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PROJECT SCHEDULING UNDER CONSIDERATION OF TEAM-BASED DEPENDENCIES BETWEEN PROJECT ACTIVITIES

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Purpose: The purpose of the paper is to propose two models incorporating the information about project activities that share the same human resources in order to achieve a more realistic estimation of project duration. Uncertainties about the duration of activities are also taken into account.
Design/methodology/approach: The objective is achieved through fuzzy modelling and linear programming, as well as through modelling of team dependencies between activities.
Findings: It was shown that the fact of sharing the same human resources by project activities may strongly influence project duration estimation and it is not advisable to ignore such information in project planning. It was also proposed how to model such dependencies and consequently arrive at more accurate project duration estimations. Simultaneously, modelling of project uncertainties and their practical importance have also been shown.
Research limitations/implications: This work contributes to unexplored subject of considering dependencies and uncertainty simultaneously in project scheduling. It contributes to the research on how to include team dependencies between project tasks and uncertainty in project scheduling to provide reliable information on project duration. However, many more dependencies between tasks should be considered and other methods of uncertainty modelling taken into account. Real world cases of terminated projects should be used as case studies.
Practical implications: The proposed models will significantly increase the accuracy of project duration estimation in all types of organisations, which in turn will help to save time and money lost as a result of project delays.
Originality/value: The paper is addressed to both researches and practitioners who deal with the problem of project scheduling. It proposes a novel method of increasing the accuracy of project duration estimation that takes into account team-based dependencies between project activities along with uncertainty.

Keywords: project scheduling, fuzzy duration, sharing resources, project duration estimation.

Category of the paper: Research paper.

1. Introduction

Knowledge of the duration of projects is crucial for effective project management and determining when an organization can leverage the project's results and products. However, the high rate of considerable project deadline overruns (Demeulemeester, Herroelen, 2002) shows that determining project duration in the phase of project planning is not an easy task. There are several reasons responsible for this issue, like uncertainty (Perminova et al., 2008), various human biases (Toet et al., 2016), project inherent complexity and newness, etc. All these issues are somehow addressed in the literature: e.g., we have the possibility to use probability or fuzzy distributions to model values that are not completely known (Bonnal et al., 2004; Chanas, Zieliński, 2001; Hullet, 2009; Malcolm et al., 1959). There is one aspect, however, that on one hand considerably adds to the complexity in developing project schedules and, consequently, determining their duration, and on the other hand is usually ignored in the description of project management methods and methodologies: the dependencies between project activities, or (here we assume the two terms to be synonyms) project tasks.

It is apparent that between tasks in the project some dependencies may occur, such as sharing the same resources (equipment or teams) or scope of some tasks being dependent on the decisions or results of others. The conclusion that these dependencies may influence the duration of related activities is straightforward. Understanding and incorporating them into the scheduling process allows for developing more nuanced and useful schedules, as they will closer reflect the project reality.

As this aspect is generally absent in the literature on project scheduling (uniquely rare references in the context of construction projects have been identified (Salkeld, 2016)), the objective of this paper is to propose two models incorporating one type of task dependency – that based on sharing the same team or the same person executing the task. We will call this dependency type team or team-based dependencies. Uncertainty about project duration will also be included in the models and will be expressed by means of fuzzy numbers.

The outline of the paper is as follows: in Section 2 we discuss the problem of team based dependencies, in Section 3 we propose two fuzzy models including information about activities that share the same resources and allowing to take into account uncertainties about the duration of project activities, and in Section 4 we illustrate the approach with a real world research project. The paper terminate with some conclusions.

The paper is based on a master thesis successfully defended at the Faculty of Management of Wrocław University of Technology (Pikiewicz, 2023).

2. Team dependency

As mentioned above, the problem of dependencies between different tasks in projects is a complex one. The team dependency will be the main focus of this paper – this dependency type is fairly universal for different types of projects, as several teams working on one project is a common practice.

Team dependency occurs when more than one team works on more than one task in the project. Teams can have different experiences, sets of skills, knowledge, and commitment to the project. All of these influence their work performance and how they fulfil their duties. For example, a new team consisting of people with little experience (e.g. in junior positions) and new to the company may work slower on all tasks assigned to them than their more experienced colleagues.

In short, it is not irrelevant who and under which conditions performs individual project tasks. If two or more tasks are performed by the same team under the same conditions, this must be taken into account when scheduling the project. Including such a dependency in project scheduling can improve its relevance. If the PM knows that the team has lower (higher) work performance, they can expect that the project activities that have been assigned to them may take longer (shorter) than anticipated. Taking such pieces of information into account, PM can obtain a more reliable indication about planned project duration. We are going to propose two models for the project planning stage that include this information type. They will be based on a fuzzified standard model that will be presented in the first place.

3. Proposed models

3.1. Fuzzified standard model

To incorporate information about the work performance of the teams into the scheduling process, we propose an extended version of standard linear programming model used to optimize project duration (Swanson, 1973). The extension consist in replacing crisp task durations with fuzzy ones, modelled by means of triangular fuzzy numbers. A triangular fuzzy number $\tilde{t} = (t^a, t^b, t^c)$ (Zadeh, 1965) is defined as a triple of crisp numbers $t^a \leq t^b \leq t^c$, where the extreme values are seen as possible to the degree 0, the intermediate value as fully possible (to the degree 1), and the possibility degree diminishes linearly between the intermediate and the extreme values. The extreme values are the optimistic or pessimistic ones, depending on the situation being modelled. Arithmetical operations and relation between fuzzy numbers themselves and between a fuzzy number and a crisp number can be defined in many ways. In the following, we will specify the choice we made in this paper.

The basic model uses the following notation:

Objective function $\min \tilde{z} = \tilde{x}_N, N \epsilon \mathbb{N}$ (1)

Subject to:

$$\tilde{x}_j \geq \tilde{x}_i + \tilde{t}_{ij} \tag{2}$$
where $A_{ij} \in \mathcal{A}, i, j \in \mathbb{N}$,
$\tilde{x}_j, \tilde{x}_i \geq 0$,

where:

$\mathbb{N}$ – set of nodes in the network, $\mathbb{N} = \{j: j = 1, \dots, N\}$, where N denotes number of nodes in the network,

$E = \{(i,j), i, j \in \mathbb{N}$: such that there exists a link from i to $j\}$. Note that all couples (i,j) in set E satisfy $i < j$,

$\mathcal{A}$ – set of activities in the network, $\mathcal{A} = \{A_{ij}: (i,j) \in E\}$,

$\tilde{t}_{ij} = (t_{ij}^a, t_{ij}^b, t_{ij}^c)$ - fuzzy duration of activity A_{ij}: all three values of the fuzzy number are provided by the PM, with the additional constraint $t_{ij}^a > 0$. Note that t_{ij}^a is the optimistic value – the shortest duration possible of an activity, and t_{ij}^c is the pessimistic value – the longest possible duration,

fuzzy decision variables $\tilde{x}_j = (x_j^a, x_j^b, x_j^c)$, representing the not fully known earliest possible finish time of all activities that end at node $j, j = 1, \dots, N$. The interpretation of the three parameters of the triangular fuzzy number is analogous to the one of the fuzzy tasks duration.

The objective function (1) is the duration of the project, which should obviously be minimised. This value is equivalent to the earliest possible finish time of all the activities that have the finish node as their final node. The constraint (2) is created basing on the rules for constructing project networks: for each activity $(i,j) \in \mathcal{A}$, the node i needs to occur and the activity needs to be carried out before node j (Winston, 1991).

To properly include the consequence of introducing fuzzy numbers to the model, the following solution has been selected: the model will be calculated three times for the combination of the first, second and third parameters of the fuzzy triangular numbers $\tilde{t}_{ij}$ and $\tilde{x}_j$. Thus, three standard models will be solved and finally the fuzzy solution of the fuzzy model will be obtained. The resulting values from the three calculations are arranged to form a triangular fuzzy objective value $\tilde{z} = (z^a, z^b, z^c)$. The fuzziness expresses the uncertainty about project duration inherent to the project planning process. Obviously, other methods of solving the fuzzy linear programming model may be chosen; here, we decided to choose the simplest one, that has most chances in be applied in practice.

3.2. Proposed model 1 – team dependencies

In the 1. model we take into account the information which team is assigned to each activity A_{ij}. We assume we have K teams, and $\tilde{t}_{ij}^{k} = (t_{ij}^{k,a}, t_{ij}^{k,b}, t_{ij}^{k,c})$ stands for the fuzzy duration of activity A_{ij} if performed by team k. Additionally, we introduce the notion of the work quality of individual teams: $\tilde{q}_k = \left(q_k^a, q_k^b, q_k^c\right)$ – fuzzy quality of team $k, k = 1, \dots K.$ If the quality of work has been taken into account in $\tilde{t}_{ij}^{k},$ we can take $\tilde{q}_k = (1,1,1)$, but if the PM wants to introduce the additional information about the work quality, they can select other $\tilde{q}_k$.

We propose the following function:

$$f\left(\tilde{t}_{ij}^{k}, \frac{1}{\tilde{q}_k}\right) = (t_{ij}^{k,a} \times \frac{1}{q_k^c}, t_{ij}^{k,b} \times \frac{1}{q_k^b}, t_{ij}^{k,c} \times \frac{1}{q_k^a}) \tag{3}$$

In the (3) we chose to multiply not values of both triangular numbers in their original order, as they will not provide an interpretable result, but instead we multiply the values that have the same meaning. So to obtain the most optimistic duration of a task with inclusion of team quality, we multiply the most optimistic provided task duration $\left(t_{ij}^{k,a}\right)$ with the most optimistic quality of the team $\left(\frac{1}{q_k^c}\right)$. Other values are obtained analogously. This proceeding, described by (3), results in a fuzzy number with a straightforward interpretation:

- The first value is the most optimistic scenario, where at the same time the task has the shortest duration and the team has the highest possible quality,
- The second value reflects the most possible result, both the task and the quality parameters takes on the most possible values,
- The third value is the most pessimistic scenario, the task has the longest duration and the team has its weakest performance possible.

We propose to solve the model analogous to the fuzzified standard model, but instead of constraint (2) the following one will be used:

$$\tilde{x}_j \geq \tilde{x}_i + f\left(\tilde{t}_{ij}^{k}, \frac{1}{\tilde{q}_k}\right) \tag{4}$$

3.3. Model 2 – with teams dependencies and updating procedure

During the execution of the project PMs gain knowledge, also about the actual work of the teams. Therefore, we propose to enrich Model 1 with the data about real realizations of the tasks that have been completed up to each control point $m = 1, \dots, M$. Constraint (4) will be replaced with constraint (5):

$$\tilde{x}_j \geq \tilde{x}_i + f(\tilde{t}_{ij}, \frac{1}{\tilde{q}_k(CP_m)}), \tag{5}$$

where $\tilde{q}_k(CP_m)$ is the team quality, updated for those activities that have been completed up to the control point $CP_m, m = 1, \dots, M$ in the following way:

- $q_k^a(CP_m)$ stands for $min\left(\frac{t_{ij}^{k,b}}{t_{ij}^{k}(CP_m)}\right)$,where $(i,j)\epsilon\ C_k(CP_m)$,
- $q_k^c(CP_m)$ stands for $max\left(\frac{t_{ij}^{k,b}}{t_{ij}^{k}(CP_m)}\right)$, where $(i,j)\epsilon\ C_k(CP_m)$,
- $q_k^b(CP_m)$ can be chosen as an average of $\left(\frac{t_{ij}^{k,b}}{t_{ij}^{k}(CP_m)}\right)$ - the PM makes the choice based on the data and their experience,
- $t_{ij}^k(CP_m)$ is the actual duration of activity A_{ij} and $C_k(CP_m)$ is the set of activities completed by the control point $CP_m, m = 1, \dots, M$.

For the teams that have not completed any of their assigned tasks before the control point, the constraint (4) from the first model is used, where the quality is solely provided by the PM at the beginning of the project. It is important to emphasize that to derive a fuzzy quality of the teams in this model, all the tasks completed by the team are taken into consideration up to and including the moment CP_m. The ratios used to calculate $\tilde{q}_k(CP_m)$ reflect, for each team, the relation between the planned durations and the actual ones. This approach allows to update information about the team performance. It is important, as the team performance may strongly depend on the project. If the project requires special competencies, not needed in other projects in which the team took part, previous information on team work quality will not be relevant, but using Model 2 we can update the quality based on the most recent tasks. Full form of the Model 2 is shown in the Appendix.

4. Case study illustrating the proposed models.

The research project that is used as the basis for the case study is a research planned to take place at Wrocław University of Science and Technology at Faculty of Management. The project was unfortunately not executed, as it did not receive funding, but the planning phase was fully carried out. Data from this stage are the basis for the case study, the rest of the data are estimations made by the authors of the paper.

4.1. The project and its teams

The main aim of this project is to develop a Scrum use maturity model in organizations carrying out IT projects. Other objectives include inventing a new definition of maturity of using project's methodologies adapted to the characteristics of Scrum, and assigning goals to be achieved at each level of maturity. Researchers who planned this project highlighted that as Scrum is based on empiricism, the maturity model should be based on the knowledge and experience of people working in and with Scrum in their everyday work.

To fulfil the aforementioned goals, the tasks included in Table 1. were defined for the project. In Table 1., there is also information about the planned durations of each activity and their predecessors. The duration was assessed both by means of crisp and fuzzy numbers.

Table 1.
Tasks in case study project

ID	Task	Predecessors	Duration in days	Fuzzy duration in days
A	Identification of Scrum practices and values	-	15	(10, 16, 23)
B	Development of a glossary of Scrum terms	-	7	(2.5, 4, 10)
C	Preparation of a questionnaire and interview sheets	A, B	12	(8, 11, 14.5)
D	Implementation of the questionnaire in a survey software	C	3	(1.5, 2.5, 6)
E	Adaptation and programming of the selected data clustering algorithm in order to identify similar practices	D	20	(14, 21, 32)
F	Conducting a pilot study	E	10	(6, 10, 22)
G	Analysis of pilot study results, modification of the questionnaire and interview sheets	F	15	(9, 14, 20)
H	Conducting a proper research	G	30	(22, 28, 40)
I	Analysis of research results focused on the identification of groups of similar practices by means of a selected clustering algorithm	H	15	(10, 14, 21)
J	Analysis of research results focused on the "soft" supplementary information obtained in direct interviews	H	15	(9, 13, 20)
K	Development of the Scrum use maturity model	I, J	30	(23, 30, 45)
L	Verification of the Scrum use maturity model	K	15	(9, 13, 18)

Source: based on the plan for the project and own study.

If we examine the predecessors, it is visible that the majority of tasks were planned to be carried out in sequence, only two pairs of tasks were planned to be performed simultaneously.

The project was planned to be carried out at the Faculty of Management. The teams that could perform tasks in the project are composed of persons working or studying at this Faculty. For this project, the crucial expertise items regard project management, applications mathematics to managerial problems and knowledge of optimisation algorithms.

Based on an analysis of the competencies and expertise at the Faculty, four teams were identified that could participate in the execution of this project:

- Team 1 – employees with high level of knowledge and experience in project management area,
  - assigned tasks: C, F, G, H, J;
- Team 2 – employees with medium to high level of knowledge of mathematics and project management,
  - assigned tasks: K, L;
- Team 3 – students and PhD students at the Faculty,
  - assigned tasks: A, B, D;
- Team 4 – computer scientists with a medium level of expertise in algorithms,
  - assigned tasks: E, I.

The proposed method of allocation allows the skills of each team to be used effectively by selecting the tasks that require their specific knowledge. The choices were also made in such a way that the tasks are demanding enough for the expertise of the team members. The suggested approach is cost effective and allows for the personal development of team members and can lead to increased motivation of work.

When there are several teams working on a project performing more than one task, it is obvious that the dependency of the teams working on different tasks in the project occurs. To be able to use the models with team dependencies, PM managing the project needs to assess the quality of each of the teams. This is the last information required along with the duration of each task in the form of a crisp and fuzzy triangular number and their assignment to the teams. The qualities of each team are summarized in the Table 2. below.

Table 2.
Teams quality in the form of crisp and triangular fuzzy number

Team	Crisp quality	Fuzzy quality
Team 1 – high project management	1.2	(1, 1.15, 1.3)
Team 2 – mathematics and project management	1.15	(1, 1.1, 1.25)
Team 3 – students and PhD students	0.8	(0.7, 0.8, 0.95)
Team 4 – computer science	1.05	(0.9, 1, 1.15)

Source: based on the plan for the project and own study.

Looking exclusively at crisp values gathered in Table 2., it can be seen that three teams have a higher performance than the organisational average (assumed to be 1), only the students got a lower score. However, when the fuzzy quality is considered, the information is not as inambiguous any more. Team 4 may be better or worse than the average, depending whether the pessimistic case occurs or not. For Teams 1 and 2, the situation is clearer: in the worst case scenario they work as an average team, in the best case they have a higher performance.

When all the required data is collected, we can proceed to the implementation of Model 1 with team dependencies - first at the moment 0 of the project. This will allow us to gain a first insight into the possible duration of the whole project, as well as individual tasks. Moreover, PM can observe the impact of different qualities of the teams and how they influence the tasks duration.

Using fuzzy data from Tables 1 and 2, Model 1 was applied, with the following results:

Table 3.
Triangular decision variables at the moment 0 of the analysed project

Decision variable	x_j^a	x_j^b	x_j^c
$\tilde{x}_1$	0	0	0
$\tilde{x}_2$	2.6	5	14.3
$\tilde{x}_3$	10.5	20	32.9
$\tilde{x}_4$	16.7	29.6	47.4
$\tilde{x}_5$	18.3	32.7	55.9
$\tilde{x}_6$	30.4	53.7	91.5
$\tilde{x}_7$	35	62.4	113.5
$\tilde{x}_8$	42	74.6	133.5
$\tilde{x}_9$	58.9	98.9	173.5
$\tilde{x}_{10}$	65.8	110.2	193.5
$\tilde{x}_{11}$	67.6	112.9	196.8
$\tilde{x}_{12}$	86	140.2	241.8
$\tilde{x}_{13}$	93.2	152	259.8

Source: own study.

The information about the expected finish times for tasks can be of great value for the PM, especially if it is not averaged by force, but presented including the uncertainty. Basing on this information and a risk analysis, schedules and some deadlines can be altered to better reflect the possible finish times. In Table 3. it can be seen that for some tasks the difference between the most optimistic and pessimistic values is quite large. The reason behind it is that is it a research project. Such projects are highly uncertain, the duration of their tasks depends on many factors and is difficult for foresee exactly (Klaus-Rosińska, 2019). It can be noticed that, as a result, the finish times vary strongly and this affects the duration of the whole endeavour. It is crucial for the PM to be aware of this, as it reflects how the task may be carried out by the teams. Moreover, the knowledge about different possible values of finish times shows how much time the different stages of the project may take in various scenarios. It allows the PM to be better prepared for both optimistic and pessimistic scenarios and plan accordingly. In research projects it is crucial to know the possible values of the project finish time, because of the need to meet very strict deadlines, such as submitting project documentation to the Ministry or other academic institutions, or sending reports on the progress of the research (Klaus-Rosińska, 2019). In addition, the PM can monitor more closely those tasks with a wide range of possible finish times that they perceive as vital to the project, to ensure that they are completed before the important deadlines.

To gain a better understanding how the fuzzy information about the task finish times can be used, one of the decision variables will be analysed. The finish time of the task G (x_8) (*analysing the results of the pilot study and making adjustments to the questionnaires*) marks the end of the preparation phase of the project. After this task a proper research will be carried out. The finish time of this task will determine when the main research phase can start. It will influence planning the interviews and the travel required to conduct them and the moment when certain teams will be needed in the project, so that they can schedule their other research and teaching activities accordingly. The possible finish times for this task determined using

Model 1 are represented by the fuzzy number $\tilde{x}_8 = (42{,}74.6, 133.5)$. It can be seen that it covers a fairly wide range, as the difference between the optimistic and the pessimistic finish times equals to 91.5 days (with around 55% and 80% deviations from the most possible time). This task is carried out by Team 1, with the average work quality in the worst case scenario and much better work quality in more positive scenarios. Having this information at their disposal, the PM can take measures to ensure that the quality of the team is high enough to fall into the more optimistic interval of the task duration values.

Another way of analysing the results is to plot a graph of a triangular fuzzy number to observe the degree of possibility of each value. The graph makes the triangular fuzzy number and all the possible values more visible for the decision maker. For example, such an approach can be used to analyse the tasks that have strict deadlines. In this way, the PM can notice what other values are highly possible and be better prepared for these scenarios. The analysis of the graph in this case study was applied to the values of the objective function. The graph of the project duration obtained through calculations of Model 1 is shown in Figure 1.

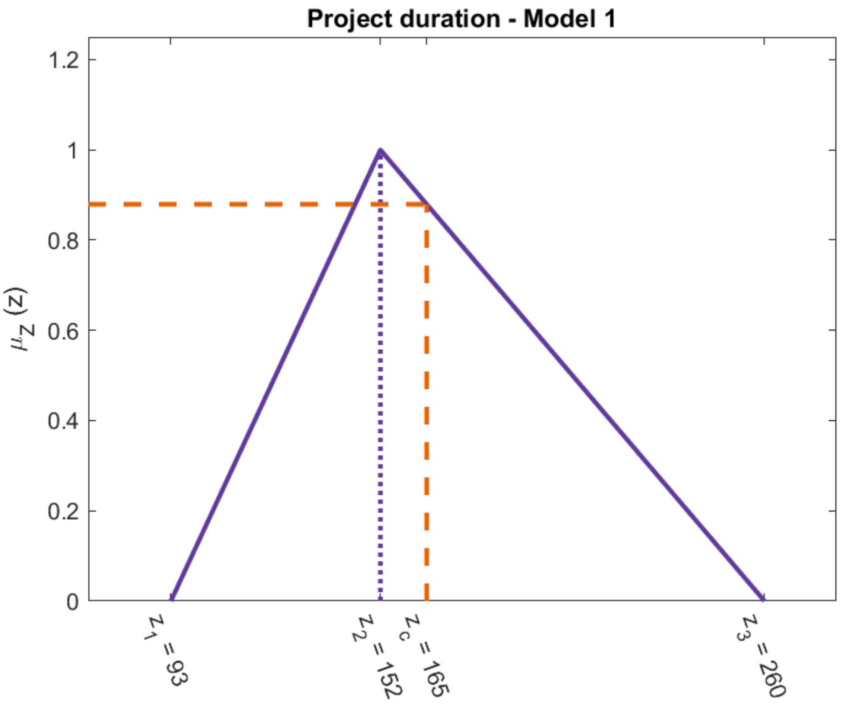

Figure 1. Fuzzy project duration including team dependency.

Source: own study.

In Figure 1. it is visible that as the decision variables had wide range of possible finish times, the duration of the entire project obviously has this feature, too. This wide range also follows from the characteristics of research projects mentioned before. In Figure 1., the y-axis shows the degree of possibility of each value of the project duration, and x-axis shows the different possible project durations. The shape of the triangle was formed based on the three values of the fuzzy triangular number $\tilde{z} = (93{,}152{,}260)$ and their degree of possibility. The project duration equal to 152 days is the most possible one. With this information the

PM can plan the most possible deadline and the moment when the results can be presented. However, they should not base this decision solely on the most possible duration, because there are also other durations that are possible and should not be neglected. Since the difference $z_2 - z_1$ is smaller than the difference $z_3 - z_2$, it can be concluded that durations longer than the most possible one are a serious issue here. The PM should be more prepared for the pessimistic scenarios.

In Figure 1. the duration equal to 165 days was marked. It is the duration of the project obtained from the standard model with crisp parameters and variables, it is shown by means of the orange dashed line with the label z_c. It allows us to compare the two approaches. It can be noticed that in this case, this duration is more pessimistic than the most possible one in the fuzzy model. It still has a high degree of possibility and the PM should take it into the consideration. Its degree of possibility can be calculated as follows:

$$\mu_z(165) = \frac{z_3 - x}{z_3 - z_2} = \frac{260-165}{260-152} = 0.88 \tag{6}$$

Next, the second version of the fuzzy model can be calculated to check how this influences the results (Model 2). One update was performed for the Team 1. It was selected because it has been assigned the most tasks and it is more interesting to observe updates and deriving quality from actual realizations.

The hypothetical control point took place after finishing the task G – *Analysis of pilot study results*. It is assumed that up to this point tasks A-G have been completed and the actual realizations of durations were as follows:

- Task A – 17,
- Task B – 6,
- Task C – 10,
- Task D – 3,
- Task E – 23,
- Task F – 8,
- Task G – 13.

Task C, F and G were performed by the team whose quality will be updated and the model will be recalculated with this newly gained knowledge.

First the quality of performance on each task is calculated as described in the Model 2: the most possible duration is divided by the actual duration of the task. From these values the maximum, minimum value needs to be identified. The new, updated fuzzy quality of team 1 is $\tilde{q}_1 = (1.08, 1.1, 1.25)$. It can be noticed that this new quality differs from the one provided at the beginning of the project. The most optimistic quality is lower by 0.05, the most possible is also lower by the same amount. These are negative changes after the update. Positive change can be observed for the most pessimistic value, it is larger by 0.08. The positive information is that even after the update, the team still is more efficient that the organisational average. However, seeing these differences highlights how important it is to perform systematic project control and updates throughout such uncertain projects. Especially quality of the teams should be based on their more recent work, as their performance may change due to different factors, such as characteristics of the tasks, the team engagement in the project etc. Now this new quality is used in the calculations of the final estimated duration of the remaining tasks assigned to Team 1, which are H and J. The durations of the tasks that have been completed before the control point are treated in the model as crip values. New finish times for the remaining tasks are shown in Table 4.

Table 4.
Triangular decision variables updated after the 1st control point – updated quality of Team 1

Decision variable	x_j^a	x_j^b	x_j^c
$\tilde{x}_9$	**91.6**	**99.5**	**111**
$\tilde{x}_{10}$	98.8	111.3	129.6
$\tilde{x}_{11}$	**100.3**	**113.5**	**134.4**
$\tilde{x}_{12}$	118.7	140.7	179.4
$\tilde{x}_{13}$	126	152.5	197.4

Source: own study.

In Table 4. the finish times of the tasks assigned to Team 1 are shown in bold. The first thing to notice is that the difference between the values is smaller than in finish times obtained from the model at moment 0. The quality of Team 1 does not have such a wide range of possible values as it was estimated previously, and this influences the range of possible durations of their tasks. For tasks H and J there is also another reason, the updated quality. It may be interesting to look not only at the finish times, as these also depend on the previous tasks, but also at the duration of the tasks assigned to Team 1. As an example, the duration of task H is analysed. In this model, the final duration of the task is the product of a function of the duration of the task and quality of the team. Before the update, the fuzzy duration of the task H was $\tilde{t}_{8,9}^1 = (16.9, 24.3, 40)$, and after the update it is $\tilde{t}_{8,9}^1 = (17.6, 25.5, 37)$. The most pessimistic duration is now smaller, thus the worst possible scenario is better. But the most optimistic and most possible scenarios have become slightly worse. Taking that into consideration, this update allows for more realistic estimates of the remaining tasks and their durations.

The duration of the entire project, in the form of a fuzzy triangular number, is shown in Figure 2, after the update of the quality Team 1 and with the data about actual durations of tasks A, B, C, D, E, F and G.

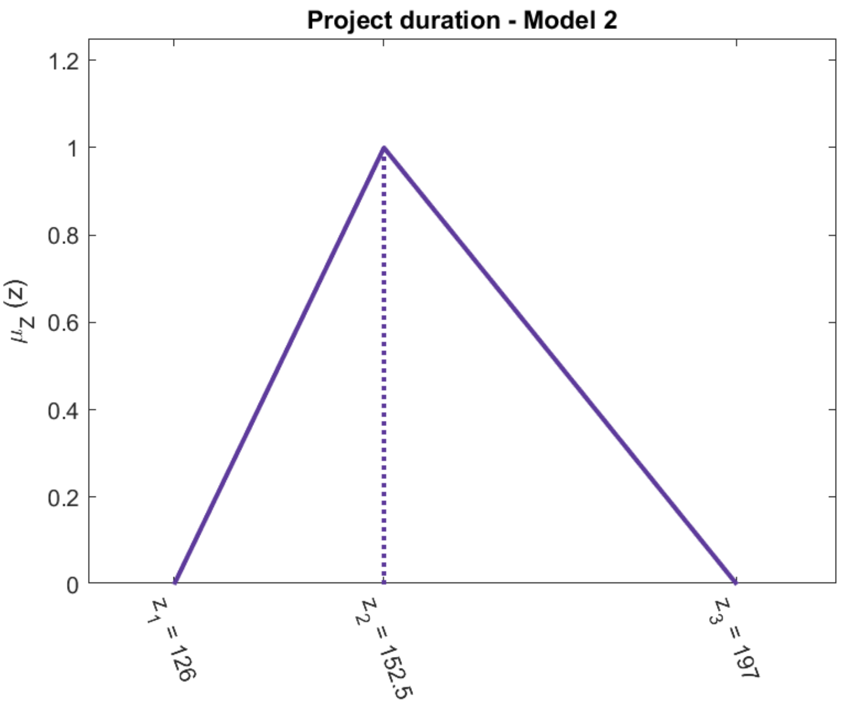

Figure 2. Fuzzy project duration updated after the 1st control point.

Source: own study.

After the updating procedure the fuzzy project duration is now $\tilde{z} = (126{,}152.5{,}197)$. The first thing to notice in Figure 2. is that the support of the triangle is now much narrower, as the difference between the most optimistic and pessimistic project duration has become smaller. As more than half of the tasks have been completed before the control point, the level of uncertainty is now lower, as it only affects the remaining tasks and not the entire project. The same tendency is observed here: the most pessimistic duration is much smaller, the most optimistic and possible are larger, with the most optimistic being larger by a greater amount than in the fuzzy project duration obtained from the model at moment 0. The reasons are the same as for the finish times of the tasks. The updated fuzzy project duration still has the same negative tendency. With this update, the PM will have a clearer vision on the end of the project and for what possible deadlines they should be prepared. It also shows how important the updating procedure is in project schedule management, as at the beginning of the project the knowledge about this particular undertaking is very limited.

5. Conclusions

Accurately determining project durations is crucial for effective management and timely achievement of project objectives. However, bypassing the information on dependencies between project activities hinders accurate scheduling. In addition, the inherent uncertainty in projects poses further challenges in developing schedules and estimating tasks durations. To tackle these two obstacles and enable creating more reliable schedules, we proposed two forms of a fuzzy model with the team dependency. The first model we introduced is applicable for the moment 0 of the project to gain a first insight into the possible duration of the project and its activities. Knowledge acquisition throughout the project was used by us in the second proposed model to enhance the estimation accuracy – the quality of the team is updated, basing on their performance in the ongoing project. Simultaneously considering team dependencies (this aspect has not been considered in the literature so far) and uncertainty constitutes a novel solution to improving project scheduling.

It should be noted that the problem of identifying and understating task dependencies is a complex one, as they can vary between different types of project and comprise many different aspects. Construction projects have different characteristics of tasks than the IT industry or research projects. Moreover, the environment of various types of the projects also differs, which will also influence the occurrence of different dependencies. It shows that this neglected area is worth of researching and understanding as it is not a trivial problem. The dependency researched in this paper could also be further analysed, for example inclusion of the learning curve of each team could be an important and promising approach. Modelling several dependencies simultaneously is also an interesting direction of research.

In this paper triangular fuzzy numbers were employed. There are however many other types of fuzzy numbers that can be explored in the context of such models. It is important to consider that in some cases other types of fuzzy numbers may better reflect the current state of knowledge and subjective information about the project. Moreover, the approach to calculating fuzzy model was simplified, to be more accessible for PMs. Other, more sophisticated methods can be used in the future to improve the quality of the proposed mathematical models.

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Appendix

The final form of the Model 2 is as follows:

Objective function: $$\min z = \tilde{x}_N, N \in \mathbb{N} \quad (10)$$

Subject to:

$$\tilde{x}_j \geq \tilde{x}_i + f(\tilde{t}_{ij}, \frac{1}{\tilde{q}_k(CP_m)}), \quad (11)$$

$$\text{for } k = 1, \ldots, K \ s.t. A_{ij} \in \mathcal{R}_k, i, j \in N, k = 1, \ldots, K, m = 1, \ldots, M,$$

$$\tilde{x}_j \geq \tilde{x}_i + f(\tilde{t}_{ij}, \frac{1}{\tilde{q}_k}), \quad (12)$$

$$\text{for } k = 1, \ldots, K \ s.t. A_{ij} \in \mathcal{A}_k \wedge \mathcal{C}_k(CP_m) = \emptyset, i, j \in \mathbb{N},$$

$$\tilde{x}_i, \tilde{x}_j \geq 0,$$

where $i, j \in \mathbb{N}$.

Together with the information about completed tasks a new element of the model comes into play. Because some of the tasks that the teams are working on can be completed before the control point CP_m and their real durations will be known, the set of activities of each team $\mathcal{A}_k$ needs to be divided into two further subsets:

- $\mathcal{C}_k(CP_m) \subset \mathcal{A}_k$ – set of completed tasks of the team,
- $\mathcal{R}_k \subset \mathcal{A}_k$ – set of remaining tasks of the team k,
- The remaining tasks include those in process, thus we have $\mathcal{C}_k \cup \mathcal{R}_k = \mathcal{A}_k$.

The set of completed tasks will no longer be subject to decision making; their actual durations are already known, therefore, they can be treated as constant and not variables.