOR	-	
46		✓	✓	✓	✓	-	-	-	-	-	-		MIP	GA	
Elimam and Dudin [47]		✓	✓	✓	✓	-	-	-	✓	-	-	Total cost	MIP	CPLEX and AMPL	
Current study	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	Profit and schedule flexibility	-	MINLP Scenario-based	BARON	

minimize costs, all logistics costs (purchasing, ordering, transportation, and inventory), cost of renewable resources, reward/fine for early/late delivery and costs of compressing the project activities are considered. On the other hand, considering the time value of money is quite effective in the obtained results, but since in the real world, factors affecting the project implementation are rarely certain, considering the possibilities is an investigation necessity; this is why the bank interest rate and the housing price increase rate are involved in considering the time value of money. To check different possible situations, three possible cases: 1) optimistic, 2) probable, and 3) pessimistic have been considered for the calculation of the due time of the items. Table 1 presents a summary of the literature review.

3. Problem definition

Past decades' traditional strategies addressed project scheduling and material ordering separately; the project schedule was completed first, and then a material ordering schedule was prepared by considering the activity time as a specific parameter. Hence, the project managers did not consider the trade-off between different cost elements (material ordering/storage, procurement, rewards/fines) for the project completion time, causing the total project cost to increase [46]. However, since, according to the PMBOK project management standard, a project is implemented in the best way when all areas are integrated, "integration" has received more attention in recent years so that projects are implemented the best. Therefore, the "project supply chain" has been raised to show the obsolescence of traditional strategies in project management. The presentation of different models in recent years for "integration" is a step towards standard and principled implementation of projects even if the models are not comprehensive and inclusive. On the other hand, one objective is to complete construction projects at the employer-client agreed due time, and any delay in this regard will dissatisfy the client and increase the employer's costs. One reason for these delays is later-than-schedule project-required material/resource supply, which will cause the labor force to stay idle, and the employer to incur losses due to the increase in the price of materials and resources (with the passage of time due to the increase in the inflation rate), the customer to be dissatisfied, and so on. Therefore, this study aims to supply the project-required materials/resources on time, determine their ordering amount, and purchase them based on the project schedule, reducing costs due to delays and maintenance. It is also possible, by changing the time of some activities within their floating limits and compressing their execution time (although the project may face some cost increase), to plan projects in such a way that they are completed on time or even earlier than that requested by the client.

As mentioned above, one reason for delays in the project due date is late material supply, which postpones the implementation of activities. A measure that can help solve this problem is to decide on the parts that are not ready-made and should be built separately before installation; if these are built inside the site or are outsourced under contracts, delays are highly reduced. Such decisions are planned and carried out under procurement management, which is a part of project management. In the case of outsourcing, it is necessary to determine both the potential suppliers and the procurement implementation method (and time). Another material-supply-related issue that needs investigation is the optimal supplier selection, where such issues as the ability to supply the requested amount of materials in full, appropriate discounts, minimum distance traveled to deliver materials to the project site, acceptable material quality/price and minimum shipping cost/delivery time need a thorough investigation. Other important factors that highly affect making the results of calculations more consistent with the real world are the time value of money, bank interest rates, and increase in the housing price; based on the studies, these are almost ignored and applied in only a few researches. As this research is aimed to consider, as much as possible, more real conditions, it has used these factors in its modeling.

Since the most important issue in any project, from the contractor's point of view, is to reach the highest possible profit, it is very important to consider all incomes and expenses in the model. As mentioned before, adapting to real-world conditions necessitates considering not only the time value of money, bank interest rate, and housing price increase rate but also all costs - purchasing, ordering, shipping, warehouse storage, renewable resources, labor force, fixed equipment, water/electricity, compressing activities - and incomes - client-paid money, that obtained due to early project delivery and bank account interests.

According to the proposed model, a holistic view of sustainability is taken into account from the point of view of energy consumption and GHG emissions. The assumption is that each activity has its own unique energy consumption that is associated with it. Several types are taken into account when calculating GHG emissions. As described in the section 1, a variety of greenhouse gases (GHGs) are released by construction activities at a variety of levels. Hence, in order to fully grasp the concept of sustainability, the model also looked into local job opportunities as the social dimension, as the importance of local job opportunities is extensively discussed in the introduction.

To solve the aforementioned problems, the presented model has the following features:

- It is related to a construction project implemented under a fixed price contract; the contractor gets a portion of the money in cash and the rest by owning some construction units. Cash payments are in the form of installments paid at the beginning of each implementation period, and if the payments do not cover all the costs of that period, the contractor will pre-sell some units (considering the time value of money in that period) in order to cover the costs.
- It considers the time value of money to determine the maximum net present value
- It minimizes the deviation from the schedule by the maximum use of the flotation of the activities in determining their start time and the latest completion time.
- It determines the amount of materials needed in each period.
- It determines the best supplier by considering the ability to supply the requested amount of materials in full, appropriate discounts, minimum distance traveled to deliver materials to the project site, acceptable material quality/price, and minimum shipping cost/delivery time.
- It determines the required renewable resources.
- It considers the delivery time of the materials in different scenarios.

3.1. Model assumptions

- All the project SC-/logistics-related activities are managed in a centralized, integrated manner.
- The starting and finishing activities are virtual.
- The network of activities is of the Activity On Node (AON) type and does not include loops.
- The project schedule involves inter-activity relationships and the time of the activities is known.
- The start time of an activity lies within its total flotation range.
- Prerequisite relationships in the project are of the finish-to-start type.
- Project activities are done nonstop.
- The project completion time is agreed upon with the employer.
- The type and amount of materials required for each project activity are determined based on its schedule.
- The amount of material *m* needed for activity *j* is independent of the activity time.
- As the storage space in the project site is known and limited, ordering/purchasing excess materials incurs costs.
- Materials may be supplied from more than one supplier.
- Supplying materials involves quantity discounts.
- In each period, the interest rate is based on the latest one announced by the central bank, and its effects are considered in the project costs/revenues.
- Project funding is through the employer's cash payments at the beginning of each period or presale of units, if necessary.
- If a unit is pre-sold in a period and all the money is not used, the remaining part will be saved in a bank account with daily interest (paid in sum at the end of the month) until the next period to be used to cover the costs.
- The time reduction Effects of some project activities are considered in the costs to reach the time agreed with the client.
- All the units are assumed to be sold before the planning horizon so that the increased age of the building unit may not cause its price to decrease.
- If a building unit is sold in period t and its income is not fully consumed, the remaining part will be saved in a bank account with daily interest to be used in the next period.

3.2. Modeling

3.2.1. Indices, parameters, sets, and decision variables

Indices

J = 1, 2... N: Index of the project activities m = 1, 2..., M: Index of the materials used in the construction of the project t = 0, 1…, H: Index of time s = 1, 2..., S: Index of suppliers k = 1, 2..., K_{ms}: Index of the discount range of the price of materials r = 1, 2..., R: Index of renewable resources q = 1, 2..., Q: No. of building units to be owned by the contractor (based on the contract) g = 1, 2, …, G: Index of GHG type

Sc = 1, 2, and 3: Considered scenarios

Sets

Pred(j): Set of prerequisites of activity j

Succ(j): Set of post-requirements of activity j

Parameters

NS_j: No. of post-requirements of activity j (number)

T_j^{max}: Maximum reduction of a unit of time of activity j (time unit)

V_j: Lower bound of the activity execution time (compressed activity execution time) (time unit)

Dd: Project completion date based on the agreement and schedule (time unit)

H: Project planning horizon (time unit)

L_{ms}^{sc}: Due time for supplier s to deliver ordered material m (time unit)

Pe: Fine assigned for completion later than the scheduled deadline (price unit)

Re: Reward assigned for completion earlier than the scheduled deadline (price unit)

δ_{mks}: Unit price of material m in discount range k purchased from supplier s

R_{jm}: Required material m to complete activity j (same unit as material m)

R_{jr}: Required renewable resource r to complete activity j (same unit as resource r)

CR_j: Cost of reducing one unit from the time of activity j (price unit)

G_{ms}: Cost of ordering material m to supplier s (price unit) h_m: Maintenance cost of material m (price unit) d_j: Execution time of activity j (time unit)

B_t: Budget of period t to be paid, in cash, by the employer to the contractor based on the contract (price unit)

AC_{rt}: Cost of renewable resource r period t (price unit)

Ψ_{mks}: Quantity limit of material m bought from supplier s in discount range k (same unit as material m)

K_{ms}: No. of discount ranges proposed by supplier s for material m (number)

α: Bank interest rate (%, announced by the government)

μ: Monthly housing price increase rate (% announced by the government)

ρ^{sc}: Probability corresponding to scenario sc

A_{qt}: Sale/presale price of a building unit in period t (price unit)
(P/F,α%,t): Once-payment present value if α is the rate of capital return
(F/P, α%, t): Once-payment future value if α is the rate of capital return
EN_j: The energy consumed by activity j
EM_{gj}: The amount of GHG type g emitted by activity j
LJ_j: Total jobs created for local communities by the activity j
ENE: Total allowed energy consumption upper bound imposed by the government
EMI: Total allowed emissions imposed by the government
LJO: The lower bound for the limitation of local communities' job opportunities

Decision variables related to the project management x_{jt}^{sc}: 1, if activity j starts in period t under scenario sc, and 0, otherwise z_{jt}^{sc}: 1, if activity j is reduced t time units under scenario sc, and 0, otherwise
ω_{qt}^{sc}: 1, if building unit n is sold in period t under scenario sc, and 0, otherwise
IB_t^{sc}: Budget remained (from previous period) in period t under scenario sc
TC_t^{sc}: Total implementation costs of activities of period t under scenario sc es_j^{sc}: Earliest start time of activity j under scenario sc ls_j^{sc}: Latest start time of activity j under scenario sc
TS_j^{sc}: Total flotation of activity j under scenario sc

Decision variables related to the supply chain
λ_{mkst}^{sc}: 1, if material m is ordered to supplier s in discount range k in period t under scenario sc, and 0, otherwise
P_{mkstj}^{sc}: 1, if material m required by activity j is ordered to supplier s in discount range k in period t under scenario sc, and 0, otherwise
I_{mt}^{sc}: Inventory of material m in period t under scenario sc
RA_{rt}^{sc}: Renewable resource r available under scenario sc in period t

3.2.2. Mathematical modeling

Considering the symbols presented above, the proposed mathematical model is as follows:

$$Max\ E\left(O_1^{sc}\right) = \sum_{sc=1}^{3} \rho^{sc}.O_1^{sc} = \sum_{sc=1}^{3}\sum_{j=1}^{N} \rho^{sc}.NS_j.\left(TS_j + \sum_{t=1}^{T^{max_j}} t.z_{jt}^{sc}\right) \tag{1}$$

$$\begin{aligned} Max\ E\left(O_2^{sc}\right) &= \sum_{sc=1}^{3} \rho^{sc}.O_2^{sc} \\ &= \sum_{sc=1}^{3}\sum_{t=1}^{H-1}\sum_{q=1}^{Q} \rho^{sc}.A_{qt}.\omega_{qt}^{sc}.\left(\frac{P}{F},\alpha\%,t\right).(1+\mu)^t \\ &\quad + \sum_{sc=1}^{3} \rho^{sc}.IB^{sc}{}_H\left(\frac{P}{F},\alpha\%,H\right) \\ &- \left[\left(\sum_{sc=1}^{3}\rho^{sc}.\left(\sum_{t=Dd}^{H} Pe(t-Dd)x_{Nt}^{sc} - \sum_{t=es_N}^{Dd}\mathrm{Re}(Dd-(t+d_N))x_{Nt}^{sc}\right)\right).\left(\frac{P}{F},\alpha\%,t\right)\right. \\ &+ \sum_{sc=1}^{3}\sum_{j=1}^{N}\sum_{t=1}^{T^{max_j}} \rho^{sc}.t.CR_j.z_{jt}^{sc}.\left(\frac{P}{F},\alpha\%,t\right) \\ &+ \sum_{sc=1}^{3}\sum_{m=1}^{M}\sum_{K=1}^{K_{ms}}\sum_{s=1}^{S}\sum_{t=1}^{H-\tilde{L}_{ms}-d_j+1}\sum_{j=1}^{N} \rho^{sc}.\delta_{mks}.R_{jm}.P_{mkstj}^{sc}.\left(\frac{P}{F},\alpha\%,t\right) \\ &+ \sum_{sc=1}^{3}\sum_{m=1}^{M}\sum_{s=1}^{S}\sum_{t=1}^{H-\tilde{L}_{ms}-d_j+1} G_{ms}\sum_{k=1}^{K_{ms}} \rho^{sc}.\lambda_{mkst}^{sc}.\left(\frac{P}{F},\alpha\%,t\right) \\ &+ \sum_{sc=1}^{3}\sum_{m=1}^{M}\sum_{t=1}^{H-1} \rho^{sc}.h_m.I_{mt}^{sc}.\left(\frac{P}{F},\alpha\%,t\right) \\ &\left.+ \sum_{sc=1}^{3}\sum_{r=1}^{R}\sum_{t=1}^{H-1} \rho^{sc}.AC_{rt}.RA_{rt}^{sc}.\left(\frac{P}{F},\alpha\%,t\right)\right] \end{aligned} \tag{2}$$

$s.t$:

$$\sum_{t=1}^{H} t.x_{Nt}^{sc} \le H; \forall sc \in 1,2,3 \tag{3}$$

$$\sum_{t=es_i}^{ls_i} t.x_{it}^{sc} + d_i - \sum_{t=1}^{T_j^{max}} t.z_{jt}^{sc} \le \sum_{t=es_j}^{ls_j} t.x_{jt}^{sc} = 1; \forall i \in Succ(j), \forall sc \in 1,2,3 \tag{4}$$

$$\sum_{t=es_j}^{ls_j} x_{jt}^{sc} = 1; \forall j \in 1,2,...,N, \forall sc \in 1,2,3 \tag{5}$$

$$\sum_{t=1}^{T_j^{max}} t.z_{jt}^{sc} \le 1, \forall j \in 1,2,...,N,\ \forall sc \in 1,2,3 \tag{6}$$

$$\begin{aligned} I_{mt} &= I_{m(t-1)}^{sc} + \sum_{k=1}^{K_{ms}}\sum_{s=1}^{S}\sum_{j=1}^{N} R_{jm}P^{sc}_{mks(t-\tilde{L}_{ms})j} - \sum_{j=1}^{N}\sum_{\tau=Max\left(t-d_j+1,es_j\right)}^{Min\left(t,ls_j\right)} R_{jm}X_{j\tau}^{sc}; \forall m \\ &= 1,2,...,M, \forall t = 1,2,...,H, \forall sc \in 1,2,3 \end{aligned} \tag{7}$$

$$\sum_{j=1}^{N}\sum_{\tau=Max\left(t-d_j+1,es_j\right)}^{Min\left(t,ls_j\right)} R_{jr}.x^{sc}{}_{jt} \le RA_{rt}; \forall t \in 1,2,...,H, \forall r \in 1,2,...,R, \forall sc \in 1,2,3 \tag{8}$$

$$\psi_{m(k-1)s}\lambda_{mkst}^{sc} \le \sum_{j=1}^{N} R_{jm}P_{mkstj}^{sc} \le \psi_{mks}\lambda_{mkst}^{sc}; \forall m = 1,2,...,M, \forall s = 1,2,...,S, \forall t = 1,2,...,H, \forall k \in 1,2,...,K_m, \forall sc \in 1,2,3 \tag{9}$$

$$\sum_{k=1}^{K_{ms}} \lambda_{mkst}^{sc} \le 1; \forall m = 1,2,...,M, \forall s = 1,2,...,S, \forall t \in 1,2,...,H, \forall sc \in 1,2,3 \tag{10}$$

$$\sum_{k=1}^{K_{ms}}\sum_{s=1}^{S}\sum_{t=1}^{H-1} P_{mkstj}^{sc} = 1; \forall j = 1,2,...,N, \forall m \in 1,2,...,M, \forall sc \in 1,2,3 \tag{11}$$

$$\sum_{k=1}^{K_{ms}}\sum_{s=1}^{S}\sum_{t=1}^{H-1} t.P_{mkstj}^{sc} + \widetilde{L}_{ms} \le \sum_{t=es_j}^{ls_j} t.x_{jt}^{sc}; \forall j = 1,2,...,N, \forall m \in 1,2,...,M \tag{12}$$

$$\begin{aligned} TC_t^{sc} &= \sum_{t=1}^{H-1}\sum_{m=1}^{M}\sum_{K=1}^{K_{ms}}\sum_{s=1}^{S}\sum_{j=1}^{N} \delta_{mks}R_{jm}.P_{mkstj}^{sc} + \sum_{t=1}^{H-1}\sum_{m=1}^{M}\sum_{s=1}^{S} G_{ms}\sum_{k=1}^{K_{ms}} \lambda_{mkst}^{sc} + \sum_{t=1}^{H-1} \\ &\quad \times \sum_{m=1}^{M} h_m.I_{mt}^{sc} + \sum_{t=1}^{H-1}\sum_{r=1}^{R} AC_{rt}.RA^{sc}{}_{rt} + \sum_{j=1}^{N}\sum_{t=1}^{T^{max_j}} t.CR_j.z_{jt}^{sc} \end{aligned} \tag{13}$$

$$TC_t{}^{sc} \le B_t + \sum_{q=1}^{Q} A_{qt}\omega_{qt}^{sc}.(1+\mu)^t, \forall t \in 1,2,...,Dd \tag{14}$$

$$IB_t^{sc} = IB_{t-1}^{sc}\left(\frac{F}{P},\alpha\%,1\right) + B_t + \sum_{q=1}^{Q} A_{qt}\omega_{qt}^{sc}.(1+\mu)^t - TC^{sc}{}_t, \forall t \in 1,2,...,H \tag{15}$$

$$\sum_{t=1}^{H} \omega_{qt}^{sc} = 1; \forall q = 1, 2, ..., Q \tag{16}$$

$$B^{sc}{}_{t>Dd} = 0, \forall t \in Dd, ..., H \tag{17}$$

$$TC^{sc}{}_{t>Dd} = 0, \forall t \in Dd, ..., H \tag{18}$$

$$es_j^{sc} = \max\left\{ es_i + d_i - \sum_{t=1}^{T_i^{max}} t.z_{itsc} \right\}; \ \forall j = 1, 2, ..., N, \ \forall i \in Pred(j) \tag{19}$$

$$ls_j^{sc} = \min\left\{ ls_i - d_j + \sum_{t=1}^{T_i^{max}} t.z_{itsc} \right\}; \ \forall j = 1, 2, ..., N, \ \forall i \in Succ(j) \tag{20}$$

$$TS_j^{sc} = ls_j^{sc} - es_j^{sc} \tag{21}$$

$$\sum_{j=1}^{N} \sum_{t=1}^{H} \sum_{sc=1}^{3} x^{sc}{}_{jt}.EN_j \leq ENE \tag{22}$$

$$\sum_{g=1}^{G} \sum_{j=1}^{N} \sum_{t=1}^{H} \sum_{sc=1}^{3} x^{sc}{}_{jt}.EM_{gj} \leq EMI \tag{23}$$

$$\sum_{j=1}^{N} \sum_{t=1}^{H} \sum_{sc=1}^{3} x^{sc}{}_{jt}.LJ_j \geq LJO \tag{24}$$

$$x_{jt}^{sc}, \lambda_{mkst}^{sc}, P_{mkstj}^{sc}, z_{jt}^{sc}, \omega_{qt}^{sc} \in [0, 1], I_{mt}, RA_r \geq 0, TS_j, ls_j, es_j \in int \tag{25}$$

Expressions (objective functions) 1 and 2 maximize, respectively, the expected value of the schedule flexibility by floating all the activities and the project's net profit value (NPV) by considering the time value of money under all scenarios. The first objective function is aimed to use the post-requirements of each activity, in each scenario, as a weight to highlight the value of on-time/early completion of the project's initial activities; using flotation and compression variables is aimed for on-time and earlier activity completion, respectively. In objective function 2, the project income is the sum of the presale of the contractor-owned units and the cash paid by the employer in each period, including the daily interest of the bank account, interest rate, and the housing price increase rate. Regarding costs, the first expression indicates the cost/income due to the late/early project completion, the second expression shows the cost due to the compression of some activities to reach the agreed due date, the third to fifth expressions are related to the project logistics costs that show, respectively, the cost of supplying the project-needed materials from different suppliers, considering their discounts, the cost of ordering and the cost of inventory holding, and the last expression is the cost of the project renewable resources that varies in different scenarios depending on how the material delivery time varies. As shown, the net profit is obtained from the difference between the planned revenues and costs of the project, considering the time value of money.

Constraint 3 ensures the project planning horizon or the customer-agreed due date, and Constraint 4 ensures that an activity starts within its floating range (earliest and latest start time). Constraint 5 ensures that an activity can start only in one period of time. Constraint 6 ensures that activity j can take only one value from the range assigned to compression. Constraint 7 ensures the inventory level of each material (needed in a period) based on the warehouse inventory, the amount ordered and the amount consumed. Constraint 8 ensures that the renewable resources available in a period affect and limit the simultaneous implementation of activities. Constraint 9 ensures that the discount for each material in each order depends on the ordered amount. Constraint 10 restricts the amount of discounts that a material can be ordered from a supplier within a certain range. Constraint 11 ensures that the materials needed for each activity can be ordered only once. Constraint 12 ensures that an activity cannot start until all its required materials are delivered, considering its due date. Constraint 13 ensures that all the activity implementation costs of period t are calculated. Constraint 14 ensures that the activity implementation costs of each period are covered by the employer's cash payments and incomes from presales (if necessary). Constraint 15 ensures that the budget of each period is calculated based on the amount remained from the previous period and kept in a bank account with daily interest, as well as those received and spent in that period. Constraint 16 ensures that a building unit can be sold only once. Constraint 17 ensures that the employer's paid budget will last only until the project's due date. Constraint 18 ensures that the implementation costs of activities in each period will continue only until the due date. Constraints 19 and 20 show the equations needed to calculate the earliest and latest start time of the activities, considering the prerequisite relations and the possibility of their compression. Constraint 21 ensures that total floating is calculated. Constraints 22 and 23 are defined for complying with the government regulations for the energy consumption and emissions respectively. Constraint 24 ensures that the lower bound set for local job opportunities is observed. Finally, Constraint 25 specifies the range and type of the decision variables.

4. Numerical experiments under the scenario-based mode

This section introduces the case study, uses the proposed model, explains how it functions, and presents the results of the related calculations. An effort has been made for the model solution data to be as realistic as possible so that the investigations are close to the real conditions and the suggestions can be used practically in other projects. Three scenarios are proposed for the material delivery to enable investigation of the effects of late deliveries and the delay in the implementation of activities. As stated before, since one reason for delays in projects is the material deficit or the increased delivery time, three scenarios 1 (pessimistic), 2 (probable), and 3 (optimistic), with probabilities of, respectively, 0.2, 0.5 and 0.3 have been considered (based on the opinion of the experts of the mentioned) to make the proposed model to conform more to real conditions.

4.1. Introduction of the case study

The case studied is a 20-story commercial office building in the north of Tehran, under the following conditions:

- The contract is such that part of the sum is paid in cash at the beginning, and the rest is in the form of 5 similar, equal-area office units, which can be pre-sold if the cash does not cover the implementation costs, or else, sold after the project completion if not presold.
- The project planning horizon is 35 months, and the project should finish in 29 months.
- It is assumed that the units are sold before the planning horizon.
- The considered renewable resources are water, electricity, labor force, machinery, and equipment, and the price of the labor force, machinery, and equipment is a weighted average of the needed types.
- Structure, carcassing, electrical-mechanical installation, finishing, and facade are the first-level activities to simplify the work.
- Materials are in 4 categories: structural, architectural, electrical, and mechanical.
- Suppliers of materials are in 5 categories: structure, architecture (1 & 2), electrical and mechanical.
- The price of categorized materials is considered as the weighted average of each category.
- The annual bank interest rate is 18 %, and the housing price increase is 72 %.
- The unit presale/sale price, according to the seller (contractor), except the annual increase in the housing price, is a percent increase/

Table 2
Values of the objective functions based on the interest rate and housing price increase rate.

Optimal value of objective function 3	Optimal value of objective function 2	Optimal value of objective function 1	Annual bank interest rate	Annual housing price increase rate
−0.1108	169.536.131.815	163	%18	%72

Table 3
Compression of activities in problem 1.

Activity	Compression limit	Real compression
1	2	2
2	3	3
4	2	2
5	3	3
6	4	0

decrease for different periods before/after the project delivery; the annual increase in the housing price is included in the input data.

- The employer's cash payment to the contractor varies in the 2-5 billion range in each period, and the base price of a unit presale, having its minimum value in period 1, is 8 billion.
- The proposed mix integer nonlinear programming model is solved by GAMS software and Baron Solver.
- In formulating the multi-objective function, the LP-metric method has been used, where the first and second objective functions have weights of, respectively, 0.2 and 0.8 based on the experts' opinions.

$$MaxObj_3 = \left[w.\frac{Obj_1 - Obj_1^*}{Obj_1^*} + (1-w).\frac{Obj_2 - Obj_2^*}{Obj_2^*} \right]$$

- The AON network of the project is as follows:

Table 4
Earliest activity start time in problem 1.

Scenario Activity	1	2	3
1	1	1	1
2	3	3	3
3	6	6	6
4	6	6	6
5	10	10	10
6	14	14	14

Table 5
Latest activity start time in problem 1.

Scenario Activity	1	2	3
1	10	10	10
2	12	12	12
3	17	17	17
4	15	15	15
5	19	19	19
6	23	23	23

Table 6
Total floating of activities in problem 1.

Scenario Activity	1	2	3
1	9	9	9
2	9	9	9
3	11	11	11
4	9	9	9
5	9	9	9
6	9	9	9

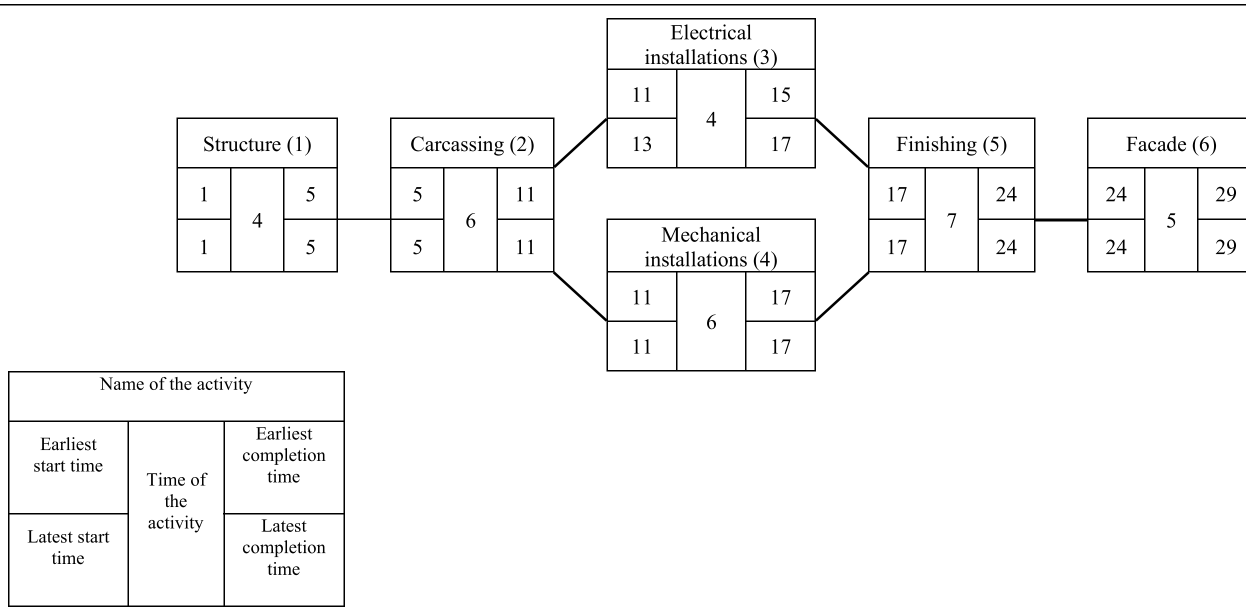

Table 7
Optimal schedule found for objective function 1 by solving the sample problem under scenarios 1, 2, 3, respectively. (Gray cell: Activity Duration Unit/ Red Crosshatch Cell: Compression Unit).

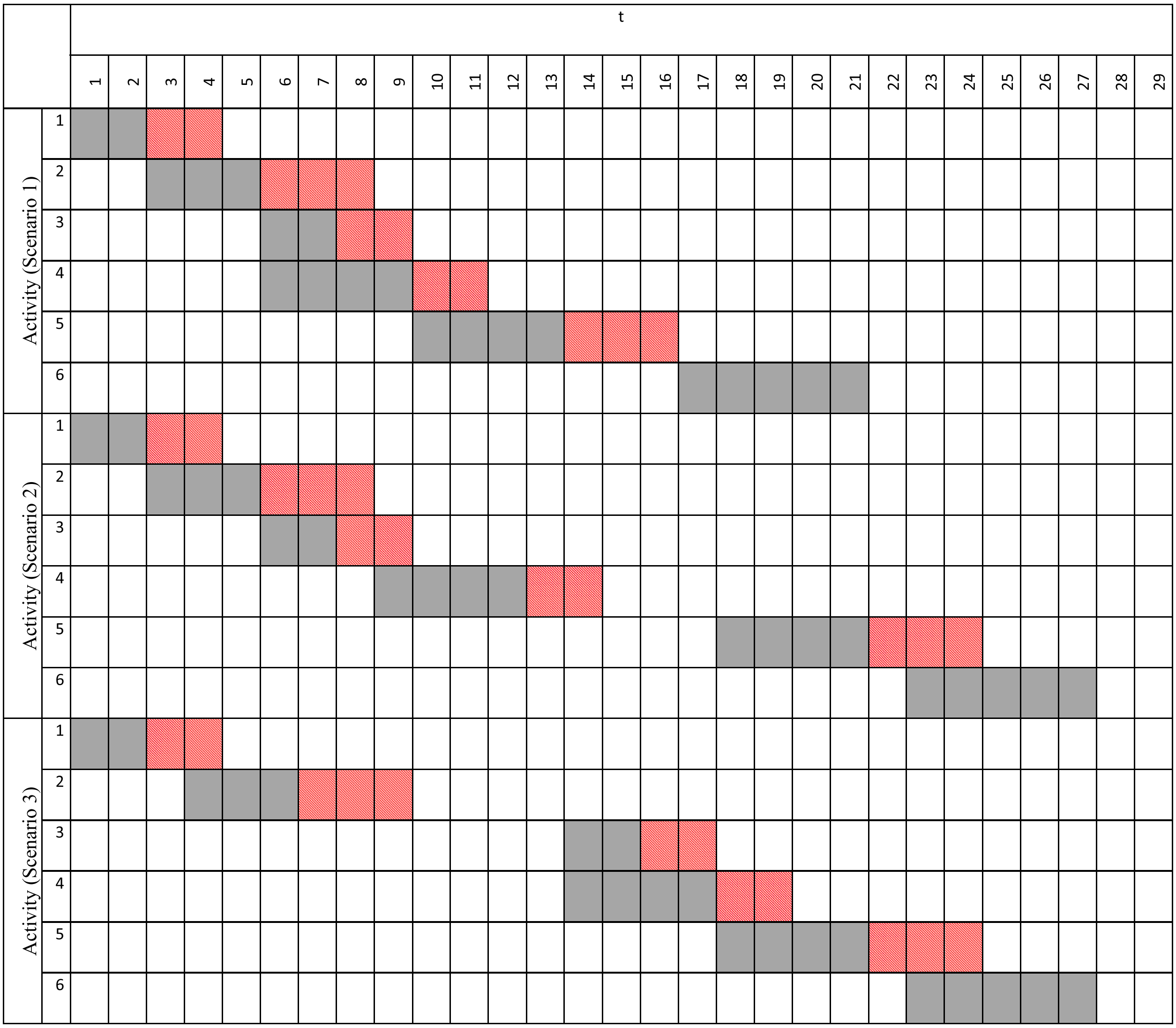

Table 8
Compression of activities in problem 2.

Activity	Compression limit	Real compression
1	2	1
2	3	2
3	2	1
4	2	0
5	3	1
6	4	0

4.2. Numerical results of the case study

This section presents the GAMS software solution and the numerical results of the model used in the execution of the case study. Table 2 shows the values of the model objective functions with the interest rate and the housing price increase rate considered for a weight of 0.2 for objective function 1 and 0.8 for objective function 2 under different scenarios mentioned in the previous section.

4.2.1. Scheduling

This section presents the variables related to the scheduling of activities/orders, shows the extent and amount of the compression of the project activities used in problem 1, in Table 3, and lists the earliest start time, the latest start time, and the floating of all activities in, respectively, Tables 4, 5 and 6 to optimally solve the problem with objective function 1. According to the optimal schedule in Table 7 obtained from solving the problem with objective function 1 in scenario 1, activity 1 starts in period 1 and ends in period 2 and is compressed by two units. Activity 2 starts in period 3 and ends in period 5 and is compressed by three units. Activities 3 and 4 begin in period 6 and are completed in periods 7 and 9, respectively, and each is compressed by two units. Activity 5 starts in period 10 and ends in period 13 and is compressed by 3 units; finally, activity 6 begins in period 17 and lacks compression because it lacks activities after that. Table 7 shows the schedule of activities in scenarios 2 and 3 with analyses similar to scenario 1. According to Table 3, all activities, except 6, have been compressed the highest to maximize the schedule flexibility. The effect of this action is visible in the floating of all the activities shown in Table 6, where the floating of activities has increased, and none is critical because the total

Table 9
Optimal schedule found for objective function 2 by solving the sample problem under scenarios 1, 2, 3, respectively. (Gray cell: Activity Duration Unit/ Red Crosshatch Cell: Compression Unit).

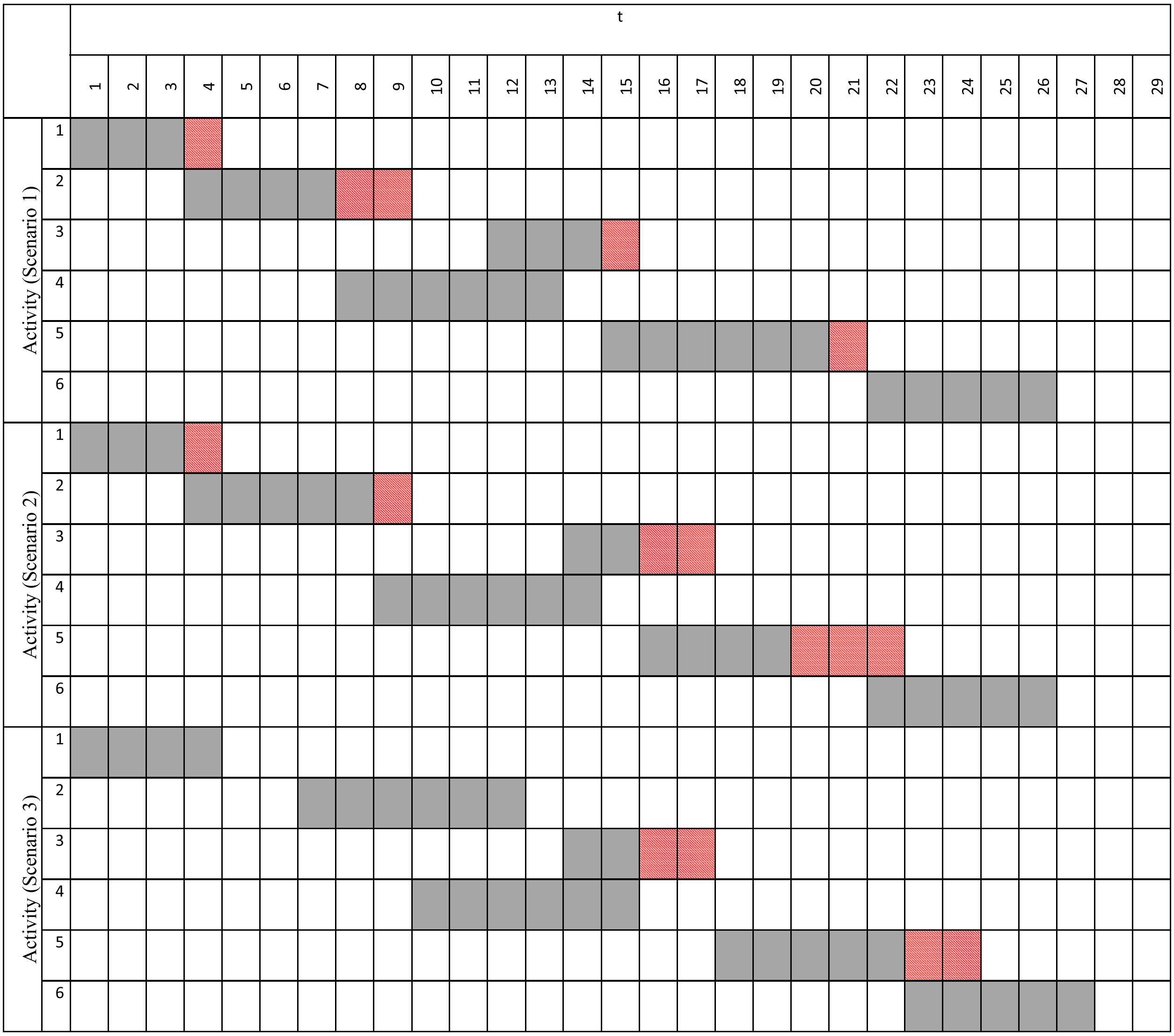

Table 10
Compression of activities in problem 3.

Activity	Compression limit	Real compression
1	2	0
2	3	0
3	2	0
4	2	1
5	3	2
6	4	4

Table 11
Earliest activity start time in problem 3.

Scenario Activity	1	2	3
1	1	1	1
2	5	4	5
3	11	10	11
4	11	10	11
5	16	16	17
6	21	20	21

floating of none is 0.

Table 8 shows the extent of compression of project activities along with the rate used in problem 2. According to the optimal schedule in Table 9 obtained from solving the problem with objective function 2 in scenario 1, activity 1 starts in period 1 and ends in period 3, and is compressed by one unit. Activity 2 starts in period 4 and ends in period 7 and is compressed by two units. Activity 3 begins in period 12, is completed in period 14, and is compressed by one unit. Activity 4 starts in period 8 and ends in period 13 with no compression. Activity 5 runs from period 15 to 20 and has 1 unit compression, and, finally, activity 6 starts in period 22 and ends in period 26 and lacks compression. Table 9 shows the schedule of activities in scenarios 2 and 3 with analyses similar to scenario 1. Table 8 shows that the compression level of the activities is lower than that in problem 1 because of the related costs, but some compressions have been applied for the rewards of early delivery.

Table 10 shows the extent of compression of project activities along with the rate used in problem 3, and Tables 11, 12, and 13 show,

Table 12
Latest activity start time in problem 3.

Scenario Activity	1	2	3
1	3	4	3
2	7	7	7
3	14	15	16
4	13	13	13
5	18	19	19
6	23	23	23

Table 13
Total floating of activities in problem 3.

Scenario Activity	1	2	3
1	2	3	2
2	2	3	2
3	3	5	5
4	2	3	2
5	2	3	2
6	2	3	2

respectively, the earliest start time, the latest start time, and the floating of all the activities for the optimal problem solution with objective function 3.

According to the optimal schedule in Table 14 obtained from solving the problem with objective function 3 in scenario 1, activity 1 starts in period 1 and ends in period 4, and is not compressed. Activity 2 starts in period 6 and ends in period 11 and has no compression. Activity 3 begins in period 14 and is completed in period 17 with no compression. Activity 4 starts in period 13 and ends in period 17 with one unit compression. Activity 5 runs from period 18 to 22 and has 2 units compression and, finally, activity 6 starts in period 23 and ends in the same period with 4 units compression.

Table 14 shows the schedule of activities in scenarios 2 and 3 with analyses similar to scenario 1. Table 13 shows that the floating of all the activities is lower than that in problem 1 due to the weight of objective function 1 (0.2) in problem 3.

Tables 15, 16, and 17 show the ordering time (P) for problems 1, 2, and 3, respectively, where the effects of uncertainty on the due date is also obvious. These tables show that the ordering times have been so selected that, under different scenarios for the material due date, the inventory needed for each activity is available before it starts.

In problem 3, the floating time for activities in question 3 is reduced since objective function 1 is given a smaller weight than it does in problem 1, resulting in a reduction in floating time from question 1 in question 3. As a result of this adjustment, other objectives are prioritized over maximizing floating time, thereby causing less activity compression as a result of this adjustment.

In problem 1, objective function 1 is highly prioritized, resulting in a maximum compression of activities, which in turn will result in additional flexibility and floating time being made available. According to Table 3, all compressible activities except activity 6 are fully compressed, leading to increased floating times across all the activities in the schedule, in accordance with Table 6.

On the other hand, when the weight is adjusted for problem 3, the focus shifts due to the change in weight. It is evident from Table 10 that compression levels for most activities are significantly lower than those for others, and some activities are not compressed at all. Due to this, a tighter schedule with less flexibility is created in the schedule, resulting in a reduction in the total floating time as shown in Table 13.

A vital component of achieving this outcome is the trade-off between achieving higher floating times and accommodating competing objectives at the same time. If the prioritization of scheduling flexibility is reduced, fewer activities can be compressed and scheduling constraints tightened, resulting in high floating times.

4.2.2. Cost and budget

This section studies the results found from the optimal model solution as regards the cost and budget. To this end, Table 18 shows the sales time of each unit under different scenarios for the problem with objective function 1.

It is worth mentioning that since profit is not explicitly stated in objective function 1, units are sold only to compensate for the deficit of the available budget in problem 1. In Fig. 4 which shows this budget, the effect of the unit sale on its increase is clear; for instance, in scenario 1, where units are sold in periods 10, 11, 12, and 14, the jump in the available budget is obvious.

Fig. 5 shows the total cost for problem 1 under different scenarios; coordination between the sale of units and the increase in the project costs is clear.

An interesting point in Table 19 which shows the sales times of the units under different scenarios for the problem with objective function 2, is that the units are sold later than the optimal solution of problem 1 due to the high increase rate of the housing price.

In Fig. 6, which shows the available budget for problem 2, the effect of the unit sale on its increase is evident; for instance, in all 3 scenarios, the jump in the available budget is noticeable when units are sold in period 20.

Fig. 7 shows the total cost for problem 2 under different scenarios; coordination between the sale of units and the increase in the project costs is explicit.

Table 20 shows the sales time of the units under different scenarios for the problem with objective function 3; the sale time in this problem is the middle state of problems 1 and 2.

Fig. 8 shows the available budget for problem 3, and the effect of the unit sale on its increase; for instance, in scenario 3, the jump in the available budget is obvious when units are sold in periods 12, 17, and 18.

Fig. 9 shows the total cost for problem 3 under different scenarios; coordination between the sale of units and the increase in the project costs is clear.

4.3. Sensitivity analysis

To analyze the model sensitivity to the interest rate, the problem was solved with monthly rates of 1.5, 2, 2.5, 3, and 3.5 %, the results of which are shown in Fig. 10. As shown, for rates more than 2 %, the expected discounted interest has a descending trend compared to the increase in the interest rate. Still, for 1.5 % interest per month, the expected discounted profit is less than the expected discounted profit for an interest rate of 2 %.

Next, the problem is solved again by changing the rate of the housing price increase variations to study the related effects on the presale time of the units. Table 21 shows the presale time of units under various scenarios with no increase in housing price. As shown, units are pre-sold at the beginning of the project because there is no reason to keep them in many cases unless under a budget deficit.

Table 22 shows the presale time of units under different scenarios with a 72 % increase in the housing price; as shown, the change is significant compared to the case with no increase, and units are generally pre-sold later. However, some units are sold under some scenarios in period 1 to compensate for the deficit of the available budget. Obviously, the late sale of units occurs due to the high increase in the housing price to earn more profit.

Effects of changes in the weighting of functions are shown in Fig. 11; in both graphs, the horizontal axis is the weight of objective function 1, and functions are ascending with respect to their weight, which is a logical behavior. The analysis in Fig. 11 demonstrates that changes in the weighting of objective functions can significantly impact project outcomes. When balancing schedule flexibility and project net profit,

Table 14
Optimal schedule found for objective function 3 by solving the sample problem under scenarios 1, 2, 3, respectively. (Gray cell: Activity Duration Unit/ Red Crosshatch Cell: Compression Unit).

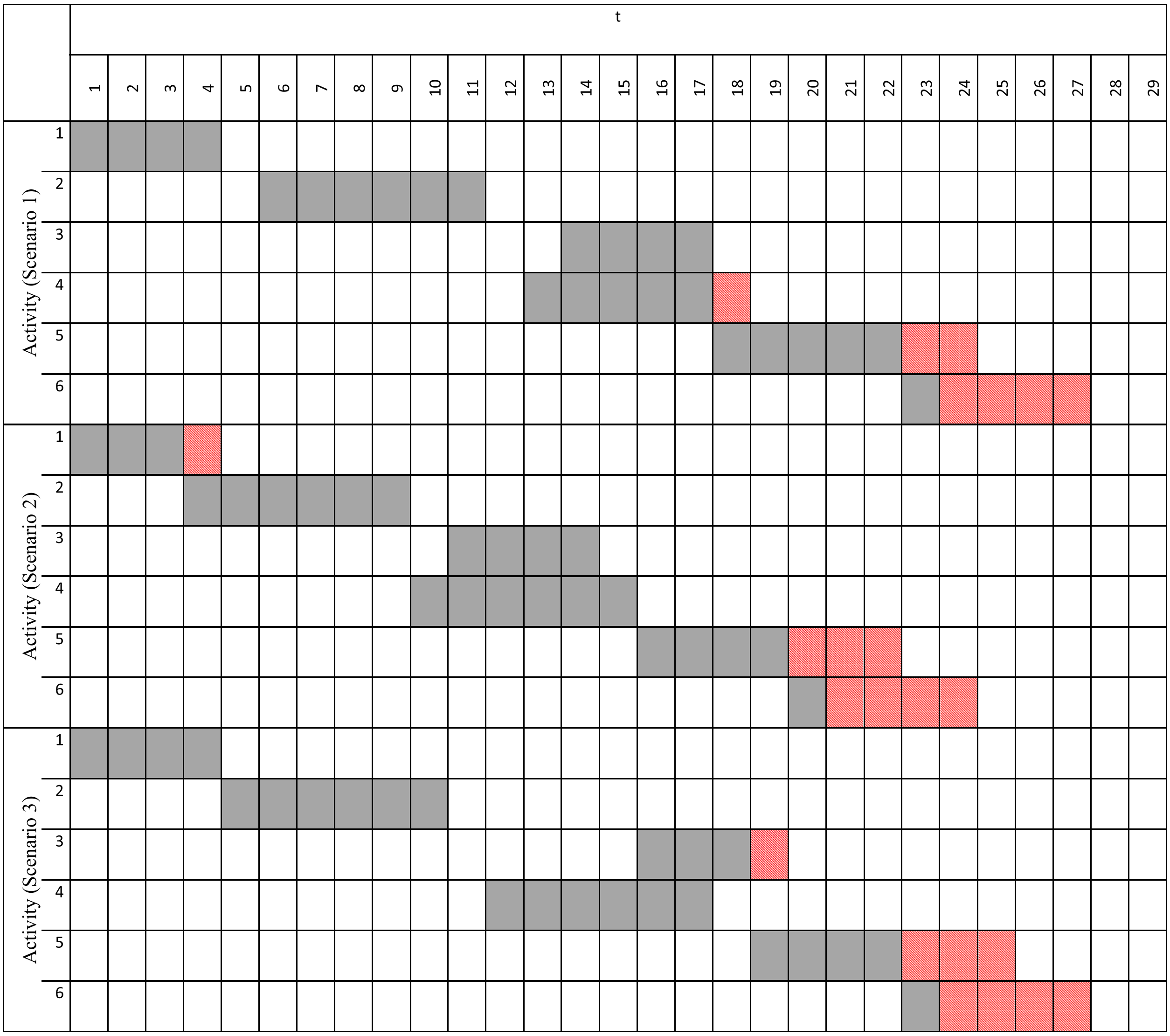

Table 15
Ordering time (P) for objective function 1.

Activity	Scenario	Due date	Supplier	Discount Interval	Ordering time
1	1	0	1	2	1
	2	0	1	2	1
	3	0	1	2	1
2	1	0	3	2	3
	2	1	3	2	3
	3	2	3	1	2
3	1	0	4	2	6
	2	1	4	2	5
	3	2	4	2	12
4	1	0	5	2	6
	2	1	5	2	8
	3	2	5	2	12
5	1	0	3	2	10
	2	1	3	2	14
	3	2	3	2	16
6	1	0	2	1	17
	2	1	1	2	22
	3	2	2	1	21

Table 16
Ordering time (P) for objective function 2.

Activity	Scenario	Due date	Supplier	Discount interval	Ordering time
1	1	0	1	2	1
	2	0	1	2	1
	3	0	1	2	1
2	1	0	2	2	4
	2	1	2	2	3
	3	2	2	2	5
3	1	0	4	2	12
	2	1	4	2	13
	3	2	4	2	12
4	1	0	5	2	8
	2	1	5	2	8
	3	2	5	2	8
5	1	0	2	2	15
	2	1	2	2	14
	3	2	2	2	16
6	1	0	2	1	22
	2	1	2	1	21
	3	2	2	1	21

Table 17
Ordering time (P) for objective function 3.

Activity	Scenario	Due date	Supplier	Discount interval	Ordering time
1	1	0	1	2	1
	2	0	1	2	1
	3	0	1	2	1
2	1	0	2	2	6
	2	1	2	2	3
	3	2	2	2	3
3	1	0	4	2	14
	2	1	4	2	10
	3	2	4	2	14
4	1	0	5	2	13
	2	1	5	2	9
	3	2	5	2	10
5	1	0	2	2	16
	2	1	2	2	13
	3	2	2	2	16
6	1	0	2	1	23
	2	1	2	1	19
	3	2	3	1	21

Table 18
Sale time of each unit in problem 1.

Scenario Activity	1	2	3
1	14	1	1
2	11	9	17
3	1	17	16
4	10	17	16
5	12	22	17

managers should carefully consider how different weights assigned to these functions influence the project's success. Managers should use this insight to tailor their decision-making based on the specific priorities and constraints of their projects, ensuring a balanced and optimized approach to project management.

Fig. 12 shows the Pareto diagram for the desired bi-objective problem; the functions have descending behavior towards each other. As both are of the maximization type, the descending behavior is a sign of a conflict between them. By understanding this conflict managers can make informed decisions to achieve the desired trade-off between schedule flexibility and financial gains in project management.

Fig. 13 shows the effects of the early-completion reward factor on the project duration in various scenarios; the project length, in all 3 scenarios, decreases when this reward increases. This increase compensates for the project compression costs; hence, the model compresses the activities and reduces project completion time. Utilizing an early-completion reward system can significantly reduce project durations. The cost of implementing such incentives is outweighed by the gains in efficiency and the reduction in project completion time. This approach can be a strategic tool to enhance project performance and meet tight timelines while managing expenses effectively.

This research has considered three major factors as innovation: 1) activity compression (cost-time trade-off), 2) activity floating, and 3) probability for the due time of consumables. A summary of the effects of these factors on the model solutions is as follows:

4.3.1. *Effects of considering activity compression (cost-time trade-off)*

Table 3 shows that in solving the single-objective problem that maximizes the schedule flexibility, all activities, except 6, have been compressed the highest to maximize the schedule flexibility. The effect of this action is visible in the floating of all the activities shown in Table 6, where the floating of activities has increased, and none is critical because the total floating of none is 0. The reason is that when increasing the "schedule flexibility" is the only problem objective, no cost is considered for compressing the activities, but when the problem objective is profit maximization (with an inverse relationship with cost), the activity compression level (Table 8) is lower than that in problem 1 due to the application of the compression costs; of course, some compressions are for earning early completion rewards.

4.3.2. *Effects of considering activity floating*

Since the compression and floating of activities are aligned, as mentioned earlier, effects of increasing compression can be observed in floating, e.g., in Table 6, where using compression increases floating, and no activity is critical because the total floating of none is 0.

4.3.3. *Effect of considering probability for the due time of consumables*

Tables 15, 16, and 17 show the ordering time (P) for problems 1, 2, and 3, respectively, where the effects of uncertainty on the due date are also apparent. These tables show that the ordering times have been so selected that, under different scenarios for the material due date, the inventory needed for each activity is available before it starts.

5. Summary, conclusions, and suggestions for future studies

As stated before, since integration-related issues have become popular in recent years in various fields due to the need for more science-industry communication and making the scientific conditions similar to the real world, "project management" is an area that has become quite popular due to the growth of project-oriented organizations and the increasing number of projects in various fields.

To this end, the mathematical model used in this study has objective functions that maximize the profit as well as the flexibility of the project schedule. Since, in real conditions, the interest rate affects the determination of the time value of money, the proposed mathematical model

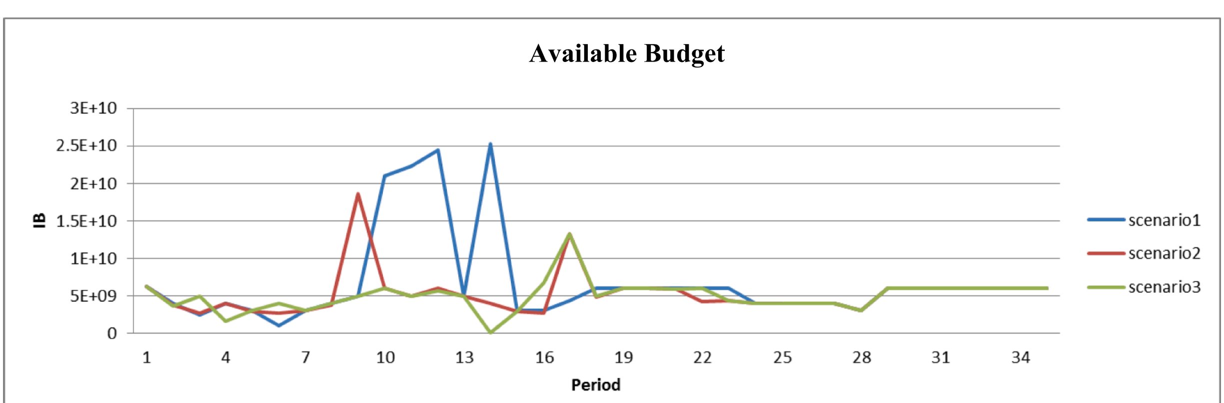

Fig. 4. Available budget for problem 1.

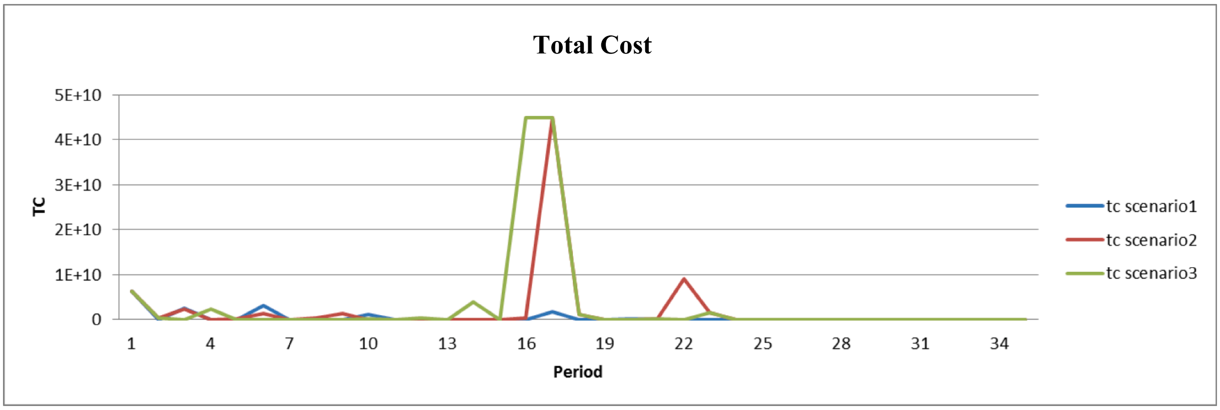

Fig. 5. Total cost for problem 1.

Table 19
Sale time of units in problem 2.

Scenario Activity	1	2	3
1	1	15	1
2	20	1	20
3	20	20	20
4	20	15	20
5	20	20	20

Table 20
Sale time of units in problem 3.

Scenario Activity	1	2	3
1	17	15	1
2	16	1	12
3	17	15	18
4	1	14	17
5	16	14	18

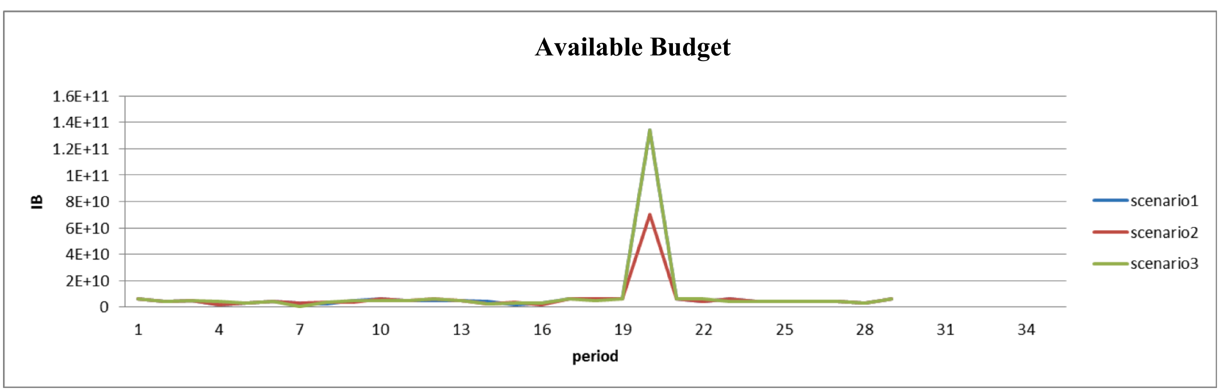

Fig. 6. Available budget for problem 2.

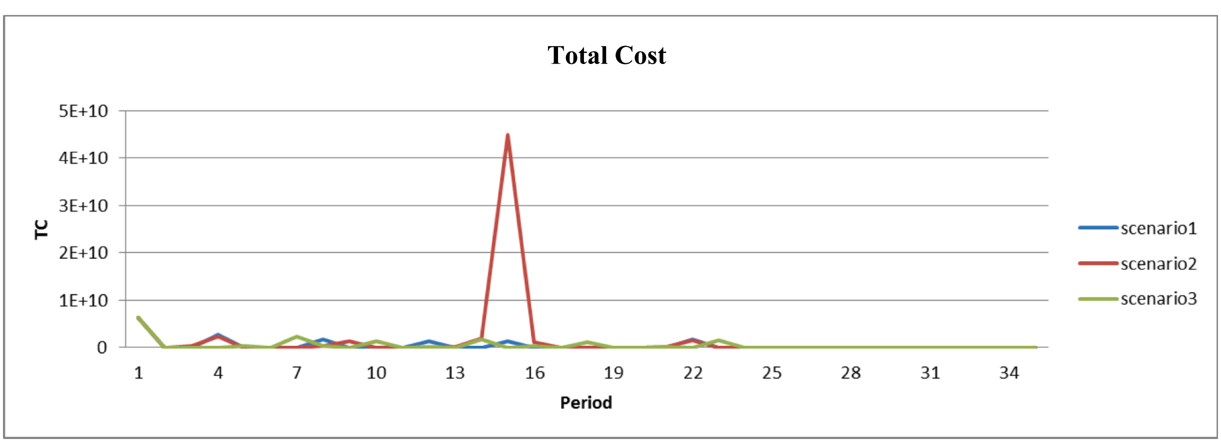

Fig. 7. Total cost for problem 2.

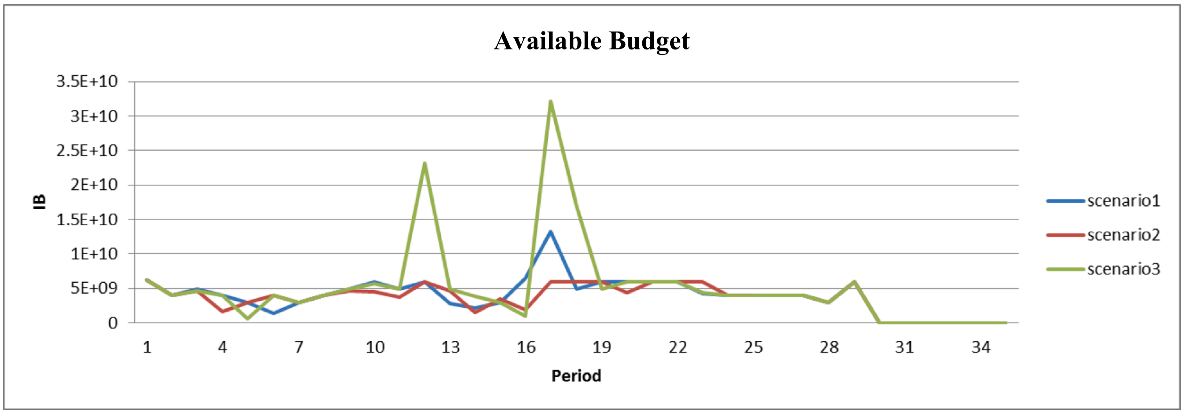

Fig. 8. Available budget for problem 3.

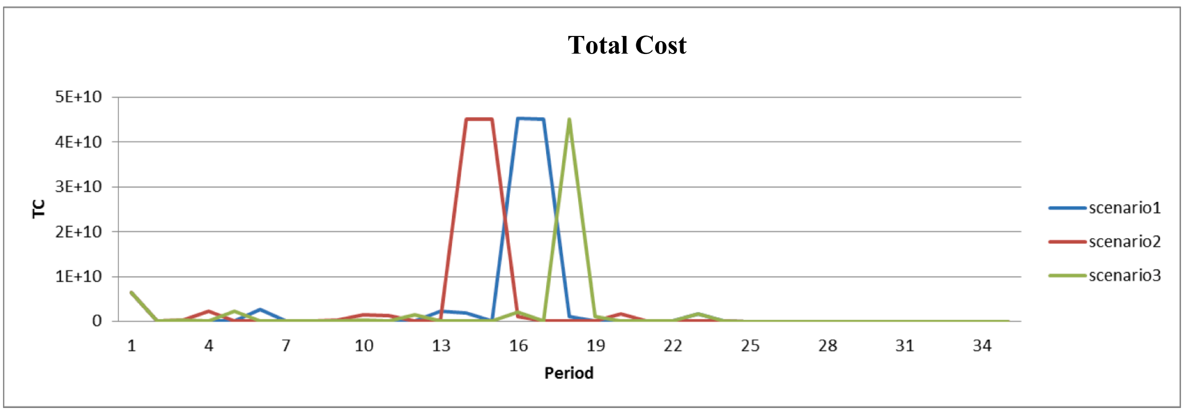

Fig. 9. Total cost for problem 3.

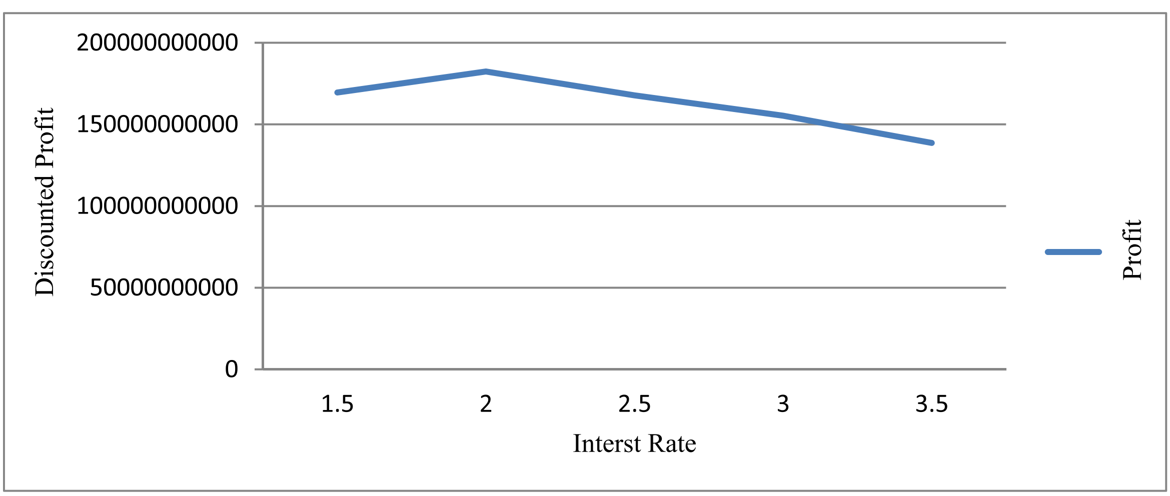

Fig. 10. Sensitivity of the expected discounted profit to the interest rate variations.

considers the effects of the interest rate as well as the rate of the housing price increase in calculating the income and costs to comply with the real conditions. This model also addresses the issue of the time-cost trade-off under the "time compression of activities" title so that compression helps, as much as possible, the project due date not to change or even finish earlier than scheduled. To prevent the due date from postponing, different scenarios use two modes to solve the model: 1) order as early as possible, which increases the maintenance cost, and 2) compress activities to compensate for the delay, which increases the total cost, but the objective functions select the best compression combinations. The mathematical modeling was aimed to 1) maximize the project schedule flexibility for the highest stability against unexpected/sudden events and 2) maximize the project profit by considering the difference between income (employer payments, product sales, and daily bank-account interest) and costs (logistics and compressing time of activities) to reach the agreed due date; the time value of money was also considered to adapt to the real world conditions.

The due date was examined under optimistic, probable, and

Table 21
Presale time of units under different scenarios, with no increase in the housing price.

Scenario Activity	1	2	3
1	1	2	1
2	2	1	1
3	2	2	1
4	2	2	1
5	2	2	1

Table 22
Presale time of units under different scenarios, with a 72 % increase in the housing price.

Scenario Activity	1	2	3
1	17	15	1
2	16	1	12
3	17	15	18
4	1	14	17
5	16	14	18

pessimistic modes so that the results can be checked in different situations. Modeling was done once to make its results comparable with the case, where it was examined scenario-oriented. After finalizing the model and ensuring its correctness, it was solved with real data from a case study related to a commercial-administrative project carried out in the International Construction and Industry Company in Tehran, and the calculation results regarding its performance and implementation were assessed to determine its practical efficiency. The data needed to solve the model were tried to be as real as possible to help investigations be close to the real conditions and the suggestions be applicable in practical projects. For practical analyses, the model results were considered, comparatively, in different scenarios proposed for the material delivery time in three optimistic, probable, and pessimistic cases so as to see how material delivery delays affected the implementation of activities. Next, the scheduling problem of the desired project was solved under three scenarios, and the optimal solution was examined in each scenario. Then, sensitivity analyses were performed by coordinating the problem components (costs, budgeting, scheduling, compression, and ordering), different possible cases were compared, and results were presented. The following suggestions can be considered as research opportunities to develop the model proposed in this research:

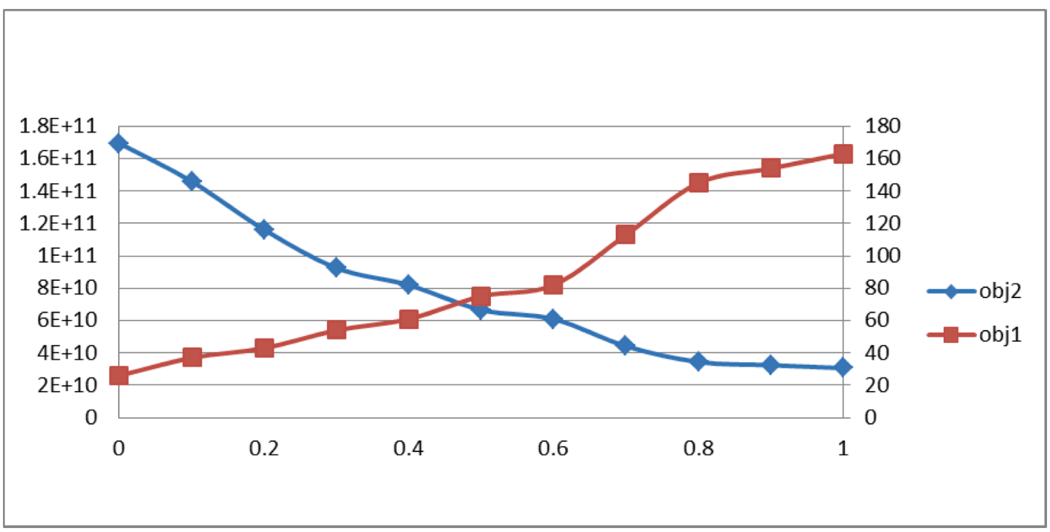

Fig. 11. Changes in the values of the objective functions relative to weighting.

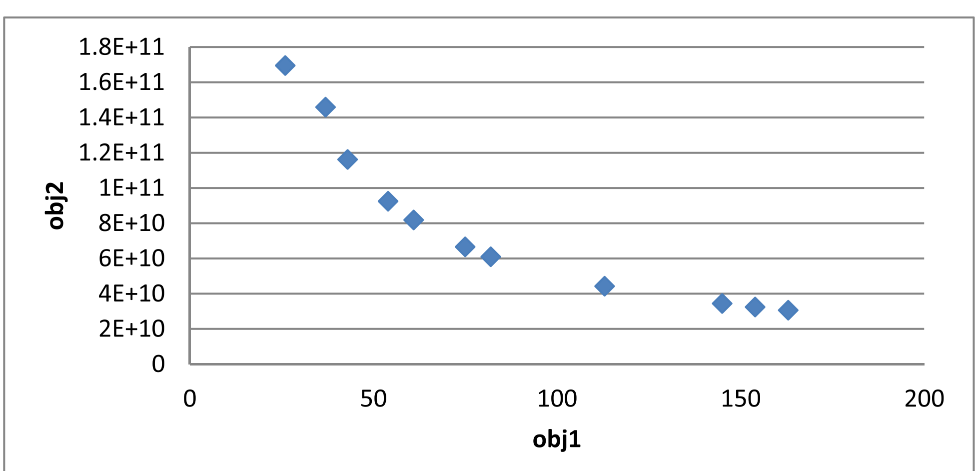

Fig. 12. Pareto diagram for the desired bi-objective problem.

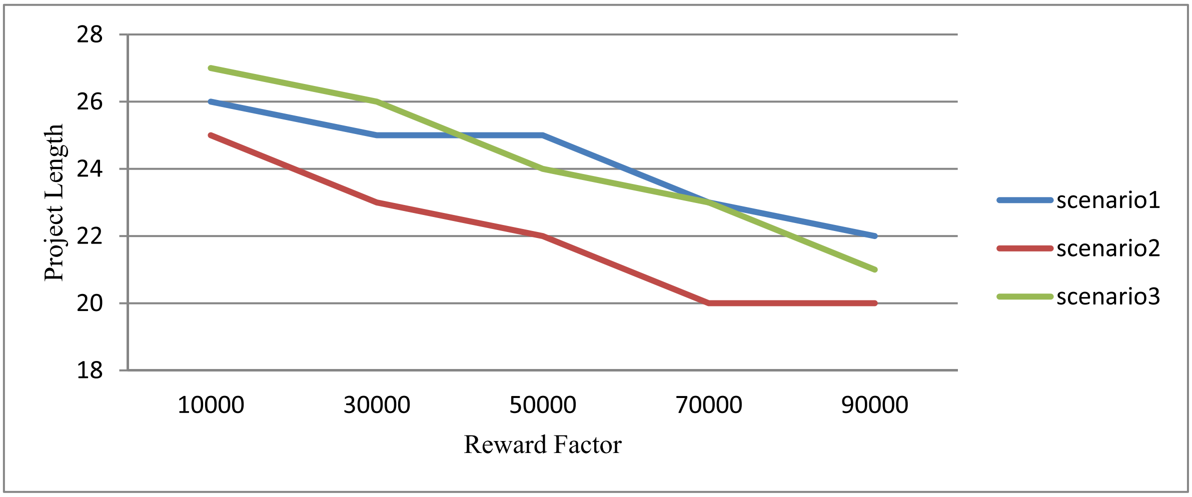

Fig. 13. Effects of early-completion reward factor on the project length.

- Considering the uncertain demand for project activities.
- Considering uncertain implementation time for project activities.
- Considering interest and inflation rates as functions of time.
- Using non-deterministic scheduling methods such as PERT and GERT.
- Using metaheuristic methods to solve the problem in a shorter time or with larger dimensions, considering the complexity of the proposed model and its solution time.
- Considering all of the sustainability dimensions (economic, environmental, and social).
- Considering upper bound for emissions and lower bound for local communities' job opportunities.

Ethical approval

This is a theoretical/applicable study. The Amirkabir University of Technology Research Ethics Committee has confirmed that no ethical approval is required.

Consent to participate

Not applicable.

Consent to Publish

Not applicable.

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CRediT authorship contribution statement

Mohammad Amin Edalatpour: Software, Investigation, Formal analysis, Data curation, Writing – review & editing. **Seyed Mohammad Javad Mirzapour Al-e-Hashem:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Sahar Ghasemi:** Data curation, Formal analysis, Software, Writing – original draft, Investigation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial, non-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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