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Sustainability-Oriented Project Scheduling Based on Z-Fuzzy Numbers for Public Institutions

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Abstract: A new approach to sustainable project scheduling for public institutions is proposed. The approach is based on experts' opinions on three aspects of sustainability of project activities (human resources consumption, material consumption and negative influence on local communities), expressed by means of Z-fuzzy numbers. A fuzzy bicriterial optimization model is proposed, whose objective is to obtain a project schedule of an acceptable sustainability degree and of acceptable duration and cost. The model was inspired and is illustrated by a real-world infrastructure project, implemented in 2019 by a public institution in Poland.

Keywords: sustainability; project management; scheduling; public infrastructures; Z-fuzzy number

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1. Introduction

In this paper the problem of project scheduling in the context of sustainability is considered. The work concentrates on public administration, where sustainability issues are an immediate consequence of the public administration ethics principles [1]. Ethics pose an even more sensitive issue for government than for corporations or other private sector organizations because government, by definition, must serve all interests in a society [2]. Public administration has to observe the law, organize work in a just and ethical way, be totally transparent, serve the public interest in all its endeavors. Thus, exploiting and harming human beings, damaging human health, damaging the environment, acting against the interests of individuals: all this is irreconcilable with the mission of public administration [1]. Also, public organizations differ from private organizations and have other basic goals than profit-oriented organizations. These goals include public accountability, honesty, openness, responsiveness to policy, fairness, due process, social equality, balanced criteria for the distribution of manufactured goods, and correct moral behavior [3]. This means that public administration has to include sustainability as a factor in all their everyday activities.

This obligation results also from the generally accepted conviction that public administration is generally less advanced in the adoption of modern project management standards (see [4,5] for more details). Public projects are often not quite successful [6,7], which means that public money is not spent in an efficient way or is spent not according to the society's expectations. Thus, all possible steps should be undertaken in order to increase public money spending efficiency and acceptability, and sustainable project management may be one the remedies [8]. Also, developed project stakeholder management, strongly linked to sustainability [9], is necessary for efficient and effective project management. In short, sustainable project management may be a way to increase the success rate of projects realized by public institutions.

Sustainability means taking care of people and the world. But of course, even though public organizations are not profit-oriented, their goals (public accountability, responsiveness to policy, etc.) also obligate them to control expenditures and, as far as possible, minimize them, if more important goals are not compromised through the savings. In public organizations trade-off decisions have to be made every day, and sustainability and cost-related criteria are an integral part of them.

The goal to be addressed in this paper is connected to project schedules in public organizations, while we adopted the following definition of schedule: "A schedule is a timetable showing the forecast start and finish dates for activities or events within a project, program or portfolio" [10]. Scheduling will be understood as "a collection of techniques used to develop and present schedules that show when work will be performed" [10], and the goal will consist in introducing a sustainable project scheduling model for organizations, focusing on public institutions. To this end a model that aims to generate, under certain assumptions, a project schedule that will be sustainable and yet acceptable also from the economic perspective is proposed. A first attempt in this direction was undertaken in [11]. This present paper offers a modification and extension of the proposal put forward there. No other attempt related to sustainable scheduling was identified in the literature.

The aim of this paper is to propose an optimization model for public project scheduling that allows to take sustainability issues into account. Individual project activities will be evaluated by experts as to their suitability from three perspectives (in three dimensions), while expert expertise and available sources of information will be considered, too. This is important because sustainability evaluation can be a sensitive subject and may depend on the subjective perspective of a given expert (some public institution employees are more eco-oriented or emphatic, some less, some are more knowledgeable, some less, also local citizens and organizations may have different expertise and attitudes). In order to model such a complex situation (for the first time in the context of project scheduling) Z-fuzzy numbers are used. The proposed bicriteria model will generate a trade-off project schedule —of an acceptable duration and cost, but also of an acceptable degree of sustainability (or the answer that such a schedule does not exist). The approach will be illustrated by means of a real-world example of a public schedule, which constituted, by the way, an inspiration for this paper.

The structure of the paper is as follows. In Section 2 a literature review is presented, which proves that our approach is a novel one with respect to sustainable project management and the application of Z-fuzzy numbers in this context. In addition to reviewing literature on sustainable project scheduling, approaches to modeling multi-objective project scheduling as adopted in this article are reviewed. Section 3 presents the theoretical model proposed in this article. Basic assumptions and notations related to sustainability, scheduling problem formulation, the bicriterial problem solution adopted and Z-fuzzy numbers are presented. The section closes with the final model proposal. In Section 4 the model is applied to a real-world public project that was implemented by a certain Polish public institution, which showed itself open to new management solutions. This institution also cooperated in the research and helped to establish the applicability of the method proposed in this paper. The obtained results are discussed in Section 5. Finally, the conclusions of the study are presented in Section 6.

2. Literature Review

2.1. Sustainable Project Scheduling

Our literature research included publications from two different databases: Scopus and Google Scholar. The literature was reviewed according to different combinations of the following search phrases: "project," "planning," "scheduling," "sustainable," "sustainability," "green," "public project." For several databases, it was necessary to modify initial test criteria, so that the number of results produced was appropriate. In most cases too many results were obtained and narrowing down the criteria was needed, but there were also cases when the search had to be extended (e.g., S6 from Table 1) because no interesting results were found initially. The search terms and search results are summarized in Tables 1 and 2. Finally, 18 literature outputs were found in total. Because some of the results from different databases overlapped with each other, the final number of articles described was smaller than this number and equaled 15 (four related to project scheduling, four related to project planning and seven related to public projects). It is also worth mentioning that the literature review was restricted to publications from recent years. The year 2016 was added as lower constraint. Three different categories were assigned to the search criteria and literature is discussed in each of the categories separately, for better readability. At the end the results are discussed with special attention to the tools and methods that were used in this article, namely, in relation to the usage of fuzzy numbers. The literature review showed that there exists a gap in the literature in the area of sustainable public project planning and sustainable public project scheduling.

Table 1. Search criteria used in the literature review together with their categories.

ID	Search Term	Category
S1	"project" AND "scheduling" AND ("sustainable" OR "green" OR "sustainability")	scheduling
S2	"project" AND "planning" AND ("sustainable" OR "green" OR "sustainability")	planning
S3	"project planning" AND ("sustainable" OR "green" OR "sustainability")	planning
S4	"public project" AND ("sustainable" OR "green" OR "sustainability")	public projects
S5	"project scheduling" AND ("sustainable" OR "green" OR "sustainability")	scheduling
S6	"sustainable scheduling" AND "project management"	scheduling
S7	"sustainable scheduling" AND "project"	scheduling
S8	"sustainable planning" AND "project"	planning
S9	"sustainable project planning"	planning
S10	"public project" AND "sustainable"	public projects
S11	"sustainable project" AND "public project"	public projects

Table 2. Summary of search results obtained for different databases.

Search Term	Year Filter	Database	Results Found	Results Reviewed
S1	≥2016	Scopus	34	1
S2	≥2016	Scopus	1742	0
S3	≥2016	Scopus	35	3
S4	≥2016	Scopus	15	4
S5	≥2016	Google Scholar	4700	0
S6	≥2016	Google Scholar	10	0
S7	≥2016	Google Scholar	95	3
S8	≥2016	Google Scholar	7680	0
S9	≥2016	Google Scholar	54	3
S10	≥2016	Google Scholar	2800	0
S11	≥2016	Google Scholar	101	4

First, the literature related to sustainable scheduling is summarized. In [12] the authors presented a scheduling method by solving the discrete time/cost trade-off problem (DTCTP) for more than 500 project activities using a genetic algorithm and a heuristic. The sustainability aspect was reduced to the fact that in sustainable project management resources should be used economically, so that the shorter project duration is achieved at lower cost. No relation to the three dimensions of sustainability (i.e., social sustainability, environment sustainability, economic sustainability) was given. Sustainable Job-Shop scheduling approaches were presented in [13,14], but the three dimensions of sustainability were not considered, either. In [13], authors considered energy efficiency, while in [14] carbon emission was considered. Similarly, reference [15] described sustainable production scheduling in the context of minimizing pollution.

As far as sustainability in relation to project planning is considered, even fewer relevant references were found (although the set of reviewed articles was equally represented as in the case of project scheduling). The idea of integrating sustainability into traditional project management methods in the context of construction projects was presented in [16]. Although the authors often used the term "sustainable project planning" and indicated the need for a proper definition of "sustainable project planning," they rather focused on the sustainable aspects of project control, risk response strategies and communication. No concept of sustainable project scheduling was presented. An evolutionary optimization method for sustainable project planning shown through the example of developing a sustainable port was presented in [17], but the sustainability aspect was reduced to carbon emission only. A sustainable project pre-planning phase was discussed in [18], including the observation that green project planning requires more effort than traditional project planning. The authors of [19] tried to list the barriers to integrating sustainability rules into construction projects. Lack of a systematic approach to sustainable project planning is on the list of barriers.

The most relevant set of publications was found for public projects, but here also a lack of in-depth insight into sustainability can be observed. Sustainable public projects were discussed in [20]. The authors presented an evaluation measure of the sustainability of a public project that included carbon emission, resource utilization, renewable energy and impact on the surroundings, when evaluation information is fuzzy. A fuzzy analytical hierarchy process (FAHP) was used for evaluation. This work considered many important dimensions of sustainability in the context of public projects, but it focused on public project management in general. Project scheduling was not considered. Different sustainability objectives for major public projects and their evaluation by different project stakeholders (government, owner, contractor, designer, end user, university, NGOs) were presented in [21]. The evaluation was based on interviews. Five economic, nine social and four environmental objectives were listed. The results came from the Hong Kong region. A sustainability-oriented evaluation method for public government projects was presented in [22]. It was based on a judgment matrix and an analytic hierarchy process. The authors developed a bid evaluation index that can be used for selecting the best bidder according to sustainability criteria. As in the case of [21], the method was evaluated in a Chinese context. The social dimension of public infrastructural projects in an Italian context was presented in [23]. The aspect of social sustainability was discussed in the context of inconveniences that appear when building a new infrastructure, like relocation of the residents. The authors of [24] proposed an interesting classification of infrastructure projects that takes into account a sustainability dimension. Public infrastructure projects in the context of sustainable project controlling were presented in [25]. Sustainability controlling methods were analyzed by the example of a road tunnel construction project. The paper showed that project control mechanisms are used differently for different sustainability dimensions. The authors of [26] focused on a method for estimating the social sustainability of a public infrastructure project, motivated by the observation that this aspect of social sustainability is often mentioned in the literature.

Summing up, there are not many literature positions that refer to sustainable project planning or sustainable project scheduling, in the context of public projects. What is more, only two positions were found [20,22] that present sustainable methods based on the theory of fuzzy numbers, and in none of them Z-fuzzy numbers were used. The method presented in this article tries to fill in this research gap.

2.2. Multi-Objective Project Scheduling

Sustainable project scheduling is bound to be a multi-objective scheduling problem, and sustainability can never constitute the sole criterion. Therefore, literature concerning general multi-objective project scheduling problems was also reviewed here. In [27] one can find a review of the state of art—not only with respect to the criteria used (needless to say that sustainability has not been used as a criterion in such models), but also to the parameters and decision variables of the models.

Parameters include precedence relationships between project activities, information on the nature and quantity of needed and available resources, activity duration, cost and project budget. The prevalent decision variables are start times and finish times of activities. Constraints refer to requirements set for the project deadline, the available budget, the available quantity of resources, etc.

Of course, project scheduling can be seen as a more general problem. It may cover problems where it was possible to reduce the duration of activities on the critical path against a certain cost [28] or preempt or interrupt them [29]. In this article, however, the setting was limited to the basic version of the project scheduling problem [30] where the decision variables were the start times of activities, with the other activity features remaining fixed.

As far as computational complexity is concerned, exact mathematical models tend to be complex if an integer solution is required. In the case of resource-constrained project scheduling, oftentimes 0–1 problems occur [30], and the integer nature of the model cannot be avoided. If the exact solution of the problem is too complex computationally, various heuristics are known and may be applied.

3. Theoretical Model

3.1. Sustainability Modeling

It is assumed that each project activity per se may violate sustainability requirements in three different aspects: human resources consumption, materials consumption and influence on the environment. Thus, each activity can be evaluated with respect to its sustainability in each of the three domains.

- In the domain of the human resources consumption, the activity is evaluated on the basis of the answer to the question of whether it causes work overload, tiring or exhaustion of humans, forcing humans to work overtime without their consent, in their free time. The higher the evaluation value, the less the activity is a cause of these negative phenomena.
- In the domain of materials consumption, we evaluate the over-wasting of materials and the usage of materials that by themselves or whose extraction is harmful to the environment. The higher the evaluation value, the less the activity wastes materials, and the less the materials and their extraction are harmful to the environment.
- In the domain of the influence on the environment (understood here above all as the local community where the public institution in question operates), the evaluation of an activity is higher the less negative influence the activity has on both the physical and human environment (e.g., the less noise or dirt its execution generates, the less reduction in green spaces it causes, etc.).

It is also assumed that in the case of some activities, it is possible to increase their sustainability degree in one or more of the aspects, but this will take time (which means delaying their start times with respect to the earliest possible one) and generate an additional cost. The improvement of the sustainability degree, linked to delaying the activity start times, can be achieved in the following ways:

- In the human resources consumption aspect: other human resources than initially planned can be assigned to the activity. They may be less experienced, but it will save the initially assigned employees from overworking and give their colleagues an opportunity to develop their experience and show their potential. The activity costs more money, but its sustainability index will also increase. Another possibility here is to outsource the activity, even for higher costs, so that the workload of the employees diminishes. Both measures—assigning other employees or outsourcing an activity—may mean a delay in the activity start times; the unexperienced employees have to be trained and freed from their normal duties, an external company has to be searched for and a contract with it has to be negotiated. Both measures are also linked to an additional cost: a training cost for the employees and the additional cost for paying the external company. However, in relation to sustainability, the more balanced the human consumption is, the more social benefits it brings, which increases social sustainability.
- In the materials consumption aspect: substitute materials can be used, whose usage is less harmful from the environmental point of view. However, this will require

additional time (searching for possible suppliers, choosing the best offer, contract signing, waiting for delivery, etc.) and additional cost (prices of eco-materials are usually higher, but also the cost of the extra work needed from the purchase department of the public institution will generate additional cost) of bringing the materials to the organization. But better material used increases environmental sustainability.

- In the environmental (local community-related) influence aspect: different measures are possible, depending on the context; for example, in case of too much noise caused by cumulation of various projects in one area, the activity start time can be postponed in order not to coincide with other projects. Such a measure does not only mean waiting longer for the activity to start but may also generate additional cost: if a contract was signed for hiring heavy equipment, some fixed fees for waiting will have to be incurred.

It is assumed that the sustainability degree of an activity in each of the three aspects will depend on the moment when the activity is started and that if this moment is shifted forward in time, the sustainability degree will not diminish (in other words, postponing the start of an activity cannot decrease the sustainability degree, but can increase it). This assumption may be restricting in some cases, but usually the start of the activities is postponed in order to be more sustainable (e.g., time is used to train employees, or to supply environmentally friendly materials, or to develop/learn greener technology, or to shift nighttime tasks to daytime to avoid noise, etc.). Also, it is assumed that postponing the activity start is not desirable from the point of view of staying within deadlines and may be the cause of extra cost. Additionally, it is assumed that the sustainability measures in the three aspects can be aggregated, to give one total sustainability measure of each activity, which is a non-decreasing function of the starting moment of the activity.

Let us denote the measures of the three dimensions of sustainability mentioned above as $S_i^r(s),\ r = 1,2,3,\ i = 1,\ldots,N$, where r = 1 refers to human resources consumption, r = 2 to materials consumption, r = 3 to the influence on the environment and $s \in [0, H)$, where H is the furthest possible acceptable horizon for the project to terminate and stands for the starting time of the respective activity. It is assumed that $S_i^r(s),\ r = 1,2,3,\ i = 1,\ldots,N$ are non-decreasing functions of s. The total sustainability degree of the ith activity is defined as in (1) (the formula used here is only an example, weighted sums or other formulas can be considered):

$$S_i(s) = \frac{1}{3}\sum_{r=1}^{3} S_i^r(s). \quad (1)$$

3.2. The Scheduling Problem Formulation

It is assumed that at the starting decision moment (s = 0) the activities have a certain level of sustainability (measured as in (1)), which in some cases may be increased at an additional cost if the activities start later than at s = 0. The two criteria chosen as optimization criteria are thus:

- The average level of sustainability of all project activities,
- The total cost of improving the sustainability of project activities with respect to moment s = 0.

It is assumed that other parameters of the project (like activity duration or cost not related to sustainability improvement) cannot be changed. The decision variables are the start times of individual activities. The main problem parameters are the planning horizon H, the number of activities N, and the duration of ith activity $T_i,\ i = 1,\ldots,N$.

For the ith activity, $C_i^*(s)$ stands for the cost of achieving a sustainability degree of $S_i(s)$. As stated above, both $C_i^*(s)$ and $S_i(s)$ are non-decreasing functions of s. As can be seen from (1), the sustainability degree $S_i(s)$ of each activity is dependent on its start time, which means that sustainability is connected to the project's schedule. The same observation is true for $C_i^*(s)$. In this article an assumption is made that $C_i^*(s)$ is a linear function of s (an example of such a function can be found in Results section and is described as the total cost per one time unit of waiting). This means that two sustainability-related measures used in this article are connected to the project's schedule.

It is assumed, for the sake of simplicity, that there are no dependencies between the considered activities. This per se unrealistic assumption is true for the majority of activities in the example project referred to in this paper and can be easily lifted in eventual applications. Also, there are no budgeting or resource constraints considered, but this omission can also be easily amended. Such a future extension will not break the assumptions made, and the problem will be solvable in polynomial time, provided that, e.g., heuristics are used to obtain a sufficiently good solution.

The problem is to determine a schedule *SH*, which will be understood as the set of starting times for each activity $\{s_i\}_{i=1}^{N}$, $0 \le s_i \le H - T_i,\ i = 1, \ldots, N$, maximizing objective (2) (the total sustainability of the project) and minimizing objective (3) (the cost of achieving respective sustainability degrees).

$$O1 = \frac{1}{N} \sum_{i=1}^{N} S_i(s_i) \to max, \tag{2}$$

$$O2 = \sum_{i=1}^{N} C_i^*(s_i) \ \to min. \tag{3}$$

The resulting problem is a bicriterial one, with one objective being maximized and the other one minimized. Multi-objective problems, in order to be solved, have to be transformed into single objective ones. There exists a vast spectrum of possible approaches. Here we chose an interactive approach, called max-min compromise solution [31]. According to this method, the decision makers are asked to indicate the lower and upper limits to their satisfaction with the values of both objectives. Let us denote them as: O_L^1, O_U^1 for $O1$ and O_L^2, O_U^2 for $O2$. They mean that the decision makers are totally unsatisfied if the value of the first objective (maximized) is equal to or lower than O_L^1 and completely satisfied if its value is at least O_U^1. In-between satisfaction is assumed to be growing linearly. In case of the other objective, $O2$, which is minimized, the satisfaction is full below O_L^2, 0 over O_L^2 and diminishes linearly in-between. The objective function to be maximized in the final model is the minimum of the two satisfaction degrees. Such an approach will generate a max-min compromise solution (Figure 1), in which the decision makers are satisfied to some extent with both objectives.

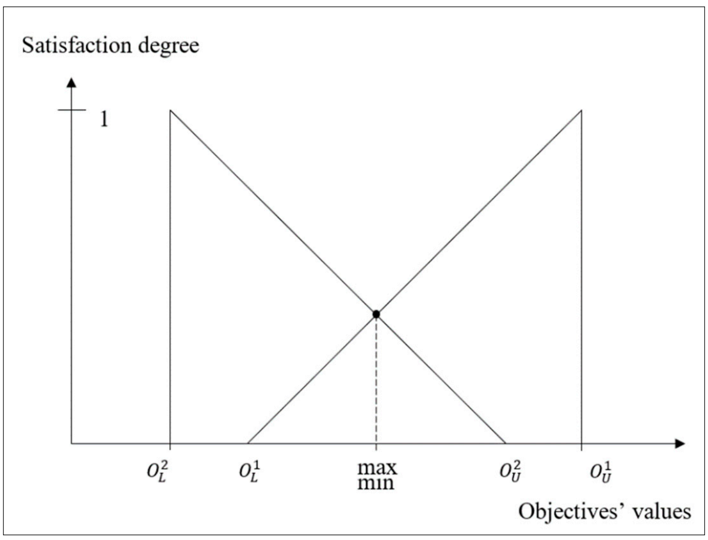

Figure 1. Illustration of the max-min compromise solution of a bicriteria problem.

3.3. The Use of Z-Fuzzy Numbers

Of course, an important problem is the determination of $S_i^r(s),\ r = 1,2,3,\ i = 1,\ldots,N$. The sustainability degree in all the three aspects is not an easily measurable feature, its evaluation is subjective and has to be based on expert opinion. What is more, various experts may have different views on the subject. Project stakeholders representing the local community, the employees, ecologists, etc., are examples of expert groups who should be asked about the sustainability degree of individual activities, but they are bound to have conflicting views. What is more, these experts will also differ with respect to their credibility. There will be more experienced and less experienced employees, more selfish and less selfish representatives of the local community, more honest and less honest ecologists, etc. Of course, it is desirable to have the possibility to consult only experienced and cooperative experts, but the reality of public institutions is such that organizational and hierarchical connections play an important role. As research on public institutions shows, executives in the public sector are much less willing to delegate power, even to more experienced employees. Also, financial restrictions make it often impossible to have access to highly qualified external experts and the necessary expertise is not always available [32]. That is why one aim considered in this paper is to include in the model both the subjectivity and the undetermined nature of the sustainability degree evaluation and the problem of experts' credibility. In order to achieve this goal, $S_i^r(s),\ r = 1,2,3,\ i = 1,\ldots,N$ is modeled by means of so-called Z-fuzzy numbers [33]. The ultimate bicriterial optimization model is then a fuzzy model with Z-fuzzy numbers as model parameters. This is the main difference with respect to the only known approach to sustainability-oriented scheduling in public institutions [11]—where the problem of credibility is not taken into account and classical fuzzy numbers are applied.

The notion of Z-fuzzy numbers was proposed in [33] and discussed in numerous other papers. A Z-fuzzy number is an ordered pair $\left(\widetilde{A}, \widetilde{Z}\right)$, where $\widetilde{A}$ and $\widetilde{Z}$ are fuzzy numbers and the support of $\widetilde{Z}$ is included in the interval [0,1]. It is assumed here that both $\widetilde{A}$ and $\widetilde{Z}$ are triangular fuzzy numbers, which is of sufficient generality from the point of view of potential applications in public institutions: more complicated fuzzy numbers may occur in future implementations, for now, triangular fuzzy numbers are more than sufficient.

$\widetilde{A}$ represents a magnitude whose exact value is not known at the moment. $\widetilde{A}$ is represented by three crisp numbers $\underline{a}, \hat{a}, \overline{a}$, such that $\underline{a} \le \hat{a} \le \overline{a}$. Its so-called membership function μ_A, defined as in (4) and based on expert opinions, represents for each x the possibility that, according to the experts, x will actually be of the unknown magnitude.

$$\mu_A = \begin{cases} 0 \text{ for } x \le \underline{a} \\ \frac{x-\underline{a}}{\hat{a}-\underline{a}} \text{ for } \underline{a} < x \le \hat{a} \\ \frac{\overline{a}-x}{\overline{a}-\hat{a}} \text{ for } \hat{a} < x \le \overline{a} \\ 1 \text{ for } x > \overline{a} \end{cases}. \quad (4)$$

$\widetilde{Z}$ is a triangular fuzzy number defined analogously by three crisp numbers $\underline{z}, z, \overline{z}$, such that $\underline{z} \le \hat{z} \le \overline{z}$, and an analogous formula for μ_Z as in (4), with the additional condition $0 \le \underline{z} \le \hat{z} \le \overline{z} \le 1$. $\widetilde{Z}$ represents the credibility of the expert opinion $\widetilde{A}$. The closer to 1 the numbers $\underline{z}, z, \overline{z}$ are, the higher the credibility of $\widetilde{A}$. The higher the difference $\overline{z} - \underline{z}$, the higher the non-determinacy of the credibility of $\widetilde{A}$. In the literature it has been proposed to choose $\widetilde{Z}$'s from a list of triangular fuzzy numbers, each of which corresponds to a linguistic expression, like (credibility) high, medium, low, etc. An example of the "dictionary" for the values of $\widetilde{Z}$ can be found in Figure 2.

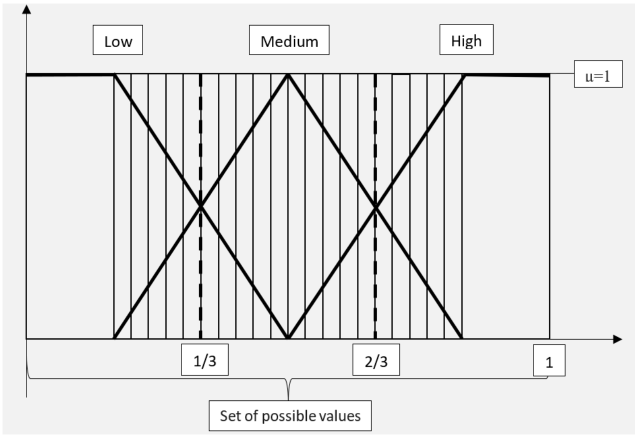

Figure 2. An example of the "dictionary" for the values of $\widetilde{Z}$.

In the literature there have been several proposals of arithmetic operations on Z-fuzzy numbers, e.g., [34–37], which differed in the procedure to encapsulate the information given by the ordered pair $\left(\widetilde{A}, \widetilde{Z}\right)$ in a simplified form (as a classical fuzzy number or in a defuzzified form, as a crisp number), in order to make possible various operations and comparisons among Z-fuzzy numbers.

Defuzzification is a method often used in practice in order to summarize the information conveyed by a fuzzy number of any type. Of course, defuzzification always entails a loss of information, but as our approach was focused on public institutions, where the introduction of mathematically complicated tools was bound to encounter considerable resistance, we took the decision to apply defuzzification at his stage.

Let us thus denote by $D\left(\widetilde{A}, \widetilde{Z}\right)$ a crisp number being a defuzzification of the Z-number $\left(\widetilde{A}, \widetilde{Z}\right)$. Here a modification of the proposal described in [36] is used. The basis of this modification is the following defuzzification Formula (5) for triangular fuzzy numbers [38]:

$$d\left(\widetilde{A}\right) = 0.25(\underline{a} + 2\hat{a} + \overline{a}). \tag{5}$$

This choice is not bounding, any other method might be selected.

Thus, it is proposed to use the following procedure (6) for the calculation of $D\left(\widetilde{A}, \widetilde{Z}\right)$:

$$D\left(\widetilde{A}, \widetilde{Z}\right) = d\left(\sqrt{d\left(\widetilde{Z}\right)}\underline{a}, \sqrt{d\left(\widetilde{Z}\right)}\hat{a}, \sqrt{d\left(\widetilde{Z}\right)}\overline{a}\right). \tag{6}$$

Equation (6) gives the defuzzification of a Z-fuzzy number as was defined in the literature in [36] (Ref. [36] is the only existing proposal so far). This approach was adopted here, but attention has to be paid to the implications of this concrete defuzzification method. The method as it was adopted here (after [36]) reflects a natural and practical approach: If the credibility $\widetilde{Z}$ is low, the evaluation $\widetilde{A}$ is simply shifted to the left, assuming it to be lower than the original one. Such an approach may be acceptable in many cases, but not always. This problem is discussed further in the conclusions section.

We propose to define $S_i^r(s),\ r = 1,2,3,\ i = 1,\ldots,N$ in the form of Z-fuzzy numbers $\left(\widetilde{A}_i^r(s), \widetilde{Z}_i^r(s)\right)$, where

$$\widetilde{A}_i^r(s) = \left(\underline{l}_i^r + \underline{k}_i^r s, \hat{l}_i^r + \hat{k}_i^r s, \overline{l}_i^r + \overline{k}_i^r s\right), \tag{7}$$

$$\widetilde{Z}_i^r(s) = \left(\underline{b}_i^r + \underline{d}_i^r s, \hat{b}_i^r + \hat{d}_i^r s, \overline{b}_i^r + \overline{d}_i^r s\right), \tag{8}$$

where all the parameters are non-negative, and $\overline{b}_i^r + \overline{d}_i^r s \leq 1$ for $s < H$.

The fuzzy valued functions (7) and (8) are non-decreasing in the sense that each of the three component classical functions determining them are non-decreasing.

Then Formula (1) for the aggregated sustainability degree of each activity takes the following form:

$$S_i^*(\mathrm{s}) = \frac{1}{3}\sum_{r=1}^{3} D\left(\left(\widetilde{A}_i^r(s), \widetilde{Z}_i^r(s)\right)\right). \tag{9}$$

3.4. Final Model

The objectives (2) and (3) are thus reformulated as follows:

$$O1 = \frac{1}{N}\sum_{i=1}^{N} S_i^*(s_i) \rightarrow max, \tag{10}$$

$$O2 = \sum_{i=1}^{N} C_i^*(s_i) \rightarrow min \tag{11}$$

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The bicriterial optimization is accomplished according to the max-min compromise approach described in Section 3.2. The minimum satisfaction of the decision maker with each of the objectives (10) and (11) is maximized. Let λ_1 stand for the satisfaction of the decision maker with objective (10) and λ_2 for the satisfaction of the decision maker with the second objective. The following pair of objectives are then considered:

$$\lambda_1 \rightarrow max,\ \lambda_2 \rightarrow max. \tag{12}$$

Objective (12) is defined using the two pairs of numbers given by the decision makers:

- O_L^1, O_U^1 for $O1$, such that $\lambda_1 = 0$ if $O1 < O_L^1$, $\lambda_1 = 1$ if $O1 > O_U^1$ and $\lambda_1 = \frac{O1 - O_L^1}{O_U^1 - O_L^1}$ for $O1 \in \left[O_L^1, O_U^1\right]$ (objective (10) is maximized);
- O_L^2, O_U^2 for $O2$, such that $\lambda_2 = 1$ if $O2 < O_L^2$, $\lambda_2 = 0$ if $O2 > O_U^2$ and $\lambda_2 = \frac{O_U^2 - O2}{O_U^{12} - O_L^2}$ for $O2 \in \left[O_L^2, O_U^2\right]$ (objective (11) is minimized).

It is proposed here to maximize the minimum of the two satisfaction objective (12), denoted as λ. The optimization model to be solved is thus finally as follows (λ stands for the minimum of the two satisfactions and is maximized):

$$\begin{gathered}\lambda \rightarrow max \\ \lambda_1, \lambda_2 \geq \lambda \\ \frac{1}{N}\sum_{i=1}^{N} S_i^*(s_i) \geq O_L^1 + \lambda_1\left(O_U^1 - O_L^1\right) \\ \sum_{i=1}^{N} C_i^*(s_i) \leq O_U^2 - \lambda_2\left(O_U^2 - O_L^2\right) \\ 0 \leq s_i \leq H - T_i,\ i = 1, \ldots, N.\end{gathered} \tag{13}$$

The result of the solution of (13) is a schedule SH, understood as a set $\{s_i\}_{i=1}^{N}$ of starting points of individual activities. The decision variables are λ, λ_1, λ_2 and $s_i, i = 1, \ldots, N$ with (5), (6) i (9) and if $C_i^*(s_i)$ is a linear function of s_i (with the coefficient C_i), a quadratic problem is considered. Although in fact the solution should be an integer (it is unrealistic to assume fractional activity start times), it is proposed—in order to avoid problems with computational complexity—to consider in the first place the relaxation with the integer constraints lifted. In practical applications, where the durations of project tasks are usually easily adjustable within small ranges (like hours), the relaxed problem should give an acceptable starting point, from which the final schedule may be constructed manually, in a fairly easy way. The relaxed problem would cause no complexity-related problems. It should be noted that both original objectives (10) and (11) are functions of decision variables s_i and all constraints (presented in (13)) are functions of decision variables λ, λ_1, λ_2 and s_i, $i = 1, \ldots, N$.

Table 3 presents some basic assumptions and the properties of the model proposed in this paper (described above in Section 3). These assumptions can be used as a reference for assessing the applicability of the model. They should also help in understanding the future research and possible extensions of the method.

Table 3. Summary of the assumptions used in the model.

Scheduling Assumptions	
activity durations	fixed
resource constraints	no
predecessor–successor constraints	no
cost constraints	no
Sustainability Assumptions	
dimensions	resource consumption, material consumption, local environment
assessment	experts' assessments
assessment representation	Z-fuzzy numbers
expert selection method	not specified
initial selection of experts	office employees (public projects)
sustainability gain	e.g., postponing activities, new materials
cost of sustainability	e.g., teaching staff, materials transportation, delay costs
Model Assumptions	
input	activities (with durations), experts' assessments of sustainability and of preferences as to the two objectives' values, the planning time horizon H
output	sustainable schedule (defined by activity start times)
model used	bicriterial optimization (max-min compromise approach) + Z-fuzzy numbers
computational complexity	polynomial
optimization criteria	sustainability (max), cost of increasing sustainability (min), reduced through the compromise max-min approach to one criterion: minimum of the satisfaction with the value of each of the objectives (maximized)
decision variables	activity start times, satisfaction with the value of each objective, minimum of the satisfaction with the two objectives
novelty (originality)	sustainability considered in project schedule
Possible Extensions	
predecessor–successor constraints	planned research
cost constraints	planned research
resource constraints	possible research (heuristics needed to maintain complexity)
more sustainability dimensions	planned research
more public projects tested	planned research

4. Results (Based on a Real-World Project)

Model (13) (implemented in Maple) was applied to an example inspired by an infrastructure project implemented by a Polish municipality in Lower Silesia. The area of the municipality covers almost 15,000 hectares and the numbers of inhabitants was almost 5000 in 2020. The management and the employees were open to new project management methods, even the more sophisticated ones. In the past they took part in an experiment regarding the implementation of a fuzzy project risk management method [39] and both the management and the employees were rather positive in their opinions with respect to the endeavor.

The project to which the model described in this paper was applied was the reconstruction of a municipal road. The project budget was about EUR 400,000, and it was realized between June and November of 2019. The following task groups were to be executed: preparatory work, surface milling, channeling, surface construction, surface elevation, widening of surface, roadsides, descents, pavement extension, clearing of culverts, cleaning of ditches, repair of retaining wall, strengthening of slopes. Most of the tasks involved pressure on the workers because of the deadline, usage of a mixture of various resources whose exploitation might damage the environment (some could have been replaced with other materials, more eco-friendly ones, e.g., the asphalt composition for the road surface [40]) and produce noise during the project realization. Thus, all the three sustainability dimensions (i.e., social sustainability, environment sustainability, economic sustainability) were at stake but were not taken into account during project realization. The project team members and the executives were aware of this and they were considering the possibility of introducing a systematic sustainability-related element into the scheduling procedure, being aware of the challenges related to sustainability that public institutions are facing (see Introduction). The authors of the paper were asked to analyze the case from the point of view of such a possibility. Thus, the proposed approach was post factum applied to the project.

The example's objective is to illustrate how the sustainability degree of a project can be influenced within the negotiated deadline and budget, with the aim of increasing the project sustainability degree—thus enhancing the human well-being without disregarding time and cost constraints.

In the example the parameters assumed in (13) were $O_L^1 = 6$ and $O_U^1 = 10$ and $O_L^2 = 80$ and $O_U^2 = 20$ (expressed in units suitable for each case). It was also assumed that the sustainability degree of the tasks could be increased with time, at some cost (thanks to assigning other team members, choosing alternative materials, etc.). At the same time, the suitability evaluation was seen as potentially not fully credible, for example, because of the lack of experience of the experts in the public institution, where sustainable project management had not been fully implemented yet.

Two cases were considered: one where the credibility of experts was fixed and could not be increased (by a higher quality of the experts or because the judgment could not be "bought in" in any form, even if the activity was postponed) and another one, where in case of the postponement of the evaluation of the sustainability degree, higher quality opinions could be gained (where it was possible to search for other experts or other sources of information, but this had to take time). Table 4 presents the data for the first case (where the second element of the Z-fuzzy numbers does not depend on time).

Table 4. Data on four project tasks without dependencies among them, where the sustainability can be increased but the credibility of its evaluation cannot.

i, T_i, C_i	$\tilde{A}_i^1(s_i), \tilde{Z}_i^1(s_i)$	$\tilde{A}_i^2(s_i), \tilde{Z}_i^2(s_i)$	$\tilde{A}_i^3(s_i), \tilde{Z}_i^3(s_i)$
1, 3, 10	$(1 + 0.6s_i, 2 + 0.6s_i, 3 + 0.6s_i)$, $(0.1, 0.2, 0.3)$	$(0.5 + 2s_i, 1 + 2s_i, 1.5 + 3.5s_i)$, $(0.2, 0.3, 0.4)$	$(5 + s_i, 10 + s_i, 11 + s_i)$, $(0.8, 0.9, 1)$
2, 4, 20	$(0.5 + 2s_i, 1 + 2s_i, 1.5 + 2s_i)$, $(0.2, 0.3, 0.4)$	$(1 + 0.6s_i, 2 + 0.6s_i, 3 + 0.6s_i)$, $(0.1, 0.2, 0.3)$	$(1 + s_i, 2 + s_i, 3 + s_i)$, $(0.5, 0.6, 0.7)$
3, 2, 5	$(1 + s_i, 2 + s_i, 3 + s_i)$, $(0.5, 0.6, 0.7)$	$(5 + s_i, 10 + s_i, 11 + s_i)$, $(0.8, 0.9, 1)$	$(0.5 + 2s_i, 1 + 2s_i, 1.5 + 2s_i)$, $(0.2, 0.3, 0.4)$
4, 1, 4	$(5 + s_i, 10 + s_i, 11 + s_i)$, $(0.8, 0.9, 1)$	$(1 + s_i, 2 + s_i, 3 + s_i)$, $(0.5, 0.6, 0.7)$	$(1 + 0.6s_i, 2 + 0.6s_i, 3 + 0.6s_i)$, $(0.1, 0.2, 0.3)$

For example, the first project task had duration $T_1 = 3$ weeks, and its sustainability degrees in the three aspects, expressed by means of $\widetilde{A}_1^r(s_1)$, $r = 1, 2, 3$, depended on the starting time s_1. If the task was started later, certain measures would be taken to increase its sustainability, and the total cost per one-time unit of waiting was equal to $C_1 = 10$. The credibility degrees of the sustainability evaluations, respectively for each sustainability aspect, were as follows $(0.1, 0.2, 0.3)$, $(0.2, 0.3, 0.4)$, $(0.8, 0.9, 1)$, thus the credibility of the experts' opinion was very low for the human resources aspect and very high for the environmental aspect. Here it was assumed that the credibility could not be changed with time, thus the experts could neither be replaced nor their expertise enhanced.

We assumed various time horizons H and for each we solved another problem (13). The following schedules SH were generated:

- for H = 10 (weeks): $s_1 = 0.33,\ s_2 = 0.1,\ s_3 = 8,\ s_4 = 8,$ with total satisfaction degree $\lambda = 0.04$;
- for H = 9 (weeks): $s_1 = 1.5,\ s_2 = 0,1,\ s_3 = 7, s_4 = 7,$ with total satisfaction degree $\lambda = 0.04$;
- for smaller H there was no schedule with a non-negative total satisfaction degree.

It can be seen that for shorter time horizons H not even the minimal satisfaction with the sustainability of the schedule could be achieved. The two schedules that could be determined had a very small satisfaction degree, close to zero. In this example (Table 4) the credibility of the sustainability evaluation was fixed, it could not be improved, which may have influenced this result: in case of the defuzzification method selected (6), low credibility lowered the overall sustainability evaluation.

In the next example (Table 5) of entry data both the sustainability and the credibility could be increased with time, of course at some cost. This cost here covered both certain measures to increase the sustainability and steps to enhance the experts' knowledge.

Table 5. Data on four project tasks without dependencies among them, where the sustainability can be increased as well as the credibility of its evaluation.

i, T_i, C_i	$\tilde{A}_i^1(s_i), \tilde{Z}_i^1(s_i)$	$\tilde{A}_i^2(s_i), \tilde{Z}_i^2(s_i)$	$\tilde{A}_i^3(s_i), \tilde{Z}_i^3(s_i)$
1, 3, 10	$(1 + 0.6s_i, 2 + 0.8s_i,\ 3 + 1s_i)$, $(0.1 + 0.02s_i,\ 0.2 + 0.02s_i,\ 0.3 + 0.02s_i)$	$(0.5 + 2s_i, 1 + 3s_i,\ 1.5 + 3.5s_i)$, $(0.2 + 0.02s_i,\ 0.3 + 0.03s_i,\ 0.4 + 0.05s_i)$	$(1 + s_i, 1 + 1.5s_i,\ 1 + 2s_i)$, $(0.5 + 0.01s_i,\ 0.6 + 0.02s_i,\ 0.7 + 0.03s_i)$
2, 4, 20	$(0.5 + 2s_i, 1 + 3s_i,\ 1.5 + 3.5s_i)$, $(0.2 + 0.02s_i,\ 0.3 + 0.03s_i,\ 0.4 + 0.05s_i)$	$(1 + 0.6s_i, 2 + 0.8s_i,\ 3 + 1s_i)$, $(0.1 + 0.02s_i,\ 0.2 + 0.02s_i,\ 0.3 + 0.02s_i)$	$(5 + s_i, 10 + 1.5s_i,\ 11 + 2s_i)$, $(0.8 + 0.01s_i,\ 0.9 + 0.01s_i,\ 1)$
3, 2, 5	$(1 + s_i, 1 + 1.5s_i,\ 1 + 2s_i)$, $(0.5\ + 0.01s_i,\ 0.6 + 0.02s_i,\ 0.7 + 0.03s_i)$	$(5 + s_i, 10 + 1.5s_i,\ 11 + 2s_i)$, $(0.8 + 0.01s_i,\ 0.9 + 0.01s_i,\ 1)$	$(0.5 + 2s_i, 1 + 3s_i,\ 1.5 + 3.5s_i)$, $(0.2 + 0.02s_i,\ 0.3 + 0.03s_i,\ 0.4 + 0.05s_i)$
4, 1, 4	$(5 + s_i, 10 + 1.5s_i,\ 11 + 2s_i)$, $(0.8 + 0.01s_i,\ 0.9 + 0.01s_i,\ 1)$	$(1 + s_i, 1 + 1.5s_i,\ 1 + 2s_i)$, $(0.5\ + 0.01s_i,\ 0.6 + 0.02s_i,\ 0.7 + 0.03s_i)$	$(1 + 0.6s_i, 2 + 0.8s_i,\ 3 + 1s_i)$, $(0.1 + 0.02s_i,\ 0.2 + 0.02s_i,\ 0.3 + 0.02s_i)$

The following schedules SH were generated:

- H = 10 (weeks): $s_1 = 0.1,\ s_2 = 0.1,\ s_3 = 8,\ s_4 = 2,$ satisfaction degree $\lambda = 0.48$;
- for H = 9 (weeks): $s_1 = 1.5,\ s_2 = 0.1,\ s_3 = 7, s_4 = 4,$ satisfaction degree $\lambda = 0.43$;
- for H = 8 (weeks): $s_1 = 0.1,\ s_2 = 0.1,\ s_3 = 6,\ s_4 = 5.8,$ satisfaction degree $\lambda = 0.39$;
- for H = 7 (weeks): $s_1 = 1,\ s_2 = 0.1,\ s_3 = 5,\ s_4 = 6,$ satisfaction degree $\lambda = 0.3$.

If the credibility degree could be increased with time, one can see that even for smaller time horizons, schedules with much higher overall satisfaction degrees could be obtained.

It can be observed that in the first case, where the credibility was fixed and could not be improved with time, even at some cost, the prudent attitude (expressed by adopting (5) and (6)) led to a situation where actually no acceptable schedule could be determined. The possibility of increasing the expertise of experts asked for judgment or of using other sources of information made it possible to obtain schedules with a shorter duration, and all these schedules had a substantially higher satisfaction degree than in the previous case.

Table 6 summarizes the experiment described above that was used to test the method.

Table 6. Summary of the experiment used to test the method.

Item	Description
tested institutions	1 public institution
tested projects	1 public project
expert selection	office employees
testing method	post factum experiment
planned extensions	more institutions researched, activity relationships included
practical aspects	real-world schedule that includes sustainability

5. Discussion

The results indicate a positive answer to the question formulated by the staff of the public institution in question: yes, it is potentially possible to incorporate dimensions of sustainability into the scheduling procedure. For the project in question, it is shown that there exists a mathematical scheduling model that takes sustainability into account, turning it into one of the objectives of a multicriterial model.

In the concrete model that was proposed, the solution also indicates an important feature: the overall satisfaction with the schedule. This indicator shows clearly that in the first version of the problem, where the expert credibility was fixed (one can have experts with a certain expertise or competences and cannot gain access to any other ones, even against payment), it is not possible to generate a schedule with an acceptable degree of satisfaction. This means that the whole project has to be rethought and redesigned.

It can be observed that in the solution the activity start times are not always integers. Of course, the fractional starting times would have to be adjusted to specific hours, days or half-days. This step would have to be performed manually (for smaller projects, like the one in question) or by means of an algorithm for bigger projects, which might introduce complexity-related problems. In such a case the use of heuristics should be considered.

The example shows a potential advantage of using models similar to (10) and (11) in the scheduling of public projects: the multicriteria approach makes it possible to find a trade-off between the cost of increasing sustainability and sustainability itself. It should be emphasized that (10) incorporates several (here, three) criteria related to suitability in its numerous dimensions as well as the credibility of sustainability evaluation. As the example in question shows, taking this credibility into account and elaborating methods and ways of increasing it may add value to the performance of public project scheduling. It is important to take into account all the sustainability dimensions and the credibility of experts evaluating them when scheduling projects that are paid with public money and realized for the public good.

6. Conclusions

In this article a general model that can be helpful in scheduling projects for which sustainability is an important issue is proposed. This is the case for many projects today, but in a special way it is true for public institutions, which have to be sustainable—in terms of taking care of people and environment—often to a higher degree than profit-oriented organizations.

The model is based on the following assumptions:

- Sustainability has to be measured in several dimensions (here, three dimensions were chosen, but this number is not a limitation).
- Being sustainable gives rise to cost and may take time—it is usually cheaper and quicker to take less care of people and the environment.
- The evaluation of sustainability is subjective and depends on the experts and information available. It may be a higher or lower quality.

These assumptions can be considered as general: they will apply to most public projects. However, in each case the approach will have to be concretized. In the paper one possible concretization is proposed.

Thus, three dimensions of sustainability are suggested to be considered: human resources consumption, material consumption and negative influence on the environment and local communities. In other cases, other measures of sustainability can be selected. The method proposed takes advantage of expert opinions and takes into account the uncertainty (credibility) level of individual expert decisions. In order to express such a complex construct in a formal way, Z-fuzzy numbers are used—to the authors' knowledge for the first time in the context of sustainability and project scheduling. Other approaches to modeling of subjective opinions and personal features can be used, too.

A model for the case where project activity sustainability can be changed is proposed, at least in some cases, for example, by paying for other activity resources or changing the time or place of activity execution. The problem of experts being asked to evaluate activity sustainability and their lacking knowledge or experience is also taken into account. Also, their opinion quality can be improved, of course at some cost. In the model a compromise solution is determined, where a trade-off between a high sustainability evaluation based on highly credible expert opinions is balanced against the cost of achieving such sustainability and of having access to high quality experts. As a result, a schedule is generated that will be acceptable in terms of "classical" project success criteria (time and cost), but at the same time will be less destructive for humans and the planet.

In real-life models many more constraints would have to be considered (e.g., the typical constraints [30] of project scheduling). What is more, for the sake of simplicity, we assume that the starting times of other tasks cannot affect the sustainability of a given activity, although in real conditions such an assumption may be untrue (e.g., 10 renovations performed at the same time increase the total noise level to an unsupportable value and thus affect the sustainability of each single renovation). Also, more research is needed on the question of how to conduct the questioning of experts and who should evaluate their credibility. One can suppose, taking into account the specificity of public institutions [32], that this process would have to be conducted intuitively, respecting the organizational and cultural context of public institutions [41], and it is clear that this will not be an easy process.

This approach is proposed, but of course not exclusively, for public institutions, whose mission includes being sustainable in all aforementioned dimensions. Its idea was inspired by a Polish municipality, which, like any other similar organization, implements a lot of large infrastructure projects where humans are often overworked and stressed, harmful materials are used, and local inhabitants are disturbed or annoyed. Moreover, the employees of this municipality are open to new project management methods, so there is a chance that further common research can be conducted. In any case, the next research steps will have to consist of case studies conducted in public institutions or other organizations ready and open for new solutions.

Of course, the acceptability of the organization employees is a sine qua non condition for the introduction of sustainable project scheduling, which will not always be easy to achieve. But it is necessary to analyze a full case study in order to validate the proposed approach. Another limitation of the research is the fact that no dependencies between project tasks were considered in the model and, of course, the difficulty to obtain the Z-fuzzy evaluations. Also, it will be necessary to introduce and investigate alternative Z-fuzzy decomposition and aggregation methods (it was mentioned that the method chosen assumes a prudent attitude, which is not always adequate, but the problem of defuzzifying Z-fuzzy numbers in accordance with real-world contexts is still an open one). The model can be also modified with respect to the aggregation method of both objectives. On the whole, the model presented here constitutes an initial proposal of a certain holistic attitude toward the scheduling of public projects: the classical Gantt charts have to be fed with pieces of information other than technically estimated durations of activities and the most technically suited resource requirements. Numerous questions have to be asked about the consequences of the choice of specific activity features, about possible scenarios and other perspectives of defining activities and project objectives in public institutions.

To sum up, hopefully the method will attract some attention to the topic of sustainable project scheduling—a subject matter that clearly is hardly present in the literature. The matter of sustainable project scheduling is especially important for public projects, because public institutions simply have to take care of humans and their planet, and public money should not be spent without taking into account human well-being and the condition of the planet. Obviously, extensive further research on a holistic approach to project defining, scheduling and using expert opinions in this process is still ahead of us.

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