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# THREE STEP PROCEDURE FOR A MULTIPLE CRITERIA PROBLEM OF PROJECT PORTFOLIO SCHEDULING

The project portfolio scheduling problem as a multiple criteria decision making problem and a three step procedure to solve this problem have been presnted. In the first step, the problem was described by a multiple criteria mathematical model. Three criteria have been considered: minimization of the sum of penalties for projects delays, minimization of resource overuse and NPV maximization. In the second step, non-dominated solutions were identified by using an elitist evolutionary algorithm for multiple optimization. In the third step, an interactive procedure has been applied to choose the final solution. An example of a portfolio of IT projects was used for computations.

Keywords: *project scheduling, multiple criteria analysis*

## 1. Introduction

Over 25% of economic activities can be managed by projects [6]. In many companies, portfolios of projects are run at the same time. A portfolio is a collection of projects and other work (also programs) that are grouped together for effective management and to meet strategic objectives [5]. Project portfolios and programs are both sets of projects. A project portfolio is managed to meet strategic goals and a program is managed to meet business objectives [26]. Projects in a portfolio compete for resources. Projects in a program have a common output, which are business goals and projects in a portfolio have common inputs which are resources availability [35].

A scheduling problem is considered in this paper. This problem involves forecasting the processing of work by assigning resources to tasks and fixing their start times [7]. Scheduling concerns the allocation of limited resources to tasks over time. It is a process of decision-making with a goal – the optimization of one or more objectives [28].

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There are many methodologies for project scheduling, and the most popular are CPM and PERT. These methods deliver schedules with an optimal finish time for the project. In real-life applications, a schedule should optimize not only the finish time of the project but also resource usage and cash flows. Moreover, these techniques are not used directly for project portfolio scheduling. These methodologies are implemented in software for project management, where a project portfolio needs to be presented as a single project. Taking these limitations into account, multiple criteria decision making methods can be used to facilitate the problem of scheduling project portfolios.

Project scheduling problems have been studied extensively for many years and many mathematical models to describe such problems have been developed.

Due to their variety, no simple classification of mathematical models for project scheduling problems exists in the literature. Icmei, Erenguc and Zappe [15] made an attempt to prepare general classification of deterministic models.

Project scheduling problems can be classified in terms of:

• the number of scheduled projects (scheduling problems for single projects or scheduling problems for multiple projects);

• the number of objective functions (scheduling problems with a single objective or scheduling problems with multiple objectives),

• the type of objective function (time optimization, resource optimization, optimization of economic factors, e.g. cost or NPV),

• the number and type of constraints.

Each project scheduling problem includes constraints resulting from the range of values a variable can take and precedence relationships. Moreover, constraints can result from time and resources (financial and non-financial).

In the project scheduling problem we can consider three types of mathematical models in terms of the number and type of constraints:

• mathematical models without any time or resource constraints [29],

• mathematical models with either time [37] or resource constraints [13, 14, 18, 36],

• problems with both time and resource constraints [2, 4, 27].

The most frequently considered type of problem in the literature is the project scheduling problem with resource constraints and time [3, 19, 30–32] or NPV [1, 9, 16, 37] optimization.

So far, few papers have considered multiple criteria problems of project scheduling or the problem of project portfolio scheduling. Even fewer have considered multiple criteria problems of project portfolio scheduling. An example of describing and solving a multiple criteria problem of project scheduling is presented in the paper by Viana and de Sousa [38]. They considered a resource constrained problem in which the project completion time is minimized, project delay is minimized and disorders in resource usage are minimized as objectives. Another example is described in the paper by Leu and Yang [24] who considered a resource constrained problem with time, cost

and resource usage optimization. Hapke, Jaszkiewicz and Słowiński [12] described a problem with three criteria: project cost minimization, project delay minimization, and resource usage optimization. A problem of project portfolio scheduling was considered by Goncalves, Mendes and Resende [10], who described a resource constrained problem with time optimization. Chiu and Tai [8] presented a resource constrained problem with an objective function in which the NPV was combined with a penalty for delays in realizing the project. A multiple criteria problem of project portfolio scheduling was described by Lova, Maroto and Tormos [25]. They proposed a model in which the problem is solved in two stages. In the first one, a optimal time schedule is prepared. In the second stage, the schedule obtained is improved in terms of resource usage. Other authors also considered scheduling problems for multiple projects in their papers, however they did not focus on a mathematical presentation but on methods for solving the problem [11, 21, 23, 26, 33, 34, 40].

The purpose of this paper is to describe a procedure for solving multiple criteria problems of project portfolio scheduling. The proposed procedure consists of three steps: describing the problem of project portfolio scheduling as a multiple criteria decision making problem using an evolutionary algorithm to obtain a sample of non-dominated solutions and using an interactive procedure to find the final solution to the problem. Computations will be carried out based on a real life example – a portfolio of IT projects.

## 2. The decision problem

### 2.1. Description of the problem

There is a portfolio of projects that needs to be scheduled. By scheduling we will understand setting the start and finish times of each activity. The resources required and available, cash flows generated by each activity and precedence relationships are defined. The project team consists of several members. Moreover, the project manager can hire additional members from outside of the team. These resources cost extra (and will be called external resources). Each activity is described by the following parameters: duration, resources required, generated cash flows.

A schedule should be a compromise solution between the following criteria:

• minimization of the sum of penalties for projects delays within the portfolio (in relation to the time defined by the decision maker),

• resource usage optimization by minimizing the cost of using additional resources (resources from outside of the project team),

• maximization of (NPV).

## 2.2. Assumptions

The following assumptions are made:

General assumptions:

- There is a set of $P$ projects, $p = 1, ..., P$.
- Each project contains $J$ activities, $j = 1, ..., J$.
- A single project is described by an AON network[1].
- The realization of a project can depend on another one (e.g. when activity $j_2$ of project $p_2$ cannot start until activity $j_1$ of project $p_1$ is finished).
- A break in realization of commenced activities is not allowed.

Time assumptions:

- Deterministic duration times are considered.
- The project portfolio is due to be completed by time $T$ ($t = 0, ..., T$) – the $t$-th time period is considered to be the interval $(t - 1, t)$.
- All projects need to be finished by time $T$.
- A penalty for delays in projects realization is foreseen.
- The delay is defined according to the planned completion time (defined by decision maker).

Assumptions regarding cash flows:

- Cash flows are generated when an activity is finished[2].

Assumptions regarding resources:

- Only renewable resources are taken into account[3] ($k = 1, ..., K$).
- There are two types of resources: internal (available in the portfolio) and external (available to the company at extra cost).
- Renewable resources are constrained at each period of time. The availability of resources can be different at each period of time.

# 3. Procedure for solving a multiple criteria problem of project portfolio scheduling

The problem defined above will be solved by using a three step procedure. This procedure consists of the following stages:

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[1]A project scheduling problem can be presented by an AOA or AON network. Using an AON network enables one to use all types of precedence relationships: finish-to-start, finish-to-finish, start-to-start, start-to-finish type.

[2]In a project scheduling problem cash flows can be generated in each time unit of an activity's duration or at the end of this activity.

[3]One may also assume that nonrenewable resources are available.

    1. Building a multiple-criteria mathematical model.

    2. Finding non-dominated solutions using the SEPA2 [41] algorithm.

    3. Identifying a solution from the Pareto set as the final solution, using the LBS [17] algorithm.

## 3.1. Mathematical model

The following symbols have been used:

$x_{jpt}$ – decision variable ($x_{jpt} = 1$ when activity $j$ of a project $p$ is carried out in period $t$, $x_{jpt} = 0$ otherwise

$d_{jp}$ – duration of activity $j$ of project $p$

$r_{jpk}$ – amount of renewable resource $k$ required by activity $j$ of project $p$

$R^w{}_{kt}$ – availability of internal renewable resource $k$ at time $t$

$R^z{}_{kt}$ – availability of external renewable resource $k$ at time $t$

$F_{jp}$ – finish time of activity $j$ of project $p$

$S_{jp}$ – start time of activity $j$ of project $p$

$LF_{jp}$ – deadline for activity $j$ of project $p$ set in the agreement

$Y_p$ – grace period for project $p$

$Z_p$ – penalty rate for delay in project $p$

$V_p$ – penalty for overuse of internal renewable resource $k$

$\alpha$ – discount rate

$cf_{jp}$ – net cash flow generated by activity $j$ of project $p$

$A_{jp}$ – set of predecessors $i$ ($i = 1, ..., I$) of activity $j$ of project $p$.

### 3.1.1. Constraints

**Decision variables.** The construction of a mathematical model starts from identifying the constraints for the given problem. There are two types of decision variables considered in the literature: variables describing the finish time of an activity [38] and decision variables describing the duration of an activity [8]. The former approach enables using a smaller number of variables but controlling resource usage is much more difficult. The latter approach enables simpler identification of resource usage but the number of decision variables is large. In this paper, the latter approach is considered.

The decision variables are binary:

$$x_{jpt} = \{0, 1\} \tag{1}$$

The variable $x_{jpt} = 1$ when activity $j$ of project $p$ is being carried out at time $t$, otherwise $x_{pjt} = 0$. There are $JPT$ variables in this problem.

**Duration of activities.** Each activity has a defined duration. A single activity needs to be finished only once. The decision variables indicate the time units when an activity is being carried out. By summing the decision variables for each activity $j$ of project $p$, we obtain the duration of that activity. Hence, we obtain the following constraint:

$$\bigwedge_{p=1} \bigwedge_{j=1, \dots, J} \sum_{t=1}^{T} x_{jpt} = d_{jp} \tag{2}$$

**Precedence relationships.** This type of constraint is based on the start and finish times of the activities involved in a precedence relationship. Recall that the time period $t$ is the interval of time $[t-1, t]$. By multiplying a decision variable by time $(tx_{jpt})$ for each time unit $\bigwedge_{t=1, \dots, T}$ we obtain the times at which each activity is being carried out. The maximum of these is the finish time of activity $j$ of project $p$:

$$F_{jp} = \max_{t=1, \dots, T} (tx_{jpt}) \tag{3}$$

The minimum of $(tx_{jpt})$ reduced by 1 (for values different from 0) is the start time of activity $j$ of project $p$:

$$\bigwedge_{x_{jpt} \neq 0} S_{jp} = \min_{t=1, \dots, T} (tx_{jpt}) - 1 \tag{4}$$

Once started, the activities cannot be interrupted which is described as follows:

$$F_{jp} = S_{jp} + d_{jp} \tag{5}$$

There are four types of constraints resulting from precedence relationships:
• Finish to start

$$S_{jp} \geq F_{ip}, \qquad i \in A_{jp}^{\mathrm{I}} \tag{6}$$

• Start to start

$$S_{jp} \geq S_{ip}, \qquad i \in A_{jp}^{\mathrm{II}} \tag{7}$$

• Start to finish

$$F_{jp} \geq S_{ip}, \qquad i \in A_{jp}^{\mathrm{III}} \tag{8}$$

• Finish to finish

$$F_{jp} \geq F_{ip}, \qquad i \in A_{jp}^{\mathrm{IV}} \tag{9}$$

**Availability of resources.** The resources available for realizing a project are equal to $R_k^w + R_{kt}^z$ (the sum of internal and external resources). The use of each resource is measured in each period of time ($\bigwedge\limits_{k=1,\ ...,\ K}\bigwedge\limits_{t=1,\ ...,\ T}$) by the sum of ($r_{jpk}x_{jpt}$) for each activity $j$ of project $p$. Hence, we obtain the following constraint:

$$\bigwedge_{k=1,\ ...,\ K}\bigwedge_{t=1,\ ...,\ T}\sum_{p=1}^{P}\sum_{j=1}^{J}(r_{jpk}x_{jpt}) \le R_{kt}^w + R_{kt}^z, \qquad k=1,\ ...,\ K \tag{10}$$

### 3.1.2. Optimization criteria

**Minimizing the penalty for project delays.** Time optimization is frequently undertaken in the literature. In most cases this criterion is defined as follows [20]:

$$\sum_{j=1}^{J}\sum_{t=1}^{T}tx_{jt} \to \min$$

This objective function minimizes the sum of the finish times of activities. Because this objective function and its value does not define the real finish time or delay of the project, a new objective function for project time optimization is proposed in this paper.

The criterion presented in this paper is based on the difference between the real and planned finish time of the project $F_p - LF_p$. If this indicator is positive, then the project is delayed. Only delayed projects are taken into account, so the maximum of $F_p - LF_p$ and 0 is considered: $\max\{F_p - LF_p,\ 0\}$. A grace period $Y_p$ is foreseen, so the delay is reduced by this value: $\max\{\max\{F_p - LF_p,\ 0\} - Y_p,\ 0\}$. The delay should be multiplied by the penalty rate $Z_p$ to obtain the penalty for the delay in project $p$. The penalties for projects delays are summed over the project portfolio:

$$\sum_{p=1}^{P}\left\{\left[\max\left[\max\left(F_p - LF_p,\ 0 - Y_p, 0\right)\right]\right]Z_p\right\} \to \min \tag{11}$$

**Resources optimization.** Optimization of resource usage is not frequently undertaken in the literature. This criterion is based on the difference between the values of available and used resources [20]. In this paper, the cost of using additional resources is minimized.

As in constraint (10), resources usage is set in each period of time and summed over all the projects in the portfolio. Then it is reduced by the value of internal resources available to obtain the required information about usage of external resources. Only when the difference between the value of resource usage and the value of internal resources is

greater than 0 an extra cost will be paid: $\max\left\{\sum_{p=1}^{P}\sum_{j=1}^{J}(r_{jpk}x_{jpt})-R_{kt}^{w},0\right\}$. This number

is multiplied by the cost of using external resources and summed over each resource type and each time unit:

$$\sum_{t=1}^{T}\left[\sum_{k=1}^{K}\left[\max\left\{\sum_{p=1}^{P}\sum_{j=1}^{J}(r_{jpk}x_{jpt})-R_{kt}^{w},0\right\}V_{k}\right]\right]\to\min \qquad (12)$$

**Optimization of cash flows.** This criterion is frequently used in the literature and this paper uses the standard criterion from the literature [1, 9, 16, 37].

According to this criterion, discounted cash flows are maximized:

$$\sum_{p=1}^{P}\sum_{j=1}^{J}cf_{jp}e^{-\alpha F_{jp}}\to\max \qquad (13)$$

### 3.1.3. The mathematical model

The mathematical model has the following structure – from formulas (1)–(13):

$$\sum_{p=1}^{P}\left[\left[\max\{\max\{F_{p}-LF_{p},0\}-Y_{p},0\}\right]Z_{p}\right]\to\min$$

$$\sum_{t=1}^{T}\left[\sum_{k=1}^{K}\left[\max\left\{\sum_{p=1}^{P}\sum_{j=1}^{J}(r_{jpk}x_{jpt})-R_{kt}^{w},0\right\}V_{k}\right]\right]\to\min, \qquad k=1,...,K$$

$$\sum_{p=1}^{P}\sum_{j=1}^{J}cf_{jp}e^{-\alpha F_{jp}}\to\max$$

$$x_{jpt}=\{0,1\}$$

$$\bigwedge_{p=1}\bigwedge_{j=1,...,J}\sum_{t=1}^{T}x_{jpt}=d_{jp}$$

$$F_{jp}=\max_{t=1,...,T}(tx_{jpt})$$

$$\bigwedge_{x_{jpt}\neq0}S_{jp}=\min_{t=1,...,T}(tx_{jpt})-1$$

$$F_{jp} = S_{jp} + d_{jp}$$

$$S_{jp} \geq F_{ip}, \qquad i \in A_{jp}^{\mathrm{I}}$$

$$S_{jp} \geq S_{ip}, \qquad i \in A_{jp}^{\mathrm{II}}$$

$$F_{jp} \geq S_{ip}, \qquad i \in A_{jp}^{\mathrm{III}}$$

$$F_{jp} \geq F_{ip}, \qquad i \in A_{jp}^{\mathrm{IV}}$$

$$\bigwedge_{k=1,\,\ldots,\,K} \bigwedge_{t=1,\,\ldots,\,T} \sum_{p=1}^{P} \sum_{j=1}^{J} (r_{jpk} x_{jpt}) \leq R_{kt}^{w} + R_{kt}^{z}, \qquad k = 1, \ldots, K$$

### 3.2. Identification of non-dominated solutions

To identify a sample of the non-dominated set, the SPEA 2 (Strength Pareto Evolutionary Approach) algorithm is used [41]. Using this algorithm, non-dominated solutions are indentified in each generation and are moved to an external set. These solutions are automatically made members of the next generation.

The main loop of the strength Pareto Evolutionary Approach algorithm can be presented as the following set of steps:

Step 1. Initialization. An initial population $P_0$ of individuals (solutions) is generated and an empty external set $\overline{P_0}$ is created.

Step 2. Performance. Fitness assignment is performed for the individuals located in $P_0$ and $\overline{P_0}$.

Step 3. Selection and updating the external set. All non-dominated solutions are copied from $\overline{P_t}$ and $P_t$ to $\overline{P_{t+1}}$.

If $\overline{P_{t+1}}$ exceeds the allowed size of the external set, it is reduced.

If the number of individuals in $\overline{P_{t+1}}$ is smaller than the allowed size of the external set, then it is filled with dominated individuals from $\overline{P_t}$ and $P_t$.

Step 4. Termination. The algorithm stops when a stop criterion is fulfilled, then individuals located in the external set $\overline{P_{t+1}}$ become candidates for the final solution.

Step 5. Mating selection. Tournament selection with replacement from $\overline{P_{t+1}}$ is used to fill the mating pool.

Step 6. Variation. Genetic operators are applied on individuals from the mating pool. The result is the population $P_{t+1}$.

Each individual is assessed according to the criteria described in section 2.1, then evaluation based on SPEA 2 is performed. A strength $S(i)$ is assigned to each individual, which represents the number of individuals that individual $i$ dominates.

$$S(i) = |\{j \mid j \in P_t + \overline{P_t} \land i \succ j\}|$$

Then the raw fitness of individual $i$ is calculated.

$$R(i) = \sum_{j \in P_t + \overline{P_t},\, j \succ i} S(j)$$

We discriminate between individuals using a density function. The density function is defined by $D(i) = 1/(\sigma_i^k + 2)$. An individual's fitness is given by $F(i) = R(i) + D(i)$.

The binary variables used in the problem are described in section 2.1, so an individual can be described by a binary matrix, in which the number of rows is equal to $JP$ and the number of columns is equal to $T$. Individual $i$ can be represented as follows:

$$i = \begin{bmatrix} x_{111} & x_{112} & \cdots & x_{11T} \\ x_{211} & x_{212} & \cdots & x_{21T} \\ \vdots & \vdots & \vdots & \vdots \\ x_{JP1} & x_{JP2} & \cdots & x_{JPT} \end{bmatrix}$$

Moreover, genetic operators (crossover and mutation) are defined. A crossover is an exchange of randomly chosen rows between two individuals. A mutation is a shift of the start time of a randomly chosen activity.

It is possible that a solution does not satisfy the constraints. To deal with the constraints, a penalty for a solution not being feasible is used. If a solution is not feasible, its performance function is transformed by multiplying by 2 in the case of a minimization criterion and by multiplying by −1 when the criterion involves maximization.

### 3.3. Identification of the final solution

The Light Beam Search [17] procedure is used in the third phase to identify the final solution among the non-dominated solutions obtained in the second phase. This method assumes the engagement of the decision maker.

Using this algorithm, a finite sample consisting of non-dominated solutions is generated at each stage. There is a middle point (from the previous iteration) and non-dominated solutions from its neighborhood in this sample. A figure illustrating the idea of the algorithm may be found in [17, p. 303]).

The procedure can be described as follows:

Step 1. Ask the decision maker to specify starting aspiration and reservation point and compute the starting middle point.

Step 2. Ask the decision maker to specify information on local preferences to build an outranking relation.

Step 3. Present the middle point to the decision maker.

Step 4. If the decision maker feels satisfied with a solution, stop.

Step 5. Calculate characteristic neighboring solutions and present them to the decision maker.

Allow the decision maker to choose solutions in the current neighborhood.

Step 6. If the decision maker wants to store a solution, add it to the set of stored solutions.

If the decision maker wants to define new aspiration or reservation points, ask the decision maker about them.

If the decision maker wants a point from the neighborhood to be the new middle point, ask the decision maker to indicate this point.

If the decision maker wants to return to one of the stored points, use this point as the new middle point.

If the decision maker wants to update information about preferences, ask the decision maker for new information.

Go back to step 3.

# 4. Multiple criteria scheduling of a project portfolio in an IT company

## 4.1. Description of the problem

The procedure described in Section 2 was implemented to schedule an IT project portfolio. The research was carried out in a company from the region of Silesia. The company deploys an ERP system.

There are about 30 deployment projects managed simultaneously by 8 teams. One team leads 3 to 4 projects. For each project 37 activities are defined (these activities are described in the company`s project guide). Each project can be described using the same set of 37 activities. A single project can be represented by a network as follows (Fig. 1).
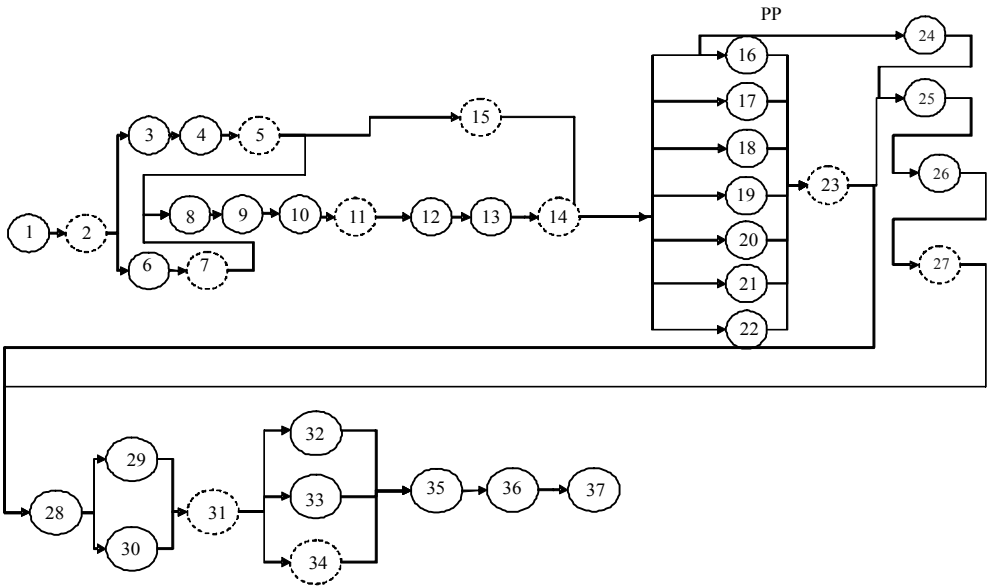
Fig. 1. Project network. Source: Prepared based on the company's project guide

A project team consists of 10 employees but in special cases additional resources can be gained from the company at extra cost.

The company signs a contract with customers. This contract includes information about the main issues of the project. In this contract a due date and a penalty rate for delays in realizing the project is defined. Payment for the project is also defined in the contract. Payment is split into 12 parts.

There are 4 projects at different levels of advancement. 27 activities of project one, and 7 activities of project two have been finished. Project three can start when activity 7 of project two is finished. Project four has not started yet. It can start at the beginning of the planning horizon.

Each project portfolio manager wants to maximize profit. That is why projects in a portfolio should be finished on time, external resources should not be used and the project portfolio schedule should maximize its NPV.

## 4.2. Building a mathematical model

In the given problem there are $P = 4$ ($p = 1, ..., 4$) projects. Each project is described by $J = 37$ ($j = 1, ..., 37$) activities and the planning horizon is $T = 271$ ($t = 1, ..., 271$) time units. The number of variables in the model described in Section 2.1 is $JPT$, so there are 40 108 variables in the problem.
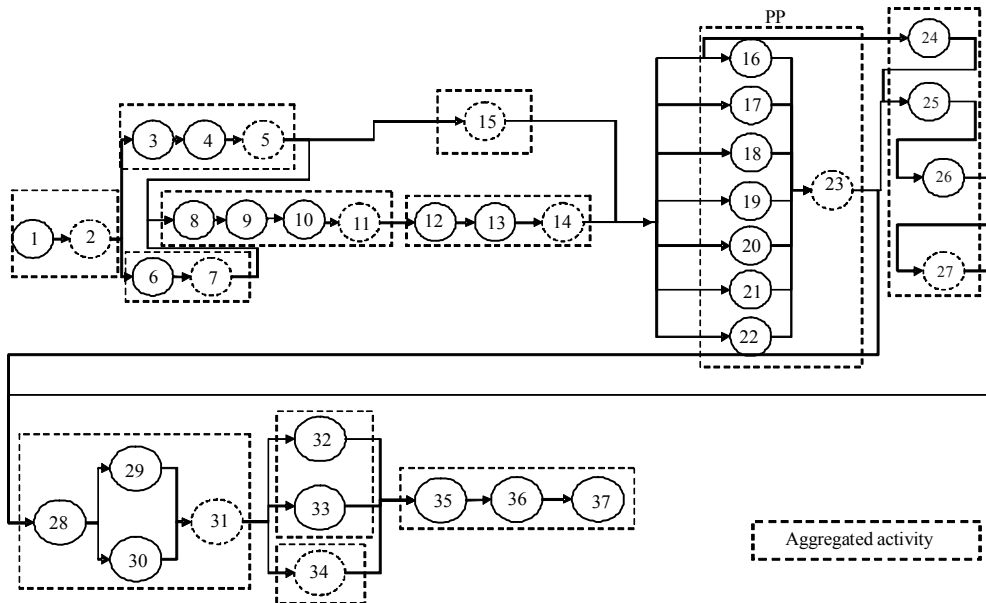
Fig. 2. Project network composed of aggregated activities

The project portfolio managers were interviewed and they claimed that no single activity is important to them but rather whole phases. This is the reason for aggregating the activities into 12 phases (Fig. 2, Table 1).

Table 1. ERP deployment – project phases

| |
|---|
| Phase 1. Preparation for deployment/defining the project |
| Phase 2. IT analysis |
| Phase 3. Preparation of technical and application environment |
| Phase 4.Configuration of application |
| Phase 5. Testing |
| Phase 6. Programming |
| Phase 7. Training |
| Phase 8. Data preparation |
| Phase 9. System testing |
| Phase 10. Implementation of all functions |
| Phase 11. Implementation of the budgeting module |
| Phase 12. Project closure |

Source: Company's project guide.

Aggregating these activities enabled reducing the number of variables to 13 008, which is still a big number.

## 4.3. Non-dominated solutions

The SPEA2 algorithm was used to find a sample of non-dominated solutions. The following parameters were used for the computations[4]:

- population: 300 solutions,
- number of generations: 10 000,
- probability of crossover: 90%,
- probability of mutation: 20%,
- probability of reproduction: 90%.

After 10 000 generations, 67 non-dominated feasible solutions were located in the external set (Table 2).

It is important to decide whether these solutions are good. We can do this by comparing them with the solutions obtained with the scheduling technique used in the company.

The company uses a simple priority rule technique. In this algorithm, activities are placed in the schedule in an order so that each is started at the earliest possible time (the time at which the precedence relationship constraints are met and resources are available).

Table 2. Non-dominated solutions

| No. | Criterion 1 | Criterion 2 | Criterion 3 | No. | Criterion 1 | Criterion 2 | Criterion 3 |
|---|---|---|---|---|---|---|---|
| 1 | 51 800.0 | 27 696.0 | 123 541.7 | 35 | 51 800.0 | 26 516.0 | 122 746.2 |
| 2 | 51 800.0 | 26 372.0 | 122 017.3 | 36 | 35 000.0 | 27 532.0 | 115 842.4 |
| 3 | 51 800.0 | 26 424.0 | 122 079.0 | 37 | 35 000.0 | 28 168.0 | 117 926.8 |
| 4 | 51 800.0 | 25 880.0 | 120 104.2 | 38 | 51 800.0 | 28 104.0 | 123 592.7 |
| 5 | 51 800.0 | 26 928.0 | 123 278.3 | 39 | 51 800.0 | 26 960.0 | 123 300.7 |
| 6 | 51 800.0 | 26 272.0 | 121 909.4 | 40 | 35 000.0 | 27 652.0 | 116 353.1 |
| 7 | 51 800.0 | 28 016.0 | 123 585.2 | 41 | 51 800.0 | 26 740.0 | 123 093.6 |
| 8 | 51 800.0 | 26 432.0 | 122 258.0 | 42 | 51 800.0 | 27 976.0 | 123 577.4 |
| 9 | 51 800.0 | 26 572.0 | 122 820.5 | 43 | 51 800.0 | 26 104.0 | 121 272.0 |
| 10 | 35 000.0 | 27 472.0 | 115 567.2 | 44 | 35 000.0 | 27 712.0 | 116 589.9 |
| 11 | 51 800.0 | 25 652.0 | 119 054.8 | 45 | 35 000.0 | 27 832.0 | 117 029.5 |
| 12 | 51 800.0 | 27 632.0 | 123 531.6 | 46 | 51 800.0 | 27 120.0 | 123 397.5 |
| 13 | 51 800.0 | 27 680.0 | 123 531.7 | 47 | 51 800.0 | 26 656.0 | 122 946.8 |
| 14 | 51 800.0 | 25 620.0 | 118 971.4 | 48 | 51 800.0 | 26 396.0 | 122 046.2 |
| 15 | 51 800.0 | 26 628.0 | 122 902.6 | 49 | 51 800.0 | 27 824.0 | 123 560.4 |
| 16 | 51 800.0 | 26 712.0 | 123 042.2 | 50 | 35 000.0 | 27 652.0 | 116 353.1 |
| 17 | 51 800.0 | 26 264.0 | 121 880.8 | 51 | 51 800.0 | 25 744.0 | 119 487.6 |

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[4]A simulation was carried out to choose these parameters.

| No. | Criterion 1 | Criterion 2 | Criterion 3 | No. | Criterion 1 | Criterion 2 | Criterion 3 |
|-----|-------------|-------------|-------------|-----|-------------|-------------|-------------|
| 18 | 51 800.0 | 28 080.0 | 123 592.6 | 52 | 35 000.0 | 27 532.0 | 115 842.4 |
| 19 | 51 800.0 | 27 056.0 | 123 361.7 | 53 | 35 000.0 | 27 940.0 | 117 787.3 |
| 20 | 51 800.0 | 25 864.0 | 119 973.4 | 54 | 35 000.0 | 27 772.0 | 116 815.2 |
| 21 | 51 800.0 | 25 908.0 | 120 133.8 | 55 | 35 000.0 | 27 640.0 | 116 104.3 |
| 22 | 51 800.0 | 27 088.0 | 123 380.0 | 56 | 51 800.0 | 26 460.0 | 122 620.2 |
| 23 | 51 800.0 | 26 296.0 | 121 934.5 | 57 | 35 000.0 | 27 984.0 | 117 831.4 |
| 24 | 35 000.0 | 27 592.0 | 116 104.1 | 58 | 35 000.0 | 27 520.0 | 115 567.4 |
| 25 | 51 800.0 | 27 360.0 | 123 473.0 | 59 | 35 000.0 | 27 700.0 | 116 353.2 |
| 26 | 51 800.0 | 25 592.0 | 118 779.6 | 60 | 51 800.0 | 26 460.0 | 122 620.2 |
| 27 | 51 800.0 | 26 896.0 | 123 254.7 | 61 | 51 800.0 | 26 736.0 | 123 042.3 |
| 28 | 51 800.0 | 26 800.0 | 123 176.5 | 62 | 51 800.0 | 25 820.0 | 119 842.4 |
| 29 | 51 800.0 | 25 924.0 | 120 198.6 | 63 | 35 000.0 | 27 984.0 | 117 831.4 |
| 30 | 51 800.0 | 26 044.0 | 121 170.6 | 64 | 51 800.0 | 26 240.0 | 121 870.5 |
| 31 | 51 800.0 | 27 376.0 | 123 485.8 | 65 | 51 800.0 | 25 588.0 | 118 725.8 |
| 32 | 51 800.0 | 26 568.0 | 122 782.5 | 66 | 35 000.0 | 27 880.0 | 117 029.6 |
| 33 | 51 800.0 | 27 112.0 | 123 380.1 | 67 | 35 000.0 | 28 260.0 | 117 978.2 |
| 34 | 35 000.0 | 27 640.0 | 116 104.3 | | | | |

The solution obtained using this technique was dominated by the solutions obtained using the SPEA2 algorithm.

## 4.4. Final solution

The final solution was identified using the LBS algorithm. This algorithm enables us to choose a solution with the cooperation of the decision maker. Thanks to this interactive procedure we are sure that the final solution is as in agreement with the decision maker's preferences as possible.

The final solution was chosen using the following steps:

Step 1. Nadir and ideal points based on the extreme values of the objective functions for the non-dominated solutions are presented to the decision maker to help him to choose a reference point.

$$z^* = \begin{cases} C1 = 35\ 000 \\ C2 = 25\ 588 \\ C3 = 123\ 592.6 \end{cases} \qquad z^{\text{nadir}} = \begin{cases} C1 = 51\ 800 \\ C2 = 28\ 260 \\ C3 = 115\ 567.2 \end{cases}$$

Step 2. The decision maker decides that the first reference point is the ideal point:

$$z^r = \begin{cases} C1 = 35\ 000 \\ C2 = 25\ 588 \\ C3 = 123\ 592.6 \end{cases}$$

Step 3. The reference point is projected into the non-dominated set. The first middle point is as follows:

$$z^v = \begin{cases} C1 = 35\ 000 \\ C2 = 27\ 984 \\ C3 = 117\ 381.4 \end{cases}$$

The value of this solution according to criterion c1 is as in the reference point given by the decision maker, the value according to the other criteria is lower.

Step 4. In the next step the decision maker was asked to give information regarding their preferences (Table 3). The decision maker is not able to accept solutions worse than the reference point by 1000 according to criterion $c1$, 200 according to criterion $c2$ and 1000 according to criterion $c3$. The decision maker prefers that the solution is optimal when $c1$ and $c2$ criteria are equal 0 and given this that the value according to criterion $c3$ is as high as possible.

Table 3. Indifference
and preference thresholds

| Criterion | $q_j$ | $p_j$ |
|---|---|---|
| $c1$ | 1 000 | 0 |
| $c2$ | 200 | 0 |
| $c3$ | 1 000 | 2 000 |

Step 5. This information on preferences was used to obtain the neighborhood of the middle point. Sample solutions are presented in Table 4.

Table 4. Sample solutions

|  | $c1$ (min) | $c2$ (min) | $c3$ (max) |
|---|---|---|---|
| $zc1$ | 35 000.0 | 28 260.0 | 117 978.2 |
| $zc2$ | 51 800.0 | 26 740.0 | 123 093.6 |
| $zc3$ | 51 800.0 | 26 460.0 | 122 620.2 |

Step 6. For the decision maker the most important criterion is to deliver projects on time. The value according to the c1 criterion delivers information about delays. In

the sample of solutions two of them have a bigger penalty for project delays. Moreover, the difference between these solutions in terms of criteria c2 and c3 does not compensate the bigger penalty for delays. That is why the decision maker decides that the value of the final solution according to the three criteria is as follows:

c1 (min)   c2 (min)  c3 (max)

35 000.0   27 984.0  117 831.4

At the end of this procedure, the final solution is obtained. It is a schedule for the project portfolio. In Table 5, the start and finish times of each activity are presented.

Table 5. Final solution – start and finish times for each activity

| Activity | P1 | P2 | P3 | P4 |
|---|---|---|---|---|
| 1. Preparation for deployment/defining the project | – | – | [0, 0] | [2, 8] |
| 2. IT analysis | – | – | [0, 0] | [8, 49] |
| 3. Preparation of technical and application environment | – | – | [0, 0] | [49, 58] |
| 4. Configuration of application | – | [0, 0] | [8, 14] | [64, 86] |
| 5. Testing | – | [11, 27] | [14, 25] | [0, 0] |
| 6. Programming | – | [1, 26] | [0, 0] | [61, 86] |
| 7. Training | – | [27, 40] | [25, 30] | [86, 106] |
| 8. Data preparation | – | [34, 59] | [32, 35] | [0, 0] |
| 9. System use | [189, 236] | [60, 110] | [40, 43] | [131, 178] |
| 10. Implementation of all functions | [236, 247] | [110, 131] | [0, 0] | [178, 186] |
| 11. Implementation of the budgeting module | [238, 259] | [0, 0] | [0, 0] | [0, 0] |
| 12. Project closure | [259, 270] | [0, 0] | [131, 142] | [186, 188] |

As mentioned above, the activities from phases 1–8 of the project one have been finished and the activities from phase nine are due to start. As we can see, realization of this project is interrupted and resumed only at the end of the realization of the project portfolio. The activities from phases 1–3 of the project two have been finished and the activities from phase 4 are due to start. This project starts at the beginning of the planning horizon as do projects three and four. The results show that the fourth project should not be added to the portfolio of this team because it will cause a long delay in the realization of the project one. Delaying project one, which is nearly finished is very risky for the company in terms of its reputation. Assumptions about not delaying an ongoing project for more than a given time should be considered.

Many methods for solving the project scheduling problem are used, like: priority rules techniques[39], evolutionary algorithms [13] or other heuristics like Pareto simulated annealing or multiobjective taboo search [12]. These techniques are quite often combined to obtain a method which delivers a single solution for the decision maker as in this paper. There are algorithms in which Pareto simulated annealing or multi objective taboo search are combined with an interactive procedure [12] to solve such a problem. In this paper, an elitist evolutionary algorithm is combined with an interactive procedure.

# 5. Summary

A procedure for solving the problem of scheduling a project portfolio has been presented in this paper. This procedure consists of three steps: building a multiple-criteria mathematical model, finding a sample of non-dominated solutions using the SPEA 2 algorithm and choosing one solution from the Pareto set as the final solution using the LBS procedure.

Presenting the problem of scheduling a project portfolio as a multiple criteria decision making problem enables better control of the realization of the project portfolio. Moreover, thanks to the procedure presented, the schedule obtained is optimized in terms of three objectives (minimizing the penalty for delays, minimizing the cost of using additional resources and NPV maximization). This procedure enables us to choose the final solution from the Pareto set, by using information regarding the preferences of the decision maker.

The disadvantages of the procedure presented above are the large number of variables and the time required to calculate the final solution (the computations in the evolutionary algorithm and interactive procedure). The results show that the procedure does not consider the risk to a firm's reputation, which occurs when an ongoing project is delayed in order to realize other projects.

The methodology presented enables better control of the realization of a project portfolio. It helps to assign a project to a team which has free resources. It also enables setting a suitable deadline for finishing a project using the available resources in agreement with a customer. Using multiple criteria decision making methods delivers better solutions, that can be obtained by a company using a simple heuristic.

Future work should consider reducing the number of variables needed in the mathematical model. Moreover, the problem should be solved using other methods and the results compared.

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