project cash flow, constraint satisfaction problem, project portfolio

Marcin RELICH[*]

FUZZY PROJECT SCHEDULING USING CONSTRAINT PROGRAMMING

Abstract

The paper aims to present an application of constraint programming techniques for project portfolio scheduling taking into account the imprecision in activity duration and cost. Data specification in the form of discrete α-cuts allows combining distinct and imprecise data, and implementing a constraint satisfaction problem with the use of constraint programming. Moreover using α-cuts, optimistic, pessimistic, and several intermediate scenarios concerning the project scheduling and cash flows can be obtained and considered in terms of different risk levels.

1. INTRODUCTION

Project management is a complex decision-making process involving the time and cost estimations. The traditional approach to project management is to consider company projects as being independent of each other [1]. However, one of the characteristics of many industrial companies concerns the management of several simultaneously developed new products (projects) using the same resources. In order to maintain agility while avoiding wasteful investments, a strong discipline of project portfolio management is needed. This requires continuous attention and balancing company resources. In a multiple-project situation the vast majority of projects share resources with other projects and thus the major issue is to find a way of handling resource scarcity according to the overall strategic direction of the company and to rescue the project portfolio that tends to be at risk of failure [1, 2].

Project management problems typically consist of resource planning and scheduling decisions. In the context of resource management, it is often required to know how much a particular project will cost, what resources are

[*] University of Zielona Góra, Faculty of Economics and Management, Licealna 9, 65-216 Zielona Góra, Poland, e-mail: m.relich@wez.uz.zgora.pl

needed, what resource allocation procedure can ensure the completion of a project in target time, etc. Those requirements can be formulated as following standard, routine questions: Does the project can be completed before a given deadline? Is it possible to undertake a new project under given (constrained in time) resources availability? What is risk level for the project portfolio?

The scheduling problems that need to be solved in order to provide answers to the above questions belong to the class of NP-complete problems. The impact of real-life constraints on the decision-making is therefore of great importance, especially for designing interactive and task oriented decision support systems. Several methods and techniques have been proposed in this field, for instance, method for scheduling projects with resource constraints [3], resource levelling tools for resource constraint project scheduling problem [4], soft computing for optimization of an investment portfolio [5], the time-cost trade-off analysis in project scheduling [6], schedule-driven project management in multi-project environments [7].

In practice, managers frequently create programs and schedules based on the expected values of activity durations. However, many real-world planning and scheduling problems are subject to change, to resources becoming unexpectedly unavailable or tasks taking longer than expected [1]. The hypothesis made in critical path method that activity durations are deterministic and known is rarely satisfied in real life where tasks are often uncertain and variable [8]. The inherent uncertainty and imprecision in project scheduling have motivated the proposal of several fuzzy set theory based extensions of activity network scheduling techniques [9]. Among these extensions can be found, for instance, resource-constrained fuzzy project-scheduling problem [10], fuzzy critical chain method [11], criticality analysis of activity networks with uncertainty in task duration [12], fuzzy repetitive scheduling method [13]. Also, considerable research effort has been recently focused on the application of constraint programming frameworks [14-16].

Constraint Programming (CP) environment seem to be especially well suited for modelling real-life and day-to-day decision-making processes at an enterprise [14, 17]. CP is qualitatively different from the other programming paradigms, in terms of declarative, object-oriented and concurrent programming. Compared to these paradigms, constraint programming is much closer to the ideal of declarative programming: to say what we want without saying how to achieve it [18]. CP is an emergent software technology for a declarative Constraints Satisfaction Problem (CSP) description and can be considered as a pertinent framework for the development of decision support system software aims.

In the field of constraint-based scheduling two strengths emerge: natural and flexible modelling of scheduling problems as CSP and powerful propagation of temporal and resource constraints. Thus, the scheduling problem is modelled as CSP at hand in the required real-life detail and it enables to avoid the classical drawbacks of being forced to discard degrees of freedom and side constraints [19]. The model formulated in terms of CSP determines a single knowledge base and it enables effective implementation in constraint programming languages, as well as the development of a task-oriented decision support system for project portfolio scheduling. As a result, the problem specification is closer to the original problem, obtaining solutions that are unavailable with imperative programming. This provides motivation to consider project management in connection with the nature of a company and to develop a reference model that combines both these fields.

Although, several researchers have recognized the importance and necessity of applying fuzzy set theory or probability theory in project scheduling and project cash flow generation and analysis, there is still a lack of a use of a declarative approach in the field. The proposed approach aims at specifying project portfolio scheduling in terms of fuzzy CSP, using constraint programming to seek a solution to the problem, and enabling analysis of cash flow uncertainty at different α-levels.

The traditional approach for project scheduling is the well-known CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique) [20]. The perception or estimation of uncertainty is encoded in the initial assignment of fuzzy activity duration and cost. Thereafter, in terms of project management, different α-cuts can be considered as separate risk levels [21]. Thus, a framework is provided for conducting risk analysis on the project cash flow with the appropriate α-cuts which limit the degree of fuzziness and essentially provide a measure of the prediction robustness. The risk levels can vary from "none", "low", "moderate" to "very high" as the α-cut moves from 1 towards 0. Moreover, at any given α-cut besides a delay or cost escalation there is also an opportunity to go ahead of schedule and reduce costs [22]. Difference between the proposed approach and PERT network diagrams concerns a number of scenarios and the use of integer numbers. PERT assumes only the absolute worst and best scenarios (everything goes worse or better than expected, respectively), whereas the proposed approach includes some possibility levels from 0 to 1.

The proposed approach for project portfolio planning allows a decision-maker perform analysis of cash flow uncertainty at different α-levels. During project implementation, the cash flow is crucial for the assessment of working capital requirements since the difference between project expenditures and payments determines the necessary capital reserves. Furthermore, an accurate cash flow is required in conducting project cost-benefit analysis, the determination of project financing requirements and in performing earned value analysis [22].

The remaining sections of this paper are organised as follows: Section 2 presents a problem formulation in terms of fuzzy CSP for project portfolio scheduling. A method for cash flow generation is shown in Section 3. An illustrative example of the approach is presented in Section 4. Finally, some concluding remarks are contained in Section 5.

2. PROBLEM FORMULATION OF FUZZY CSP

A considered reference model consists of a company and project portfolio. Its specification encompasses technical parameters, expert's experiences and user expectations in the form of knowledge base, i.e. as a set of variables, their domains, and a set of relations (constraints) that restrict and link variables. Such interpretation of model allows using the logic-algebraic method as a reference engine [14]. In this context, it seems natural to classify some decision problems as CSP. The problem formulation in terms of CSP enables a simplified description of actuality, i.e. a description encompasses the assumptions of object, implementing therein tasks, and a set of routine queries (the instances of decision problems).

In a classical form, the structure of constraints satisfaction problem may be described as follows [19]: $CSP = ((V, D), C)$, where: V – a set of variables, D – a set of discrete domains of variables, C – a set of constraints. Taking into consideration the imprecise characteristics of project management, it is assumed Fuzzy Constraints Satisfaction Problem (FCSP) as follows [23]:

$$FCSP = ((\tilde{V}, D), C) \tag{1}$$

where: $\tilde{V} = \{\tilde{v}_1, \tilde{v}_2, ..., \tilde{v}_n\}$ – a finite set of n fuzzy variables that in form of fuzzy number (a finite set of discrete α-cut) are described,
$D = \{d_1, d_2, ..., d_n\}$ – a set of domains for n fuzzy variables,
$C = \{c_1, c_2, ..., c_m\}$ – a finite set of m constraints limiting and linking decision variables.

FCSP is implemented according to the structure of the reference model, and can be also considered as a knowledge base. The knowledge base is a platform for query formulation as well as for obtaining answers, and it comprises of facts and rules that are characteristic of the system's properties and the relations between its different parts. As a consequence, a single knowledge base facilitates the implementation of a decision support system.

A knowledge base can be considered in terms of a system. At the input of the system are the variables concerning basic characteristics of an object that are known and given by the user. For instance, the variables concerning available resources in the enterprise and a sequence of project activities occur in the knowledge base describing the enterprise-project model. The output of the system is described by the characteristics of the object that are unknown or are only partially known. In the considered case, the variables include the cost and time of an activity as well as the resources usage.

A distinction of decision variables that are embedded in the knowledge base as an input-output variable permits the formulation of standard routine query containing a problem of cash flow planning in multi-project environment, such as: what is cash flow uncertainty for the given constraints (e.g. the deadline and budget, activity networks)? The method concerning the determination of admissible solutions for the above-described problem is presented in the next section.

3. CASH FLOW GENERATION

Given a set of projects $P = \{P_1, P_2, ..., P_I\}$, where the project P_i consists of J activities: $P_i = \{A_{i,1}, ..., A_{i,j}, ..., A_{i,J}\}$. The j-th activity of i-th project that is specified by the starting time of the activity $s_{i,j,1}$ (i.e. the time counted from the beginning of the time horizon H), the completion time of the activity $s_{i,j,2}$, and the duration of the activity $t_{i,j}$. The project P_i is described as an activity-on-node network, where nodes represent the activities and the arcs determine the precedence constraints between activities. According to this the precedence constraints are as follows: $s_{i,j} + t_{i,j} \leq s_{i,n}$ (for the n-th activity follows the i-th one), $s_{i,j} + t_{i,j} \leq s_{i,n}$; $s_{i,j+1} + t_{i,j+1} \leq s_{i,n}$; ...; $s_{i,j+n} + t_{i,j+m} \leq s_{i,n}$ (for the n-th activity follows other activities), and $s_{i,n} + t_{i,n} \leq s_{i,j}$; $s_{i,n} + t_{i,n} \leq s_{i,j+1}$; ...; $s_{i,n} + t_{i,n} \leq s_{i,j+m}$ (for the n-th activity is followed by other activities).

Imprecise variables determined by convex membership function $\mu(s)$ (e.g. a triangular fuzzy number $\tilde{s} = \langle a, b, c \rangle$) can be specified as α-cuts. An α-cut is a crisp set consisting of elements of A which belong to the fuzzy set at least to a degree of α ($0 < \alpha \leq 1$). An α-cut is a method of defuzzifying a fuzzy set to a crisp set at desired α-levels that correspond to the perceived risk (α=1 meaning no risk, α=0+ meaning the highest risk). Additionally, the low (α=0–) and high (α=0+) values of every α-cut represent the optimistic and pessimistic outcomes of that risk level. The main objective of fuzzy project scheduling is to apply fuzzy set theory concepts to the scheduling of real world projects where task duration can be specified as fuzzy numbers instead of crisp numbers [22].

The application of the FPS algorithm yields the fuzzy start and completion dates of activities. In the project network, the fuzzy start indicates the accumulation of uncertainty from preceding activities, whereas, the fuzzy completion date is the sum of the activity start with the activity duration. The fuzzy addition operator (+) for two triangular fuzzy numbers is defined as:

$$\tilde{s} + \tilde{t} = \langle a, b, c \rangle + \langle d, e, f \rangle = \langle a + d, b + e, c + f \rangle \quad (2)$$

The example of addition the fuzzy starting time of the activity to fuzzy the duration of the activity for three α-levels is illustrated in Fig. 1.

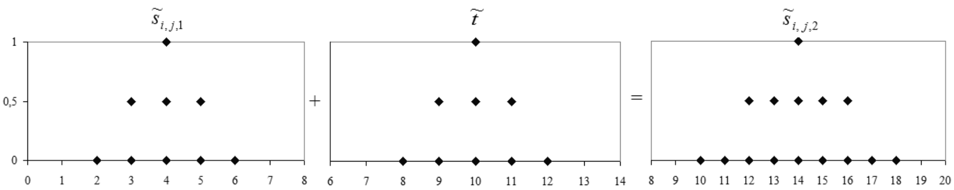

Fig. 1. Addition fuzzy numbers in terms of discretized α-cuts [source: own study]

In order to calculate the required cost per unit of time, the cost of every activity needs to be divided by its duration. However, the duration varies for different possibility measures and for optimistic and pessimistic scenarios. In the absolute best case ($\min D_\alpha$), the activity will start as early as possible and will last the minimum duration. In the absolute worst case ($\max D_\alpha$), the activity will start as late as possible and will last the maximum duration. Considering an activity with an early start and completion dates, these intervals are defined as follows [22]:

$$minD\alpha = [\alpha(b-a) + a,\ \alpha(e-d) + d] \quad (3)$$

$$maxD\alpha = [\alpha(b-c) + c,\ \alpha(e-f) + f] \quad (4)$$

where: $\min D_\alpha / \max D_\alpha$: is the interval of minimum/maximum duration of the activity at the respective α-cut,

D_α: is the α-cut of the activity duration.

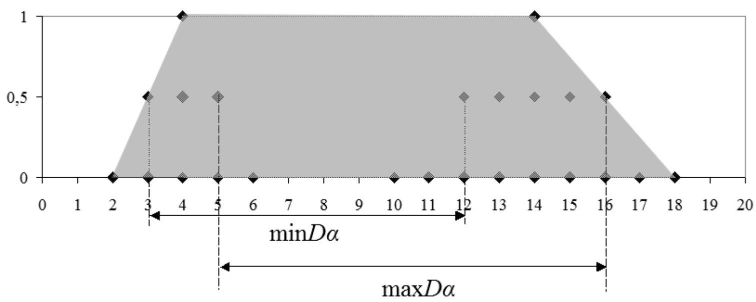

Fig. 2. Fuzzy activity start and completion date [source: own study]

Figure 2 shows an activity with a starting time of <2, 4, 6>, a duration of <8, 10, 12>, and a completion time of <10, 14, 18>. In this example, the duration intervals at α=0.5 are min$D_{0.5}$=[3, 12] and max$D_{0.5}$=[5, 16] and hence the activity cost is distributed in these intervals. In the best case, the activity begins as early as possible (3rd month) and lasts the minimum duration (9 months), whereas in the worst case, it starts as late as possible (5th month) and lasts the maximum duration (11 months). Similarly, minimum and maximum duration intervals representing optimistic and pessimistic scenarios for different possibility measures can be created for all α-levels (between 0 and 1). Consequently, the fuzzy start date and completion date mark the temporal start and completion boundaries of the activity within which the minimum and maximum duration intervals (minD_α/maxD_α) are defined for each α-cut.

The financial means are allocated to the activity $A_{i,j}$. taking into account all α-levels of a fuzzy number ($dp_{i,j,\alpha}$). If the cost for time unit is not an integer, then the cost is assigned as follows: for minD_α – the first value is less than the rest, for maxD_α – the last value is greater than the rest. Table 1 shows an example of the cost distribution for the activity equals 80 monetary units (m.u.) at five separate possibility levels. At time unit h = 3 for min$D_{0.5}$, there are 9 time units (see Fig. 2), the cost for a time unit equals 8.89 m.u., so for 8 time units (h = 4, …, 11) the cost distribution equals 9 m.u. and for first time unit (h = 3) equals 8 m.u. (80m.u. – 8*9 m.u.).

Tab. 1. An example of cost distribution for fuzzy duration of activity

h / α	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
minD_0			10	10	10	10	10	10	10	10											
min$D_{0.5}$				8	9	9	9	9	9	9	9	9									
D_1					8	8	8	8	8	8	8	8	8	8							
max$D_{0.5}$						7	7	7	7	7	7	7	7	7	7	10					
maxD_0							6	6	6	6	6	6	6	6	6	6	6	14			

The uncertainties of the duration and cost of an activity are positively correlated, so the minimum and maximum cost distribution per unit of time h of the j-th activity at the level α depict the best and the worst scenario, respectively. An example concerning the considered problem described in the constraint programming environment is presented in the next section.

4. ILLUSTRATIVE EXAMPLE

The example consists of three subsections: the description of project portfolio, the analysis of the first admissible solution of the fuzzy scheduling problem, and the analysis of cash flow distribution in project portfolio. The analyses contain the examination of project fuzzy Gantt charts and fuzzy project cash flows.

4.1. Project portfolio description

The example concerns new products development that can be considered as project portfolio $P = \{P_1, P_2, P_3\}$. It is assumed that the time horizon for the project portfolio equals 32 months ($H = \{0, 1, \dots, 32\}$) and the budget of project portfolio is fixed at 1,150 m.u. The network diagrams of the activities in the project portfolio are shown in Fig. 3-5.

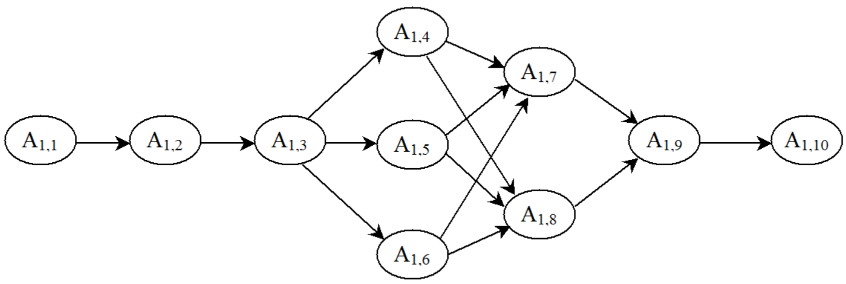

Fig. 3. Network diagram for project P_1 [source: own study]

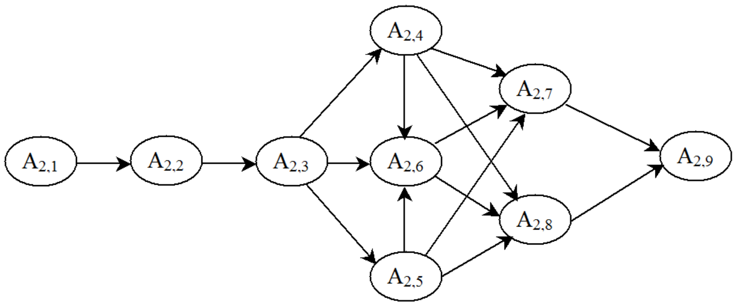

Fig. 4. Network diagram for project P_2 [source: own study]

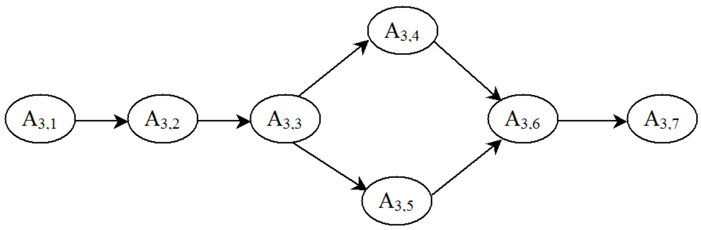

Fig. 5. Network diagram for project P_3 [source: own study]

Duration of project activities is estimated by using past experiences and/or an expert's knowledge. The different types of projects require the appropriate methods of forecasting that have been presented e.g. in [24-30]. The duration of some activities ($A_{1,7}$, $A_{1,10}$, $A_{2,4}$, $A_{2,7}$, $A_{2,9}$, $A_{3,4}$, $A_{3,5}$, $A_{3,6}$, $A_{3,7}$) is specified in the imprecise form. The sequences of activity duration for the considered projects can be described as follows: T_1 = (2, 1, 1, 6, 2, 2, "about 6", 1, 4, "about 6"), T_2 = (2, 2, 1, "about 9", 6, 4, "about 6", 4, "about 5"), T_3 = (1, 1, 1, "about 6", "about 6", "about 5", "about 4"). For instance, the duration of the activity $A_{1,7}$ is "about 6", i.e. the activity can be executed within the time period of 5 till 7 units of time.

4.2. Fuzzy scheduling

The standard routine queries formulated can be as follows: is there portfolio schedule (and if yes, what are its parameters) that follows from the given project constraints specified by the activity duration times, the deadline and budget of project portfolio? What are the fuzzy project cash flows for different risk levels? The answer to the questions is connected with the determination of the starting time of project portfolio activities s_{ij} and the allocation of financial means to the activities by different α-level $dp_{i,j,\alpha}$. For the considered project portfolio and α-level equals 1, the following sequences are sought: $S_1 = (s_{1,1}, \ldots, s_{1,10})$, $S_2 = (s_{2,1}, \ldots, s_{2,9})$, $S_3 = (s_{3,1}, \ldots, s_{3,7})$, $Dp_1 = (dp_{1,1,1}, \ldots, dp_{1,10,1})$, $Dp_2 = (dp_{2,1,1}, \ldots, dp_{2,9,1})$, $Dp_3 = (dp_{3,1,1}, \ldots, dp_{3,7,1})$.

Figure 6 presents the project portfolio schedule, in which the sequences of activity starting time are as follows: S_1 = (0, 2, 3, 4, 4, 4, 10, 10, “about 16”, “about 20”), S_2 = (0, 2, 4, 5, 5, “about 14”, “about 18”, “about 18”, “about 24”), S_3 = (0, 1, 2, 3, 3, “about 9”, “about 14”). The completion time of project P_1, P_2, P_3 equals “about 26”, “about 29”, and “about 18” months, respectively.

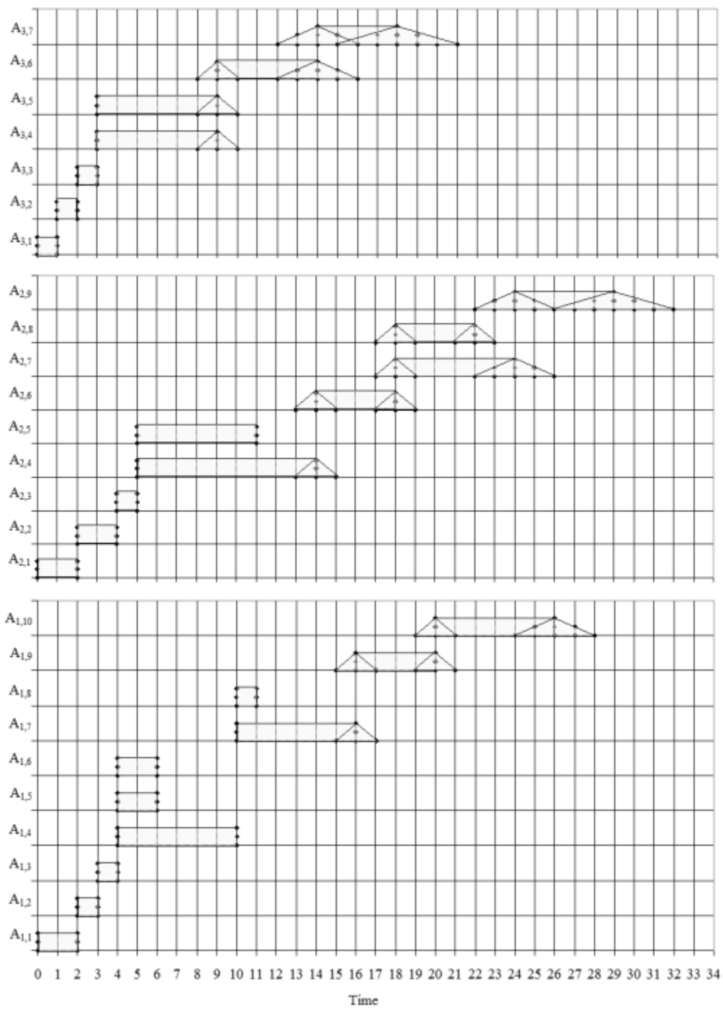

Fig. 6. Project portfolio schedule [source: own study]

It is noteworthy that using presented methodology, the level of uncertainty increases for subsequent activities according to the number of activities with the fuzzy duration. As a consequence, this can lead to the difficulties with the interpretation, because the fuzzy starting time of the activity can be greater than the fuzzy completion time. This case is presented in Fig. 6 for activity $A_{3,7}$ between 15 and 16 time unit. The proper interpretation and exploitation of the results attained by the presented method are subject to further research.

4.3. Fuzzy cash flow

Figure 7 presents five different cash flows for project portfolio (cumulative cost for project P_1, P_2, and P_3). At μ=1, the cash flow (dotted line) is equivalent to that generated from deterministic analysis. At μ=0.5, there is an optimistic scenario below and a pessimistic one above (dashed line). In turn at μ=0, the optimistic and pessimistic cash flows (solid line) have a wider spread indicating a higher degree of uncertainty. In the best case, the project portfolio will be completed in 26 months with the total cost of 921 m.u., whereas in the worst in 32 months with the total cost of 1,119 m.u.

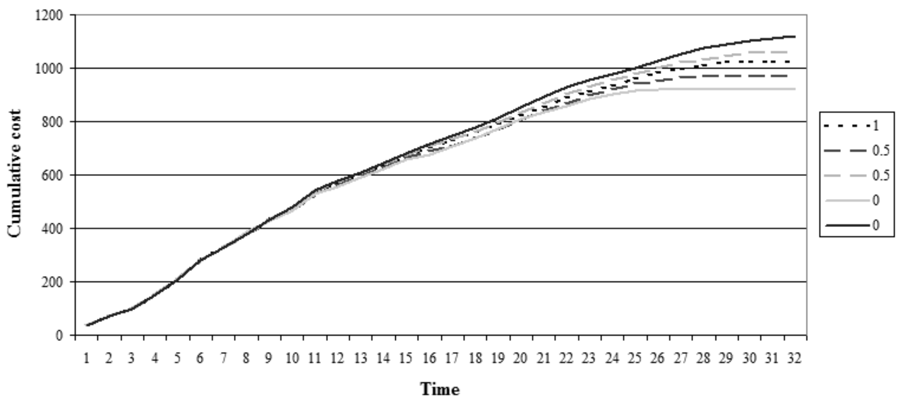

Fig. 7. Fuzzy cash flows for project portfolio [source: own study]

The presented approach allows the decision-maker to consider a wide range of analyses, including the requirement of the cost allocation in the horizon of project portfolio (Fig. 8), as well as to detail the analyses in the aspect of a single project.

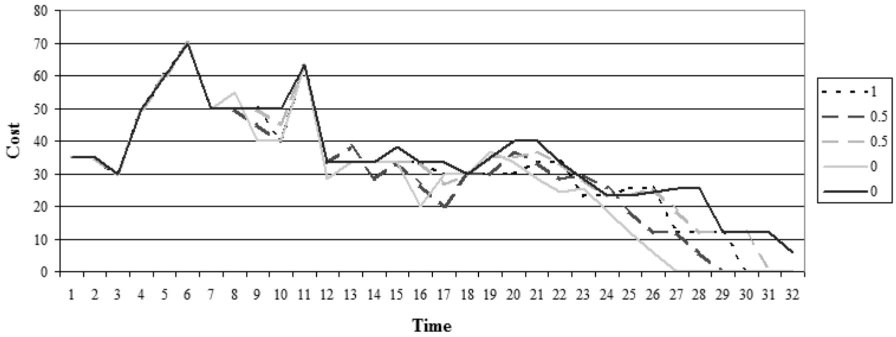

Fig. 8. Cost distribution for project portfolio [source: own study]

The feasible variants can be assessed according to a criterion such as the minimal total time, cost, relation time-cost, etc. Thus, the obtained variants provide a plan for project portfolio execution, and provide a base for further adjustment aimed at fitting to real-live execution.

5. CONCLUSIONS

Most of the projects are executed in the presence of uncertainty and are difficult to be managed, for they include many activities linked in a complex way. Hence, there is an increase in demand for new knowledge that enables the solution of problems encountered during complex project portfolio execution. In this case, knowledge concerning project management, especially project portfolio scheduling, is particularly significant. The proposed approach takes into account different form of variables (distinct, imprecise) and constraints as well as permits to formulate project scheduling problems. The model supports descriptive statement of the problem followed by its implementation in one of the constraint logic languages.

Constraint programming is an emergent software technology for declarative CSP description and can be considered as a pertinent framework for the development of decision support system software aims. CSP can always be solved with a brute force search, i.e. all possible values of all variables are enumerated and each is checked to see whether it is a solution. However, for many intractable problems, the number of candidates is usually too large to enumerate them all. CP has developed some manners (constraint propagation and variable distribution) to solve CSP that greatly reduce the amount of search needed. This is sufficient for solving many practical problems, including project portfolio planning and scheduling.

The proposed methodology can be easily incorporated into available fuzzy project scheduling software to provide a better perception of risk that is usually obscured in the conventional approach. A number of α-levels can be modified according to a decision-maker's requirements. As a result, it can assist project managers to gain deeper insight into the sources and extents of uncertainty, which consequently may lead to the avoidance of a project failure. Also, the presented approach is useful in the assessment of financial requirements during feasibility stage and project realization, as well as it may provide an evaluation of alternative proposals of a project completion. Moreover, the proposed approach tends to achieve a balance between a complexity of methodology and an intuitive, effective decision support system that is realistic in modelling uncertainty. Finally, its application in performing earned value analysis during project monitoring may also provide the useful results.

Further research focuses on the increase a number of the α-levels in order to eliminate the intersection of fuzzy starting and completion time of an activity. Moreover, future research can be aimed at comparing searching strategies in the aspect of a different number of the α-levels.

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