**A Novel Time, Cost, Quality and Risk Tradeoff Model with a Knowledge-based Hesitant Fuzzy Information: An R&D project application**

**Abstract**

This paper proposes a novel approach for identifying the best implementation situation for each activity in a project by optimizing and balancing time, cost, quality, and risk criteria under uncertain circumstances. A hesitant fuzzy linguistic term sets (HFLTs) approach is proposed to determine the status of project activities in the presence of quality and risk criteria alongside their time and cost. Afterwards, a multi-objective linear programming (MOLP) model is formulated for a time, cost, quality, and risk tradeoff (TCQRT). To validate the model, a research and development project in the food industry was investigated. The results indicate that the project’s time compared to the deterministic approach was reduced by 20%. Completing the R&D project earlier than other competitors bring higher profit than tradeoff expenses, even without considering the quality and risk tradeoff benefits of the proposed approach. Considering uncertainty in risk and quality of activities via HFLTs and also optimizing all four elements of time, cost, quality, and risk simultaneously in a project are the main values of this research. The proposed approach can be employed by managers to adopt and optimize project planning and scheduling while trading off TCQR in uncertain circumstances.

**Keywords.** Multi-Criteria Decision Making, Time, Cost, Quality and Risk tradeoff (TCQRT), Multi-objective linear program (MOLP), Hesitant Fuzzy Linguistic Term Set (HFLTs), Project Management.

1. **Introduction**

In unstable circumstances and business environments, alongside fierce competition, agile organizations are better positioned to succeed in the global market. One of the main issues in leading and surviving in global markets is new product development via research and development (R&D) projects to meet customer requirements (Mokhtarzadeh et al., 2020; 2021). To do so, R&D managers prompt to accomplish their projects as soon as possible while considering other dimensions of project management that include cost, quality, and risk (Barbosa et al., 2020).

Project management is the use of knowledge, skills, tools, and techniques concerning various activities that have been developed to meet the main objectives of a project (Project Management Institute, 2017). Project managers aim at finishing their projects in the shortest time and at the lowest cost with the maximum possible quality so that they can minimize the negative risks inherent in projects. In the 1990s, project planning researchers realized that the successful implementation of a project was not an effective option without considering the quality dimension. For this reason, quality has been added to the problem of time and cost trade-off in modeling (Ebrahimnezhad et al, 2013). Meanwhile, the impact of risk on different project objectives concerning the cost index can hinder project goals at a particular time, whereas some of the effects of risk may not be costly at a time, but in the long run, have significant consequences for the company (Rudnik & Deptula, 2015; Shrivastava & Rathod, 2016).

Project planning often reduces the amount of funding and costs involved in reducing the time it takes to carry out activities. One of the methods used to schedule a project is the trade-off method. The objective of this method is to determine the optimal amount of time and cost that should be allocated to project activities to minimize the total cost and the time it takes to complete a project (Jebaseeli & Dhayabaran, 2015; El-Kolany & Abdelsalam, 2017). Classic trade-off problems assumed that the time and cost of performing the activity can be estimated with a high degree of certainty, and perform any activity at a specified time with specific resources (Morin et al, 2017; Gerhards et al, 2017; Moghaddam, 2020). Nonetheless, during the time, project managers recognized that time, cost, quality, and risk (TCQR) factors are difficult to be predetermined with high accuracy. Accordingly, uncertain approaches such as grey and fuzzy are employed in this matter (Juenet & Orm, 2020).

The first major idea of ​​fuzzy logic was introduced in the 1960s (Mahdiraji et al., 2020). Zadeh (1965) introduced the fuzzy set theory to express the uncertainty of human thoughts in modeling. In this set, each member has a relative membership degree, and the integrity of each sentence and phrase can be indicated. Since then, some scholars have believed that the assignment of a degree of unit membership to an element, regardless of "hesitant" decision-makers, is the limitation of fuzzy sets (Hosseinzadeh et al., 2020). The most important role of the fuzzy set theory is its ability to provide unspecified or obscure information. The hesitant fuzzy sets (HFs), as well as the hesitant fuzzy linguistic term set (HFLTs), are two tools for displaying obscure and uncertain formation. Compared to fuzzy linguistic approaches, HFLTs are to reflect preferences in decision-making more properly and flexibly. HFLTs are defined as a subset of a limited sequence of sequential linguistic terms (Wei et al, 2020).

To the best of our knowledge, little research has been conducted on uncertain time, cost, quality, and risk tradeoff models. Relevant articles mainly focus on time-cost tradeoff (TCT) (Elkalle et al., 2020), and time-cost-quality tradeoff (TCQT) (Mahmoudi et al., 2020). Considering all four aspects of time, cost, quality, and risk in project planning have not been considered frequently by scholars. Furthermore, the majority of available researches in TCT or TCQT problems employ deterministic, interval, fuzzy, and interval fuzzy approaches in project planning. Considering the limitations of classic fuzzy sets, new uncertainty approaches need to be developed in the time, cost, quality, and risk trade-off (TCQRT) field (Hashemi et al., 2021). To overcome these two gaps from the literature, this paper contributes by proposing a novel multi-objective TCQRT model based on HFLTs. To consider the uncertainty in the proposed model and to make the results more practical and realistic, hesitant fuzzy information has been employed to provide a more adaptable and flexible approach for project managers in their planning affairs to reduce project time; while, optimizing the cost, quality, and risk, simultaneously. The model was implemented in a project executed in a food company in the emerging economy of Iran. The model can be applied in various industrial settings.

The paper is structured in the following order. Section 2 presents relevant concepts and a literature review on the selected plan focusing on tradeoff models and hesitant fuzzy sets. Section 3 describes the research methodology and the proposed model as well as its solving approach. Section 4 implements the proposed approach using a case study in the food industry. Finally, Section 5 discusses the research findings, limitations, and future potential research directions.

1. **Literature Review**
   1. **Fuzzy Set Theory and HFLTs**

Fuzzy set theory attempts to create closeness between classical mathematical precision and the general ambiguity of linguistic real-life variables. In a classical set, each member can have a membership value equal to 0 or 1, whereas in a fuzzy set the membership function is continuous in the range of 0 to 1. The first major idea of ​​fuzzy logic was presented by Zadeh in 1965. He introduced the fuzzy sets theory to express the uncertainty of human thoughts in modeling. In short, the fuzzy logic approach mimics the human decision-making method, in which, all possible states are considered between digital values​​ of ‘yes’ and ‘no’. The fuzzy logic inventor stated that, unlike computers, the decision-making process in humans involves possible ranges of states between ‘yes’ and ‘no’, as in (Razavi et al., 2018). In other words:

|  |  |
| --- | --- |
|  | (1) |

In this case, a membership function is a real number (). The partial value of the membership function is called the degree of membership, which shows the extent of membership of an element in a set. Therefore, the fuzzy set *A* in the universal space *U* could be represented as regular pairs of *X,* and its membership function u(x) can be shown in the following manner.

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|  | (2) |

The general form for the definition of a fuzzy set is as shown in the following equation.

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|  | (3) |

Since the initial presentation of fuzzy numbers, many scholars have focused on developing fuzzy numbers and trying to overcome the drawbacks of initial fuzzy values. Interval-valued fuzzy (IVF), intuitionistic fuzzy sets (IFS), interval-valued intuitionistic fuzzy (IVIF), intuitionistic fuzzy preferences relation (IFPR), hesitant fuzzy preferences relation (HFPR), and hesitant fuzzy linguistic terms sets (HFLTs) are some pertinent terms that were designed to increase the level of uncertainty and transfer the initial fuzzy numbers to more realistic values. In this research, because no previous researches have been conducted on the TCQR tradeoff model with these new approaches, a novel method is presented through HFLTs to optimize time, cost, quality, and risk simultaneously. Quality and risk are uncertain and judgmental factors that could be considered by HFLTs values.

Let’s suppose *S*= {S0, …, Sg} is a linguistic term set. Then, a HFLTs, hs, is defined as an ordered finite subset of consecutive linguistic terms of *S*. For instance, *S* can be defined as *S*= {S0 = none, S1 = very low, S2 =low, S3 =medium, S4 = high, S5 =very high, S6 =perfect}. Then, the HFLTs can be defined as , meaning medium to very high.

The decisions made through HFLTs will be represented as that represents the judgment of the kth decision-maker on the performance of ith alternatives regarding the jth criterion. A decision-maker might believe that the activity Ai related to criterion Cj is medium (). Meanwhile, another decision-maker may evaluate the performance of that activity in association with the same criterion as “very low to medium” (). If they can convince each other, a single linguistic term set will be obtained. Otherwise, their general evaluations could be shown as a combined set of experts’ opinions, namely ( Liao et al, 2014).

The approaches to describe linguistic descriptors include custom structure and text-less grammar (Rodriguez et al, 2021). The coefficient performance of HFLTs for ranking the hesitant fuzzy linguistic sets has been developed by a score function (Liao et al., 2020). Consider that we have being defined on the linguistic term set . The score function s(hσ) is calculated by Eq. (4).

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| --- | --- |
|  | (4) |

Besides, a definition for the variance function hσ is designed and proposed as follows (Liang et al, 2016).

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| --- | --- |
|  | (5) |

Note that (L)2, is calculated as follows.

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| --- | --- |
|  | (6) |

The logic behind this combination is based on negotiation, consensus, and convincing and it does not take any specific decision-maker into account (Farhadnia, 2015). Linguistic variables are values, not numbers, but words or sentences of natural or artificial terms. The use of a linguistic variable is a realistic approach that is closer to human knowledge (Mahdiraji et al., 2020). Usually, a hesitant fuzzy set is applied in quantitative situations while sometimes uncertainty arises from the ambiguity of qualitative meaning, rather than quantitative criteria (Liao et al, 2014). A group of researchers examined some issues related to HFs and construed the notion of fuzzy linguistic terminology for decision-making, in which they can express their preferences using comparative phrases between "very low and moderate" (Liu et al., 2020). Like the hesitant fuzzy set concept, HFLTs are used when the experts doubt using what term to evaluate a linguistic variable (Krishankumar et al., 2021). The researchers stated that in the fuzzy linguistic approach, the main point is that a linguistic variable should be evaluated with a single-linguistic term, whereas the fuzzy linguistic term set approach uses several terms to decide and evaluate a linguistic variable (Rodriguez et al, 2021). Deciding via linguistic features based on HFLTs using a pessimistic and optimistic decision-making approach has also been proposed (Chen & Hong, 2014).

* 1. **Time, Cost, Quality and Risk (TCQR) trade-off**

Time, cost, and quality dimensions, called the iron triangle, are the three most prominent and accepted criteria to measure the success of a project (Atkinson, 1999). According to Rasmy and Abdelsalam (2008), three main points are the most important factors for a successful project: (1) meeting customer requirements, (2) being completed within budget, and (3) being completed on time. On the other hand, projects are exposed to different risks (Lock, 2007). Therefore, risk is also considered a crucial aspect of project management (Söderlund, 2004; Willumsen et al. 2019). Therefore, these four factors are commonly considered in trade-off problems.

The expansion of mathematical models to balance the four factors of time, cost, quality, and risk when the parameters of any activity are not determined has been extensively considered. Different applications of decision-making methods are studied in project planning (Taghipour et al., 2020). As a case in point, a fuzzy analytical hierarchical process (FAHP) or linear fuzzy programming model with multi-objective functions could be addressed in this regard (Sanowar Hossain et al, 2016; Elkalle et al., 2020). Project planning in the form of grey numbers or a combination of fuzzy ideal and linear grey planning has been also considered (Amoozad Mahdiraji et al, 2016; Hashemi et al., 2021). A framework for successful project management with acceptable time, low cost, and highest quality using integer programming or other mathematical modeling techniques have also been studied and developed by scholars (Razavi Hajiagha et al, 2015; Khalili-Damghani et al, 2015; Khameneh et al, 2016).

Many scholars have focused on the risk management of projects using optimization and uncertainty models since failure to pay attention to project risks reduces the probability of projects’ success (Subbotin et al., 2017; Mahmoudi & Feylizadeh, 2018; Tran & Long, 2019). Furthermore, mixed integer programming (MIP), linear programming (LP), and strength, weakness, opportunity, threat matrix (SWOT) have been employed to optimize the trade-offs among TCQR factors, and in some cases, heuristic and meta-heuristic approaches were applied to solve these models (Mohammadipour & Sadjadi, 2016; He et al, 2016; Rolik, 2017; Zuo & Zhang, 2018). Some qualitative approaches have also considered risks, barriers, and failures of projects (Desanctis et al, 2018). Nonetheless, considering all devils rectangle factors in project management (TCQR) by hesitant information has not been previously analyzed.

Qualitative and hesitant information is common in the practical decision-making process. In complex decision-making problems, experts use comparative terms to express their opinions. Hesitant fuzzy linguistic term sets are a powerful tool for displaying and expressing comparative expressions. Some researchers focused on priority relationships, hesitant fuzzy linguistic terms as a new preferential structure and expanded their applications to multi-criteria decision-making (Wei et al., 2020; Zhang et al., 2021). The extension of decision-making models combined with HFLTs information has been considered by various researchers (Razavi Hajiagha et al, 2018; Ozkan et al., 2020). To the best knowledge of the authors, the application of HFLTs information has not been observed in project control and tradeoff models previously. Accordingly, we decided to employ this new uncertain approach to TCQR tradeoff problems, contributing in this way to the novelty offered by the present research. Previous researches applied other kinds of uncertainty in their tradeoff models.

In the following table, some pertinent researchers are presented. Note that *T, C, Q, R* in the third column are the symbols of Time, Cost, Quality, and Risk, respectively. In the fourth column, *F* is for Fuzzy, *G/I* for Grey or Interval, *D* for deterministic, and *S* for stratified data.

**Please insert Table 1**

As seen in Table 1, few pieces of research have considered time, cost, quality, and risk factors simultaneously (Amoozad Mahdiraji et al. 2016; Mahmoudi & Feylizadeh, 2018; Hosseinzadeh et al. 2020). Moreover, while most of the studies have considered deterministic information in their modeling approach, the prominent uncertainty approach being used in trade-off problems has been fuzzy sets theory while some have been formulated using grey or interval information. However, none of the previous studies has addressed TCQRT problems in the project management era using other newly extended uncertainty approaches, e.g. hesitant fuzzy or intuitionistic fuzzy. This research proposes a novel approach to deal with a combination of HFLTS information and TCQR tradeoff models. Hence, the problem addressed in this paper is examined for the first time. To demonstrate the usefulness of the proposed model and solving approach, a real-world case study from an R&D project in the food industry has been considered.

1. **Research Methodology**

For a considered project network, and for designing a TCQR model, a multi-objective mathematical model was formulated and solved. The research general framework is illustrated in Figure 1.

**Please insert Figure 1**

The proposed methodology deals with determining the optimal combination of activities’ TCOR. To achieve this aim, in the first step, variables and different objective functions intended for the project were determined. Next, a questionnaire was designed by following the brainstorming approach, to gather the required information to assess the risk and quality of each activity. Subsequently, a group of experts who are familiar with project management was formed to judge the project activities’ quality and risk. It is supposed that when considering HFLTs flexibility and advantages in expressing human thought, experts used HFLTs to express their judgments regarding the activities. Subsequently, each linguistic term was converted to numerical values to represent the quality and risk of each activity. The time and cost of each activity in a specific project are expected to be predetermined by the project management team.

Next, a multi-objective mathematical model was designed by considering TCQR through equations (7) to (12), alongside score and variance functions of quality and risk. Afterwards, the score function and the variance function of each activity were calculated using equations (4) to (6). Then, a normalized goal programming method was proposed to balance the TCQR of the designed model by employing equations (13) to (18). By solving the MOLP model in the final step via model (19), the optimal time for each activity emanated while trading objectives of time, cost, quality, and risk-based upon HFLTs information.

* 1. **Notations**

Table 2 presents the variables and parameters of the proposed model. Besides symbol and definition, type (*V* for variable and *P* for the parameter) and description of each symbol are denoted. The cost, quality, and risk slopes were extracted from Amoozad Mahdiraji et al (2016).

**Please insert Table 2**

* 1. **Model formulation**

In the present study, mathematical modeling was employed while the following case study was conducted to test the proposed approach. A project can be defined as a graph where *K* is the set of nodes and *A* is the set of edges. In the considered framework, the project consists of *n* activities and *m* events. Here, denotes a group of events and refers to a set of activities (Razavi et al, 2015). In this study, each project activity is shown as and it is represented in two modes, including normal mode (1) and compact mode (2) (Mahdiraji et al., 2016). For a given project network, and for designing a TCQR model, a multi-objective mathematical model was designed. In this regard, the objective functions and related constraints are described as follows.

The objective function includes minimization of cost, time, and risk, and maximization of quality. One of the goals is the minimization of the total additional cost. The other goal is minimizing the time required to complete activities that contribute to the reduction of the total duration of the project. This causes the additional cost of activities, which is against the first goal of the problem. If the time and cost of the problem for each activity are shown under normal and crashed conditions relatively, the first factor of the cost function is modeled as follows. (Razavi et al, 2015).

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|  | (7) |

As mentioned above, cost minimization is another goal of the study, which is followed by time minimization. Thus, if (xn)refers to the time of the last node of the project and (x1)is the time of the first node, the following expression is used for minimization of the total time of the project (Lotfi et al., 2020).

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|  | (8) |

To establish quality trade-offs and minimize quality loss, the third objective function is used. In case an activity is performed within the normal completion time, it results in higher quality than crash time due to each activity exerts a different effect on the quality requirements of the whole project. This is why the quality slope of each activity was taken into account for further investigation (Mohammadipour & Sadjadi, 2016; Amoozad Mahdiraji et al, 2016). The maximum quality of the project’s activities is presented as follows.

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|  | (9) |

Where the activities quality performance is determined based on HFLTs. The goal of the fourth factor is the minimization of the risk of activities that arise from the time reduction. It is possible to estimate the probability of a risk and its effects. The reduced value of risk in the whole project is determined through the following equation (Hosseinzadeh et al., 2020).

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| --- | --- |
|  | (10) |

In Eq. (10), the activities risk values are also determined by project management experts based on HFLTs.

Equations (7) to (10) were modeled to consider time-cost, time-quality, or time-risk relationships. Each linear function could be put in a similar equation. The reduced time of activity might contribute to higher cost and risk and change of quality. In this study, multiple linear programming goals were suggested to determine the activity time. The goals should simultaneously tolerate minimum cost and risk as well as the maximum quality. Alongside the objective functions, the first constraint is defined in terms of the start and end of activities. It is supposed that activity *ij* starts at the time (xi) and it is implemented during (Xij) and finishes at the time (xj). Therefore, the following expression should be applied to each activity (Razavi et al, 2015).

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| --- | --- |
|  | (11) |

The second and third constraints are concerned with the real duration of the activity (Xij). If the real duration of the activity *ij* is represented by Xij, the following two definitions should apply for intended activities (Razavi et al, 2015).

|  |  |
| --- | --- |
|  | (12) |

If decision-makers express their opinions as a set of hesitant fuzzy linguistic terms, transferring the terms into numerical values in the score function and variance function table is achieved through equations (4) to (6) for the quality and risk objective functions. Taken together, the equations (7) to (12) of the final model are presented as follows. Overall cost and project time objective functions (G1 and G2) have been normalized (Mahdiraji et al., 2020) due to different values of time, cost, quality, and risk and presented as equations (13) and (14).

|  |  |
| --- | --- |
|  | (13) |
|  | (14) |

Note that, four objective functions are considered, two of them (risk and quality) include HFLTs values. For these two, one score and one variance function are calculated separately upon the expert’s opinion by equations (4) to (6). Accordingly, four objective functions emanated. (1) Objective function for maximizing score function values of quality, (2) objective function for minimizing score function values of risk, (3) objective function for minimizing variance function values of quality, and (4) objective function for minimizing variance function values of risk. These four objective functions are presented as Eqs. (15) to (18), respectively. Note that, due to different units of measurement of time, cost, quality, and risk, the normalization of the objective function was considered and employed.

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| --- | --- |
|  | (15) |
|  | (16) |
|  | (17) |
|  | (18) |

Except for the third goal, the other objectives should be minimized. In this regard, a goal programming approach was applied (Hamta et al., 2021). First, each objective function mentioned from (13) to (18) subject to (11) and (12) were solved separately and the G1\* to G6\* values were emanated. Afterwards, a goal programming model was designed to minimize TCR and Maximize Q as presented in (19).

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| (19) |  |
| S.t: |
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In model (19), ; ; ; and are feasibility constraints (FC), indicating that the final optimal time of each activity should be limited between its normal and crash time. The amount of G\*1 to G\*6 resulted from solving models (13) to (18) separately while considering the feasibility constraints. In the objective function of the model (19), all goals were preferred less, except for the quality of each activity. Hence, minimizing di+ except d3- was considered.

1. **Case Study and Findings**

The considered case study is a production project based on the development of a new product being launched to the market by an Iranian’s based Food Company. The company is located in Iran as an emerging economy in middle-east, the headquarter office is located in Tehran the capital of Iran, and the factory is located in Karaj province. This company produces their spaghettis under the license of Switzerland and Italy with a prominent brand called SAMIRA since 1979. Besides new product development in the food industry, they also design and develop food manufacturing machines and features via a subsidiary company under the same brand. Currently, they are producing nearly 30 different products in the food and agricultural industries. The commercial name of the newly developed product is ‘spaghetti enriched with vitamin D and Zinc’. In this project, generally, four categories of major activities, including feasibility, design, supply and production, industrialization (or supply), should be implemented, each of which includes several sub-activities. The normal and crash time and cost data for each activity were collected and determined with the help of the R&D department of the studied company. New product development projects are usually considered by scholars to analyze project management concepts and methods (Jafari & Nasiri, 2019). The activities of the project are shown in Table 5 and the intended project network (activity on arrow (AOA) style with a finish to start relationship) is illustrated by Figure 2 through Bizagi modeler software.

**Please insert Figure 2**

Normal and crash values for the time and cost of each activity are represented in Table 3. Normal time is the maximum possible time that each activity requires and crash time considers the minimum time required to complete each task. The normal and crash costs are relevant to the normal and crash times of each activity, relatively.

**Please insert Table 3**

The activities (x910) and (x2124) in the above network show dummy activities with zero time and cost. According to the second step of the proposed framework, i.e. Fig. 1, quality and risk values were also considered as knowledge-based hesitant fuzzy numbers as these factors in R&D projects deal with uncertainty, especially in the food industry. Moreover, the previous experiences in R&D projects in SAMIRA Corporation indicate that uncertainty incorporates and affects the quality and risk of each activity and the project as a whole. To approximate the quality and risk of each activity, considering their uncertainty, three groups of experts including three, four, and five-person are invited to form a brainstorming session directed with a facilitator. The expert qualifications are described in Table 4.

**Please insert Table 4**

During a brainstorming group meeting with industry experts and studied company senior managers, their views were expressed in knowledge-based Hesitant Fuzzy Linguistic Term Sets following the expressions presented in Table 5.

**Please insert Table 5**

During the brainstorming sessions, to solve any disagreement between experts, the facilitator was assigned to make a negotiation between disagreed participants to reach an agreement. In case no agreement was achieved between disagreed participants, the Liao et al. (2014) method of HFLTS information aggregation was used to aggregate the experts’ opinion, see Section 2.1. Table 6 summarizes the results of the quality and risk evaluation of project activities obtained from the brainstorming sessions.

**Please insert Table 6**

Considering the knowledge-based Hesitant Fuzzy Linguistic term sets in the above table regarding the quality and the risk of each activity, the score and variance function values were obtained and presented in Table 7 for each activity via equations (4) to (6). According to step four of the proposed framework, these values indicate the score and variance of quality and risk for each activity in the studied project.

**Please insert Table 7**

To solve the numerical problem of TCQRT, the following steps were adopted, following steps 5-7 of the proposed framework, namely: (1) Formulation of TCQRT according to equations 13-18; (2) Solving each objective function while considering feasibility constraints; (3) Modeling the MOLP model and solving it via goal programming. For instance, the minimum cost of the project resulted in 5.2E-09 after solving model (13) with feasibility constraints through the GAMS software. For a clear presentation and avoiding repetition, in (20), model (13) plus feasibility constraints were presented.

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| --- | --- | --- |
|  | | |
| Feasibility constraints (F.C) |  | (20) |

We have repeated the same schedule for models (14) to (18) and solved all models plus the feasibility constraints with GAMS software. In the following, the results are presented in Table 8. Finally, the goal programming model is implemented in GAMS Software for the model (19). The MOLP model includes six objectives and was solved via goal programming.

**Please insert Table 8**

Subsequently, the goal values of each objective function were set in the model (19) and the main model was solved. The optimal time of each activity is illustrated in Table 9.

**Please insert Table 9**

As Tables 8 and 9 indicate, the multi-objective model to tradeoff TCQR factors in the R&D project, resulted in optimal values for time, cost, score functions of quality and risk, and variances of quality and risk, simultaneously. Based on the results presented in Table 9, the optimal duration of each activity (limited between normal and crash time) and the start and end date of each activity have resulted while minimizing the cost and risk and maximizing the quality of each activity. Comparing to the ordinary project scheduling based on the traditional critical path method (CPM), the end date of the project has been decreased significantly by 19.6 percent.

1. **Discussion and implications**

To analyze the results emanated from the designed model and to check the reliability and the viability of the optimal duration of each activity from the case study, first of all, the value of each objective function and the deviation from the ideal value for each function are presented in Table 10. Considering the results, the deviation of the designed model and approach from the ideal values of each function was nearly zero and for two objectives exactly zero. Thus, the results extracted from the designed model and approaches were acceptable. Figure 3, illustrates the result of the proposed goal programming model vs the ideal value of each objective function. This comparison can support the scheduled model and demonstrate that the results are nearly close to the optimal values of each objective when they are solved separately and without a trading-off approach. Moreover, as the results for cost and time were similar, they have been excluded from the figure.

**Please insert Table 10**

**Please insert Figure 3**

Secondly, the optimal time of each activity and the status of it compared to the normal and crash time has been measured and presented. As shown in Figure 4, the time of each activity in the normal and crash model was compared with the time of activities after solving the proposed hesitant fuzzy goal programming model. Activities were all in the range due to feasibility constraints discussed previously in section 4 and equation (20). Moreover, the project time resulting from the designed model compared to the deterministic time (resulted from traditional CPM) was reduced by nearly 20%. This reduction was significant and promising. Moreover, completing the R&D project earlier than competitors was also achieved. This will result in better timing to access the market and increase the market share of new products that are going to be released to the market in the future.

**Please insert Figure 4**

Comparing the results of the proposed approach in this manuscript with other project trade-off models seems impossible. As the model considered all four aspects (TCQR) alongside knowledge-based hesitant fuzzy information for the quality and risk of each activity, to the best knowledge of the authors, the HFLTS model for the TCQR problem has not been investigated previously. Nonetheless, the impact of the previous models on the completion time of the projects is comparable with our proposed approach. For instance, nearly ten years ago, Shankar et al (2011) designed a TCQ model with deterministic parameters and their model only reduced the completion date by 9%. Nearly five years later, Mohammadipour & Sajjadi (2016) presented a multi-objective TCQR deterministic model which reduced the completion time of the project by only 12%. More recently, in 2018 Tran and long, developed a model which only considered TCR and in a deterministic situation resulting in a 24%-time reduction. Although the time reduction of their model was more than our proposed approach, they have not considered uncertainty in their model and mentioned using fuzzy approaches in future recommendations, covered in this article. The proposed model in this article not only considered HFLTS but also reduced the completion time of the project by nearly 20% while minimizing cost and risk and maximizing the quality of each activity, simultaneously.

From a theoretical aspect to the best knowledge of the authors, a project management tradeoff model considering all four dimensions of time, cost, quality, and risk; while, incorporating hesitant fuzzy linguistic terms sets has not been designed and developed (according to Table 1). As the project managers need to reduce the time of their projects alongside minimizing cost and risk and also maximizing the quality of the products, tradeoff models play a significant role to achieve all of these goals through an aggregated approach (Lotfi et al., 2020). Especially in the food and agricultural new product development projects, acting as a fast response organization to meet customers’ requirements in the fiercely competitive environment is controversial. Many R&D projects fail due to considering only the time and ignoring the cost, quality, and risk of each activity and the project (Hess and Hess, 2020; Barbosa et al., 2020). According to Table 1, only on rare occasions, all four dimensions (TCQR) were considered by scholars in their tradeoff models; therefore, this research adds value to the current gap. Moreover, to consider quality and risk in tradeoff models in project management, many uncertain approaches have been developed and designed. Nonetheless, none of the previous scholars have considered hesitant fuzzy linguistic term sets to measure the quality and risk of each activity and the project. HFLTs is a technique used to facilitate Decision Makers' (DMs) judgment process in imprecise situations (Razavi Hajiagha et al., 2018). By employing HFLTs for quality and risk, decision-makers and experts of R&D projects can measure and analyze the relevant risk and quality of each activity in a simple manner. Hence, the scheduled approach in this research is not only including the TCQR tradeoff but also considering a modern and recent uncertain approach that is easy to implement in real-world cases.

From a practical perspective, the important role of R&D projects in competitive markets and especially the food and agricultural industry has been illustrated in the introduction section. Fast response organizations create higher chances to win in the market. One of the main issues in leading and surviving in competitive markets is new product development via R&D projects to meet customer requirements. To do so, R&D managers prompt to accomplish their projects as soon as possible while considering other dimensions of project management including cost, quality, and risk. This article has proposed a multi-objective tradeoff model to achieve the aforementioned goals. To consider the uncertainty in our proposed model and to make the results more practical and realistic, hesitant fuzzy information has been employed. As described previously, HFLTs are easy to understand for experts and also, they consider a high level of uncertainty in their calculations and operators. To deal with HFLTs models, many approaches are applicable (Razavi Hajiagha et al., 2018); however, in this research, score and variance functions have been applied. As the authors indicated in this manuscript, to their knowledge, this is the first TCQRT model using HFLTs values in project management, Hence, comparing the results of the proposed model with other tradeoff models in terms of results and efficiency is not applicable. Nevertheless, as mentioned in section 4, the scheduled model has reduced the time of the project up to 20%, which is really significant and promising for an R&D project. Meanwhile, the cost, risk, and quality of each activity and the whole project were under control and only penny differences were observed with their ideal values. According to Table 10 and Figure 3, the deviation from ideal values of TCQR while implementing the designed goal programming approach based on hesitant fuzzy information is neglectable.

1. **Conclusions**

To the best of our knowledge, little research has been conducted on time, cost, quality, and risk tradeoff while considering all four dimensions. Considering the limitations of classical fuzzy, new uncertainty approaches need to be developed in the TCQRT era. In this research, a novel TCQRT model has been proposed based upon HFLTs information and is implemented on an R&D project of a food sector company in the emerging economy of Iran. In the scheduled TCQRT model, four dimensions of time, cost, quality, and risk are all considered simultaneously. Remark that risk and quality are considered under uncertain conditions and death with hesitant fuzzy linguistic terms. In the designed model, it is endeavored to schedule and optimize the time of the project and each activity by minimization of cost and risk and maximization of quality simultaneously.

*From a theoretical standpoint*, the present study can be considered as an extension of previous studies in several aspects. First, the research extended the previous deterministic (e.g. Amoozad Mahdiraji et al., 2016; Moghaddam et al., 2020) or fuzzy tradeoff models (e.g. Razavi Hajiagha et al., 2015; Hashemi et al., 2021) by proposing a more flexible and applicable HFLTS framework. The HFLTS framework provides a way of dealing with uncertainty with an enhanced possibility of declaring experts’ opinions without requiring them to determine the quality or risk of projects’ activities with a single number or linguistic variable. Experts can judge a given activity’s risk or quality as medium to high, below medium, etc. Furthermore, this extension considered all of the important objectives of a project, consist time, cost, quality, and risk, in a single model compared to other researches (e.g. Mahmoudi et al., 2020; Hashemi et al., 2021). Eventually, a structured and understandable model was developed to handle the considered uncertain situation based on the concepts of multi-objective optimization in this research to trade off the TCQR simultaneously.

In empirical terms, project managers can apply the proposed model to tradeoff and schedule their projects’ activities without any necessity of neglecting or reducing the ambiguity in project activities dimensions, including quality and risk. While there is no requirement of using the proposed scale in the current study to evaluate the quality and risk of each activity by HFLTS, the proposed 7-point scale illustrated in Table 5 can be used as a guiding reference for project managers in their evaluations. The proposed method provides a more flexible and easy-to-use framework dealing with managers' ambiguity and uncertainty to handle the quality and risk aspects of their projects. The proposed framework provides an exact method of dealing with vagueness in project management. Furthermore, as described in Table 10 and Figure 3, the results of the proposed multi-objective knowledge-based hesitant fuzzy approach are more optimal than the deterministic approach and the ideal values of objectives are nearly achieved.

Fram a managerial perspective, the proposed approach can be used by project managers in three main stages, as represented in Figure 5. First, in the preparation stage, the project network including the list of activities and their predecessor relations is explored. This information is used to draw the project network. Then, at the second stage, after the data gathering, since a variety of information regarding each activity’s time, cost, quality, and risk are required to formulate the model, different tools are used to gather the information. The time and cost of activities are approximated or gathered through historical data of previous similar projects. However, since the quality and risk of activities are context-dependent, i.e. they depend on the status and environment of the project, a qualitative approach like brainstorming or the Delphi method can be used to gather the judgments of experts regarding activities quality and risk. In this stage, HFLTS can be used to provide a more flexible framework for assessing the activities’ quality and risk. Finally, at the third stage, the Project Management Office (PMO) formulates the TCQRT model, Eq. (19), and solves it using the proposed approach to find the optimal condition of project activities execution.

**Please insert Figure 5**

Due to the TCQRT problem, MOLP model, and HFLTs assumptions employed in this research, some future researches are recommendable. For instance, using IVIF and IVF could also lead to interesting results for uncertain tradeoff models in project management. Besides, to transfer hesitant information, score and variance functions are used in our research; however, other approaches in transformation such as the bi-objective score-variance-based linear assignment method are applicable also. Moreover, the considered network is an AOA in this research, and the relationship between activities is all assumed as a finish to start type. For the AON situation with start to start, start to finish, and finish to finish situations, pertinent models are designable. Furthermore, the slope function for cost, quality, and risk is calculated by a linear form as mentioned in Table 4; nonetheless, in case the relationship of these three factors with time changes to nonlinear, novel approaches and models are achievable. By and large, employing other uncertainty approaches, all possible networks, nonlinear functions, and other possible applications could be considered by future scholars.

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