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MULTIPLE CRITERIA DECISION SUPPORT MODEL FOR COMPETENT RESEARCH CONSORTIUM BUILDING

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Abstract
The article presents an analysis of the process of project consortium building and proposes a decision-making method of project members and their role selection using multiple criteria hierarchical model. The study is based on the current rules of participation in European Union research initiatives.

Keywords
competence modeling, project team building, multiple criteria decision analysis.

Introduction

Collaborative projects alongside research conducted independently by single universities, institutes or other scientific entities are one of the principle forms of scientific study. Collaborative projects are especially important in the European context, because of their strong support by the European Commission (EC), for which they are the main instruments for funding research in different areas of science. EC allocates very large funds to research and development in a number of funding programs headed by the Framework Programme (approximately EUR 50 billion for in 2007–2013). Despite the involvement of such large resources obtaining funding for a research is not an easy task, as money is granted only to projects that meet very strict criteria of the financing institution. These criteria can vary depending on the specific programme. Therefore, the institution wanting to build a project consortium around its research initiative must create a group of collaborators not only adapted to the substantive requirements of the project but also that meets the requirements of funding programme.

The level of difficulty of obtaining financing is reflected in statistics showing the effectiveness of institutions applying for the support from the specific programmes run by EC. This effectiveness can be measured be the success rate being the quotient of the number of projects selected for funding to the total number of applications. In the 6th Framework Programme the success rate amounted approximately 22%, while for the proposals submitted by the Polish institutions it was significantly lower at 15.3% [1, 2]. In the case of the seventh edition of the Framework Programme, the average success rate across the European Union remains at a similar level of 22.28% (Polish National Contact Point for Research Programmes of the European Union, Institute of Fundamental Technological Research www.kpk.gov.pl/statistics).

Analysis of the evaluation criteria in several EU research support programmes shows that one of the most important requirements for submitted projects, next to their innovation and quality of proposals, is to ensure the appropriate consortium of expertise required to achieve the intended objective of the research. The knowledge of the participants of the project consortium is always presented in descriptive way that cannot be easily used in any formal method of project members' selection. Therefore, the authors of this article propose an approach to describe the knowledge required to implement the project and the knowledge possessed by project members based on the quantitative models of competence. Formal mathematical models provide a quantitative assessment of the competence of the consortia applying for financial grant. The assessment is done via comparing skills and knowledge of potential consortium members to the intended purpose of the research. Then, the selection of the final consortium members can be done basing on these quantitative assessments.

Similarly to the majority of decisive problems, the project team selection problem has complex nature subjective to many factors. Therefore, it requires appropriate examination of its structure, identification of the set of decision alternatives, a set of decision criteria and decision problematic (choice or ranking). In this article the authors propose the hierarchical multiple criteria decision model basing on the Analytic Hierarchy Method (AHP) originally proposed by Satty [3].

Decision criteria in the problem of project team building based on EU research grants

Development of decision support method for project members' selection requires the adoption of decision criteria that are in line with a number of factors considered in the EU research grants evaluation. Official documents specifying rules of applying and participation in specific EU research support programmes contain only general evaluation criteria. The real evaluation of submitted proposals is done on complex set of criteria that are never officially published and vary depending on the specific programme and current policy of the financing institution. Thus, using the official evaluation criteria to analyze the potential of a proposal to obtain a grant may be insufficient because of their high degree of generalization. Practitioners responsible for preparing project often use a number of informal criteria, constructed on the basis of a broader look at all aspects of evaluation of proposals like for example EU strategies or policy. This approach helps to determine current trends and expectations, which in a given period may affect the positive evaluation of the proposal or in case of a large number of proposals, may provide competitive advantage over other projects.

Due to the large number of potential sources of information about factors that affect the project proposal evaluation the decision support model should take into account the set of decision criteria obtained on analysis of the following issues:

1. Formal evaluation criteria indicated in official rules for participation and call for proposal;
2. Strategic objectives outlined by the current work programme;
3. Current policy of the financing institution and its strategic objectives;
4. Reports and statistical analysis of the current or previous editions of the programme.

For example analysis of the previous 6th edition of the Framework Programme may lead to the conclusion that proposals should have taken into account the following informal criteria:

- Geographical distribution of project members;
- Balanced share of men and women in the consortium;
- Share of small and medium-sized enterprises (SMEs) in the consortium;
- Number of consortium members.

The above discussion on the formal and informal criteria for proposals evaluation indicates that in order to successful the project coordinator should follow carefully planned strategy. Obtaining the research grant in a highly competitive call is a very difficult task. According to [4] current success rate in Framework Programme is only 22% while the average cost of proposal preparation is more than 100,000 EUR. Therefore, in order to minimize the risk of proposal failure, an application should be prepare not only to meet formally presented selection criteria, but should also take into account a number of additional informal factors.

The background of the method supporting the project consortium building

Making a decision about applying for a research grant requires fulfilling several conditions indicating the ability to prepare a successful application. A coordinator considering sending a project proposal must meet the following conditions: (a) must have an idea for the research, (b) has a brief plan for implementing the research, (c) be in touch with a group of partners that could became valuable contributors and having scientific and technical potential to achieve the project goal, (d) be able to meet all eligibility requirements of selected programme, (e) have knowledge and experience in participation and preparation of project applications.

Inability to comply with any of these conditions indicates that the coordinator is not ready to prepare and submit a proposal. A usually short 3–4 month period to application preparation means that the coordinator does not have much time to do all the work related to preparation of project application (partners searching, project scope description, paperwork etc.). In this short period of time the coordinator must find potential partners, decide on their selection, assign project roles to them, estimate the project budget and its distribution. All these decisions must be made providing the best possible project configuration (in terms of partners selection and assignment) that maximizes the possibility of obtaining the financial grant. The basis for these decisions is preliminary preparation of project description consisting of project schedule, project work breakdown structure (WBS) with definitions of work packages and characteristics of all roles to be assigned within the project. This preliminary project characteristics can provide the coordinator with information on what knowledge and which competences should be required from future project partners [5–7].

The problem of project consortium building is mention in two important documents for project management professionals. These are *"Project Management Body of Knowledge"* published by *Project Management Institute* [5] and international standard ISO 10006:2003 *"Quality management systems – Guidelines for quality management in projects"* [8]. According to these two publications decisions about project members selection should be carried out in a formalised manner, according to some precisely defined criteria. The selection criteria should primarily take into account precisely described competences of project members reflecting their skills, knowledge and experience.

Project consortium building problem can be formalised as the classic assignment problem where m agents can be assigned to n tasks and not every agent is qualified to do every task, thus $m > n$ [9, 10]. Mapping this classic assignment problem to project consortium-building problems we have m teams which can be assigned to n work packages of the project. The subset of n teams assigned to work packages according to some utility function became the project consortium. However, due to problem complexity the utility function is a multiple criteria function that additionally consists of mixed quantitative and qualitative criteria. Developing of such a functions requires profound study of the nature of the project consortium building process and modeling consortium members qualifications using a formal competence model.

Mathematical models of human competence

Survey of the scientific literature in the fields of knowledge modelling, human resource management and learning management provides many different and sometimes unambiguous definitions of the notion "competence". This vast set of definitions was put together by International Standard Organization that gives very coherent and brief definition of competence. According to ISO 9000:2005 [11] the competence is "demonstrated ability to apply knowledge and skills". This simple description of the competence expresses the main idea lying behind the research described in this article. Basing on ISO definition of competence we assumed, that since competence is described as "demonstrated ability" it can be used as a measure of personal performance. There are many studies following this approach in different fields of business-oriented literature.

The main problem with competence-based formal models is how to quantitatively measure and process human competence. There are not many quantitative models for competence representation. One of the most advanced idea of this type is the approach called *competence sets* (CS). This approach was for the first time introduced by [12, 13]. These authors model competence as the set containing skills, information and knowledge possessed by a person (acquired competence set denoted *Sk*) or required to successfully perform a given job or a task (required competence set *Tr*).

In the early stage of the research on CS, competence was modelled as a classic set containing knowledge, skills and information necessary to solve a problem. However, expressing the presence of a competence in binary terms – one has a competence or not at all (or it is necessary to have a certain competence to solve a problem or not) – turned out to be insufficient regarding the continuous nature of competence. Taking this fact into consideration it was proposed to present human competence as a fuzzy set, defined as follows [14, 15]:

$$A = \{\,(x, \mu_A(x))\,|\, x \in X\},$$

where $\mu_A(x)$ is the membership function assessing the membership of an element x in relation to set A by mapping X into membership space [0; 1], $\mu_A : X \to [0;\ 1]$.

Basing on the definition of the fuzzy set it is possible to define the notion of *fuzzy competence strength* that expresses the level of competence presence or requirement. For each competence g, its strength is a function of a person P or a task E

in the context of which the competence is assessed: $\alpha : \{P \text{ or } E\} \rightarrow [0;\ 1]$. Expansion optimization methods of fuzzy competence sets are computationally more demanding but provide better accuracy and reproduction of nature of competence.

CS methods provide quantitative measure of human competence through optimization and cost analysis of the competence set expansion process [12–14]. This process is described as obtaining new skills and adding them to the actual acquired competence set *Sk* of a person. The cost and pace of obtaining new skills depends on elements of actual competence set and how close these elements are related with the new skill. Methods of optimal competence set expansion consist of determining the order of obtaining successive competences that provides minimal cost. Competences that need to be obtained are defined by set $Tr(E)\backslash Sk(P)$, where $Sk(P) \subseteq Tr(E)$. The optimisation problem is usually solved by finding the shortest path in an oriented graph, in which vertices represent competences and arcs represent the relations between them [12], [13]. The general cost of expanding competence set is given by the cost function $c(Sk(P), Tr(E))$. The form of the cost function varies in different methods for competence expansion cost analysis that can be found in the literature of CS [12–14] and can be chosen individually according to application requirements.

Team competence estimation method

The background for the Project consortium-building problem presented in Sec. 3 assumes existence of many decision criteria. According to further analysis described in Sec. 3 one of the most significant criteria of project member selection is his/her competence to accomplish all tasks planed in the project work package that the member is assigned to. If a team has all necessary competence for a work package it means that it is ready to do all its tasks, otherwise this teams has to do some effort to acquire all missing competences, which generates some additional cost. This cost can be estimated using the methods of competence sets analysis presented in Sec. 3. Therefore, methods of competence set expansion cost can be use to develop a quantitative criterion function for team assignment [6, 7, 16].

The process of team competence analysis according to project task requirements can be performed in three main steps:

1. Identification of competences required to successfully accomplishing a given task.
2. Identification of the presence of the required competences in a team being candidate for the task.
3. Computing the cost of acquiring missing competences.

Team assignment to project work packages

Modelling of any multiple criteria decision support problem requires precise characterization of the decision-making situation. Characteristic of the decision-making situation is necessary to choose an appropriate solution method [17]. The complete characteristic of the decision-making situation covers the following issues: the decision problematic (ranking, choice), the set of decision alternatives, number and characteristics of decision criteria.

Set of decision alternatives

In the analysed problem the project coordinator make a decision on assignment of candidate project teams to work packages defined for the project. Thus, the set of decision alternatives can be defined as the set of all possible assignments of candidate teams to project work packages. The assignments can be described by the binary matrix or by the sequence of elements from the set of candidates teams sorted in the order of their assignment to consecutive project work packages. For purposes of this study the authors decided to use the later one. Therefore, the decision alternatives can be described using the following formalisation:

$P = \{p_i\}$ – the set of project work packages, $i = 1, \ldots, I$

$Z = \{z_j\}$ – the set of candidate teams, $j = 1, \ldots, J$

$V = \{v^n\}$ – the set of all possible consortium variants (team to work package assignments), $n = 1, \ldots, N$

where $v^n = (v_i^n)_{i=1}^I = (v_1^n, v_2^n, \ldots, v_i^n, \ldots, v_I^n)$ – sequence of assignments in the n-th consortium variant, $v_i^n \in Z$.

Thus, the number of decision alternatives equals the number of all possible team assignment sequences. Assuming that one team can be assigned to many work packages the total number of all possible consortium variants amounts to J^I.

Number and characteristics of decision criteria

In the Secs. 2 and 3 of the article it was shown that according to project management professionals and rules for participation in EU research programmes the main criterion for project team selection is the competence to accomplish project tasks.

Moreover, the decision on the composition of the project consortium is also influenced by many formal and/or informal criteria. These criteria can be very simple quantitative criteria like share of SMEs in the project consortium, more complex quantitative criteria like geographical distribution or even qualitative criteria like for example teams' reliability. Therefore, the set of decision criteria can be a mixture of qualitative and quantitative, criteria with different scales, values (continuous, discrete, linguistic).

$K = \{k_m\}$ – the set of decision criteria, $m = 1, \ldots, M$.

For the set of decision criteria and the set of decision alternatives we can define the performance matrix E that reflects performance measures of every consortium variant for every decision criterion.

$$E = [e_{nm}] = \begin{bmatrix} e_{11} & \cdots & e_{1m} & \cdots & e_{1m*} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ e_{n1} & \cdots & e_{nm} & \cdots & e_{nm*} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ e_{n*1} & \cdots & e_{n*m} & \cdots & e_{n*m*} \end{bmatrix},$$

where e_{nm} – performance measure of n-th variant according to m-th criterion.

Decision problematics

The specific decision problematic determines the set of multiple criteria analysis methods that can be used to find the solution. In case of the given problem of competent project consortium building we are dealing with the problem of choice of one variant among several other alternatives. This problem can be equivalently solved through preparing a ranking of all decision alternatives and picking the one with the highest rank.

The exponential growth of number of consortium variants ($N = J^I$) causes the problem of relatively large number of decision alternative even for small consortia. The multiple criteria decision support methods usually requires evaluation of every alternative for every decision criteria, which gives $N \cdot M$ single evaluations. Moreover, in case of the methods basing on pair-wise comparisons of all alternatives (for example AHP method) it is necessary to do $\binom{n*}{2}$ comparisons of decision alternatives for each of M criteria. However, in the mentioned AHP method the number of pair-wise comparison can be reduced by criteria hierarchisation, but still the large number of elementary operations to perform significantly reduce usability of the method [17–21].

The large complexity of the problem can be reduced by applying some additional constraints to consortium variants. The number of $N = J^I$ is the maximal number of all possible consortium variants. However, in real life situations when project consortium has to fulfil many conditions of the research support programme, such a large number of variants do not have to be take into account. First of all, the possible number of consortium variants can be significantly reduced by applying several rules of participation set by the programme (for example: minimal number of participants, maximal number of work packages assigned to one team, etc.). Moreover, due to lack of certain competences not every team can be assigned to every work package. Taking this into consideration the total number of possible assignments can be again significantly reduced.

In this paper the proposed approach to project consortium building assumes splitting this process into three consecutive phases. The two first phases consists of reducing the number of possible consortium variants, while the third phase is the main decision making carried out on the reduced set of decision alternatives. The three-phase model of the decision support system is depicted in Fig. 1.

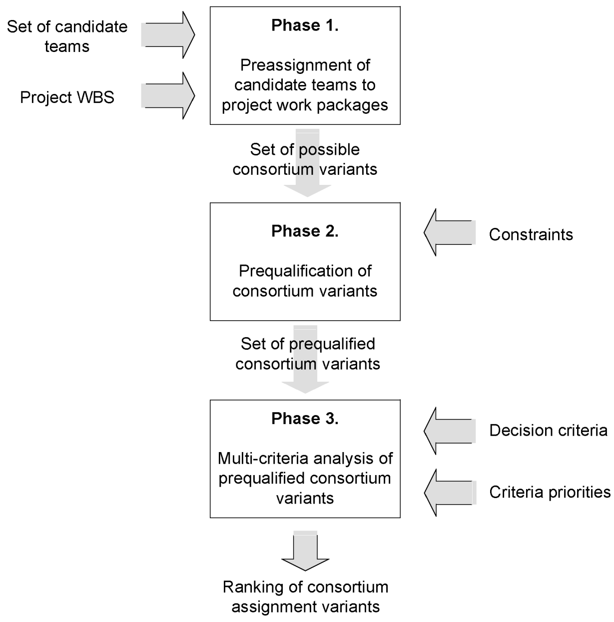

Fig. 1. Model of the decision support system for consortium members selection.

The results of phase 1 and 2 are the reduced set of consortium assignment variants. These sets are denoted:

V^{I} – reduced set of pre-assigned consortium variants after phase 1.

V^{II} – reduced set of pre-qualified consortium variants after phase 2.

$$V \xrightarrow{\text{Phase I}} V^{\mathrm{I}} \xrightarrow{\text{Phase II}} V^{\mathrm{II}}.$$

Phase 1: Pre-assignment of candidate teams to work packages

In order to reduced to total number of variants analysed on the decision making phase it is possible to apply additional conditions for every team and reducing the number of work packages to which each team can be assigned. This solution is applied in the classic assignment problem recognizing agent qualification [10] where not every agent is qualified to do every task, which is regulated by the binary parameter. In this approach agent qualifications are replaced with team competences.

$$Q = [q_{ji}],$$

where

$$q_{ji} = \begin{cases} 1, & z_j \text{ has competences to do } p_i, \\ 0, & z_j \text{ does not have competences to do } p_i. \end{cases}$$

The presence of the required competences in a team can be detected using methods of fuzzy competence set theory and the approach to team competence estimation described in Sec. 5. Using the notions from the fizzy competence set theory it is possible to define:

$Tr(p_i)$ – set of competences required to do i-th work package,

$Sk(z_j)$ – set of competences of j-th candidate team.

According to fuzzy competence set theory the cost of expansion of team's competence to meat the competence requirements of a work package can be computed through comparison of the corresponding sets $Tr(p_i)$ and $Sk(z_j)$. Due to the structure of competence in different domains and their interrelationships the task of computing the competence expansion cost is not always possible [12, 14]. In such cases it is possible to say that the team does not have competence to do the given work package. Otherwise, the team is possible to accomplish the task but only after enlarging its competences, which generates some additional cost.

Therefore, the qualification parameter can be defined as follows:

$$q_{ji} = q(z_j, p_i) = \begin{cases} 1, & c^{\mathrm{K}}_{ji} \geq 0, \\ 0, & c^{\mathrm{K}}_{ji} \text{ can not be determined,} \end{cases}$$

where $c^{\mathrm{K}}_{ji} = c^{\mathrm{K}}(z_j, p_i) = c^{\mathrm{K}}(Sk(z_j), Tr(p_i))$ – the cost of team z_j competence expansion in order to meet competence requirements of work package p_i.

Now, the reduced set of pre-assigned consortium variants can be formally defined:

$$V^{\mathrm{I}} = \left\{ \begin{matrix} v^n : v^n \in V,\ v^n = (v^n_i)^{i*}_{i=1},\ n = 1, 2, \ldots, n*, \\ \forall_{i \leq i*}\, q(v^n_i, p_i) = 1,\ v^n_i \in Z \end{matrix} \right\}.$$

Phase 2: Prequalification of consortium variants

This phase consists of applying additional constraints leading to further reduction of the consortium assignment variants. In this phase constraints are applied to whole variant, not to single team like it was in the previous phase, because these constraints are related to the qualities of the consortium seen as a whole. Two categories of consortium requirements are taken here into account:

- formal requirements defined by the official rules of participation in the financing programme;
- competence requirements defined by the project coordinator preparing the application.

Development of both categories of constraints requires the adoption of formal model of project representation. The most popular and widely used tools form project planning and visualisation is the Gantt chart. However, for purposes of this study more useful representation of project task and timeline is the project relation digraph, as it provides better background for project critical path analysis. The nodes of the project relation digraph are project states set be points in time of work packages starts and ends. The edges of the digraph are project work packages. The example project relation digraph is depicted in Fig. 2 together with the corresponding Gantt Chart.

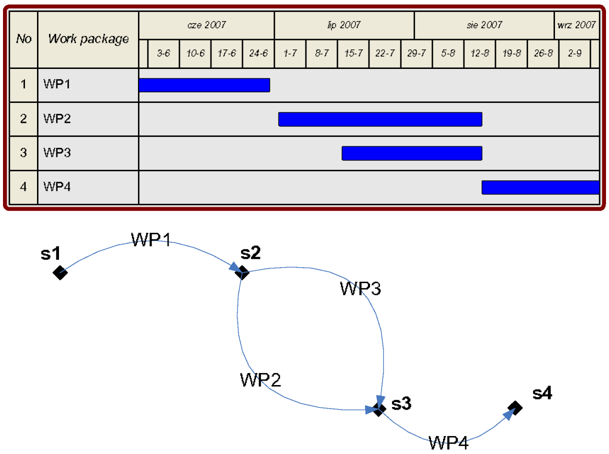

Fig. 2. Example Gantt Chart and corresponding Project Relation Digraph.

$D(S, P)$ – Project relation digraph

where

$S = \{s_k\}$ – set of project states, $k = 1, 2, \ldots, k*$,

$\mathrm{init}(p_i)$ – initial state of a work package p_i,

$\mathrm{ter}(p_i)$ – final state of a work package p_i,

$A^-(s_k) \subset P$ – set of work packages preceding a state s_k (set of edges entering a state s_k),

$A^+(s_k) \subset P$ – set of work packages following a state s_k (set of edges outgoing from state s_k),

$N^{-}(s_k) \subset S$ – set of states preceding a state s_k,
$N^{+}(s_k) \subset S$ – set of states following a state s_k.

Formal requirements defined by the official rules of participation in the financing programme

Formal requirements for the project consortium results from the official regulations of a given financing programme. These rules specify the conditions to be met by a consortium in order to be eligible to submit its application. Most often, these rules focus on number of teams creating a consortium and on number of work packages that can be managed by a single team. The most typical requirements of these type are:

– minimal number of consortium members:

$$l(v^n) \geq l_{MIN},$$

where $l(v^n)$ – number of teams in n-th variant of the consortium, l_{MIN} – minimal number of teams in the consortium,

– maximal number of work packages assigned to single team:

$$\forall_{z_j \in v^n}\ k(z_j) \leq k_{MAX},$$

where $k(z_j)$ – number of work packages assigned to j-th team, k_{MAX} – maximal number of work packages assigned to single team,

– assignment blocking of two or more parallel work packages to single team:

$$\forall_{i<i*} \neg \exists_{x<i*} \begin{pmatrix} i \neq x \wedge v_i^n = \\ = v_x^n \wedge \tau(int(v_i^n)) < \tau(\mathrm{ter}(v_x^n)) \\ \wedge \tau(\mathrm{ter}(v_i^n)) > \tau(int(v_x^n)) \end{pmatrix},$$

where $\tau(s_k)$ – time of a state s_k.

Competence requirements defined by the project coordinator preparing the application

The idea of these constraints lays in verifying the lack of competence of the whole consortium according to project competence requirements. This can be achieved by applying methods of competence expansion cost analysis, similarly like it was done in the phase 1 on the method. The cost of competence expansion computed for the whole consortium can be use as the measure of its lack of preparation to the project competence requirements. The elimination of the worst prepared variants can be done through assuming certain threshold for the competence expansion cost.

Computation of the total competence expansion cost for the whole consortium requires assuming certain aggregation model in order to find the sum of the elementary assignment for every work package and team within a current consortium. The choice of the aggregation model depends on two main factors: type of the cost function (temporal or financial) and disjoint of required competence sets defined for all work packages of the project.

The above considerations lead to definition of four models of competence expansion cost aggregation (see Table 1).

Table 1
Competence expansion cost aggregation models.

Aggregation model		Required competence sets: Disjoint $\bigcap_{p_i \in P} Tr(p_i) = \emptyset$	Required competence sets: Intersected $\bigcap_{p_i \in P} Tr(p_i) \neq \emptyset$
Cost type	Financial	Static model Aggregation of elementary costs for every work package of the project	Dynamic model Aggregation of elementary costs for every work package of the project
	Temporal	Static model Aggregation of elementary costs for work packages included in the project critical path	Dynamic model Aggregation of elementary costs for work packages included in the project critical path

– Case 1: financial cost function, disjoint required competence sets:

$$c^{\mathrm{K}}(v^n) = \sum_{i=1}^{i*} c^{\mathrm{K}}(v_i^n, p_i) = \sum_{i=1}^{i*} c^{\mathrm{K}}(Sk(v_i^n), Tr(p_i)).$$

– Case 2: financial cost function, intersected required competence sets:

$$c^{\mathrm{K}}(v^n) = \sum_{i=1}^{i*} c^{\mathrm{K}}(Sk(v_i^n, init(p_i), v^n), Tr(p_i)).$$

– Case 3: temporal cost function, disjoint required competence sets:

$$t_{\mathrm{S}}^{\mathrm{K}}(s_k, v^n) = \max_{p_i \in N_D^{-}(s_k)} (t_{\mathrm{S}}^{\mathrm{K}}(init(p_i), v^n) + t^{\mathrm{K}}(v_i^n, p_i)) =$$
$$= \max_{p_i \in N_D^{-}(s_k)} (t_{\mathrm{S}}^{\mathrm{K}}(init(p_i), v^n) + t^{\mathrm{K}}(Sk(v_i^n), Tr(p_i))).$$

– Case 4: temporal cost function, intersected required competence sets:

$$t_{\mathrm{S}}^{\mathrm{K}}(s_k, v^n) = \max_{p_i \in N_D^{-}(s_k)} \begin{pmatrix} t_{\mathrm{S}}^{\mathrm{K}}(init(z_i), v^n) + \\ t^{K}(Sk(v_i^n, init(p_i), v^n), \\ Tr(p_i)) \end{pmatrix}.$$

Models gathered in Table 1 shows that for competence requirements there are two possible constraints. The first one uses financial cost functions, while the second one uses temporal time function, whereas the aggregation model depends on the disjoint of required competence sets defined for project work packages.

The formalisation of these two possible criteria can be formalised as follows:

$$c^{\mathrm{K}}(v^n) \leq c^{\mathrm{K}}_{MAX},$$

$$t^{\mathrm{K}}(v^n) \leq t^{\mathrm{K}}_{MAX},$$

where $c^{\mathrm{K}}(v^n)$ – aggregated value of the financial cost of competence expansion computed for $n-$th consortium variant; c^{K}_{MAX} – threshold for financial cost of competence expansion; $t^{\mathrm{K}}(v^n)$ – aggregated value of the competence expansion time computed for n-th consortium variant; t^{K}_{MAX} – threshold for competence expansion time.

Multiple criteria decision making on choice of the consortium assignment variant

Among the many existing methods for multiple criteria decision analysis (MCDA) there is a group of approaches that different professionals are keen to use, due to their clear and verified theoretical background and confirmed effectiveness. However, there are still no clear guidelines for MCDA method selection. Practitioners in their choices of a specific MCDA method are usually guided by their habits and degree of familiarity with the methods. For the given problem the authors of this article decided to use the Analytical Hierarchy Method (AHP), mainly because of its ability to mix in one decision model several quantitative and qualitative criteria [17, 18, 20].

In Secs. 2 and 3 it was discussed that decision-making on selecting consortium of project teams can be based on several formal and informal criteria. These criteria can be divided into three separate groups that create higher-level criteria in the AHP criteria hierarchy [19, 21].

Competence criteria

In this group there are competence criteria described in the previous Section of the article, where they are used to reduce the set of decision alternatives. On this phase of the method they are used to select the final variant of the project consortium assignment. In this group there are two types of criteria:
– cost of competence expansion in order to meet all competence requirements;
– time of competence expansion in order to meet all competence requirements.

Reliability and confidence criteria

All these criteria are defined as qualitative and their evaluation is made in the process of subjective pair-wise comparisons of all decision alternatives. The following criteria were defined:
– ability to accomplish given tasks (estimated on the analysis of team workload in other project and its self motivation to participate in the project);
– punctuality;
– reliability.

Political criteria

These criteria depends on the current strategy of the financing institution. These criteria are often significant in specific European research programmes. In this group the authors propose the following criteria:
– geographical distribution of project consortium members (not only in terms of distance but also in term of type of the EU members state – new member, candidate, etc.)
– balanced share of men and women in project human resources;
– share of SMEs in the project consortium.

Graphical representation of the criteria hierarchy can be seen in Fig. 3.

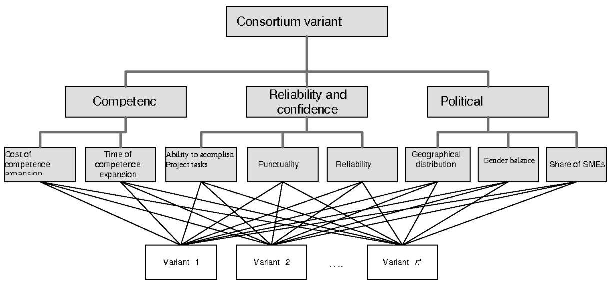

Fig. 3. Hierarchical multiple criteria decision model.

Case study

For the purpose of demonstrating the described method authors used the research project implemented between year 2003 and 2006, entitled *e-Quality: Quality implementation in open and distance learning in a multicultural European environment.* The project was financed by EU research support program *Socrates-Miniverva.* The project involved seven research teams from five countries (France, Spain, Finland, Poland and Switzerland) and one consulting company from Belgium, which was subcontracted to monitor and audit the project.

The project was successful so data collected and decisions made during team building phase can be used as a reference for validation of the proposed method. The successful project in the context of the problem examined in this article, this is a project whose coordinator made right decision regarding the choice of project members and their assignment to work packages of the project. The method can be validated by reproducing the conditions existing in the initial planning stage of the e-Quality project, using them as an input for the method and than comparing its outcomes with decisions of the real project coordinator.

Work breakdown structure for the example project

Subject of the e-Quality concerned quality issues in an open and distant learning. The scope of the project was divided into eight work packages:

- p_1 – Project organisation monitoring & management
- p_2 – Quality process in a multicultural environment
- p_3 – Design and production of core documents and ressources
- p_4 – Design Training package for staff and trainers
- p_5 – Training sessions and evaluation
- p_6 – Methodology validation
- p_7 – Communication, dissemination and mainstreaming
- p_8 – Project evaluation

The work package p_8 'project evaluation' had been assigned to the external subcontractor before the main project consortium was built. Therefore, only work packages from p_1 to p_7 are taken into consideration in the decision making process.

The project duration was set to 3 years and imposed by the rules for participation in Socrates-Minerva program. Detailed schedule of the project is presented in the form of the Gantt Charted in Fig. 4.

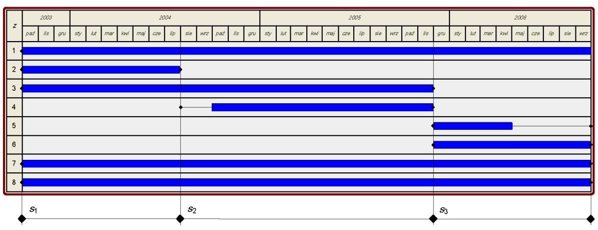

Fig. 4. The Gantt Chart for the e-Quality project.

The relation graph for work packages of the e-Quality project shown in Fig. 5 was elaborated by defining initial and final states of every work package (see Table 2) and then by determining time dependency between states and work packages (see Table 3).

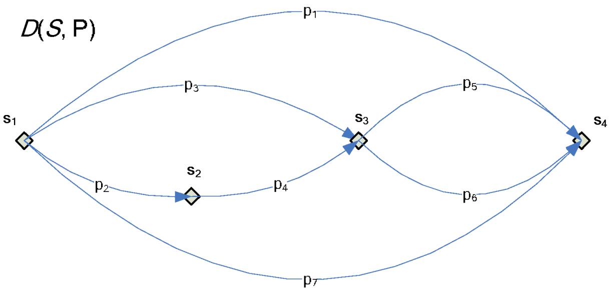

Fig. 5. The relation digraph of the e-Quality project.

Table 2
Initial and final states of the ex ample project.

	p_1	p_2	p_3	p_4	p_5	p_6	p_7
init(p_i)	s_1	s_1	s_1	s_2	s_3	s_3	s_1
ter(p_i)	s_4	s_2	s_3	s_3	s_4	s_4	s_4

Table 3
Relationships between states and work packages of the example project.

s_k	$A^-(s_k)$	$A^+(s_k)$	$N^-(s_k)$	$N^+(s_k)$
s_1	$\emptyset$	p_1, p_2, p_3, p_7	$\emptyset$	s_2, s_3
s_2	p_2	p_4	s_1	s_3
s_3	p_3, p_4	p_5, p_6	s_1, s_2	s_4
s_4	p_1, p_5, p_6, p_7	$\emptyset$	s_3	$\emptyset$

Constraints and decision criteria

The number of all theoretically possible consortium variants is large and amounts to:

$$|V| = \overline{V}_8^7 = 8^7 = 2097152.$$

Obviously, for such a large number of decision variants it necessary to decrease the complexity of the problem. Thus, five following constrains were introduced:

- $c^{\mathrm{K}}(v^n) \leq 20$ – the overall cost of competence expansion in a consortium variant cannot exceed the threshold value of 20;
- $t^{\mathrm{K}}(v^n) \leq 12$ – the overall time of competence expansion in a consortium variant cannot exceed 12 days;
- $l(v^n) \geq 5$ – each consortium variant in order to be allowed to further analysis must consist of at least five partners;
- $k(z_j) \leq 2$ – in every allowed consortium variant neither partner cannot be responsible for more than 2 work packages;
- in every allowed consortium variant neither partner cannot be responsible for work packages that overlaps in time.

The reduced set of consortium variants can be than the subject of the multiple criteria analysis. For purposes of the example five following decision criteria ware chosen:

k_1 – overall cost of competence expansion;

k_2 – overall time of competence expansion;

k_3 – external workload of a partner and its time availability;

k_4 – geographical distribution of consortium partners;

k_5 – balanced share of men and women in project human resources.

The criteria weights were set according to the AHP method by building the matrix of pair wise comparisons of decision criteria (see Table 4).

Table 4
Matrix A of pair wise comparisons of the criteria.

	k_1	k_2	k_3	k_4	k_5
k_1	1	1/2	1/6	1/3	3/1
k_2	2/1	1	1/5	1/2	4/1
k_3	6/1	5/1	1	2/1	5/1
k_4	3/1	2/1	1/2	1	5/1
k_5	1/3	1/4	1/5	1/5	1
$\sum$	12.33	8.75	2.07	4.03	18.00

Table 5
Normalized matrix B and weights of the decision criteria.

	k_1	k_2	k_3	k_4	k_5	w
k_1	0.08	0.06	0.08	0.08	0.17	**0.094**
k_2	0.16	0.11	0.10	0.12	0.22	**0.144**
k_3	0.49	0.57	0.48	0.50	0.28	**0.463**
k_4	0.24	0.23	0.24	0.25	0.28	**0.248**
k_5	0.03	0.03	0.10	0.05	0.06	**0.052**
						$\sum = 1.000$

In order to validate the consistency of pair wise comparisons the standard AHP consistency check procedure [21] was used:

$$A\cdot w = \begin{bmatrix} 1 & 0.5 & 0.17 & 0.33 & 3 \\ 2 & 1 & 0.2 & 0.5 & 4 \\ 6 & 5 & 1 & 2 & 5 \\ 3 & 2 & 0.5 & 1 & 5 \\ 0.33 & 0.25 & 0.2 & 0.2 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.094 \\ 0.144 \\ 0.463 \\ 0.248 \\ 0.052 \end{bmatrix} = \begin{bmatrix} 0.480 \\ 0.754 \\ 2.498 \\ 1.306 \\ 0.261 \end{bmatrix},$$

$$\lambda_{\max} = \frac{1}{M}\left(\sum_{m=1}^{M} \frac{(Aw)_m}{w_m}\right) =$$

$$= \frac{\frac{0.480}{0.094} + \frac{0.754}{0.144} + \frac{2.498}{0.463} + \frac{1.306}{0.248} + \frac{0.261}{0.052}}{5} =$$

$$= \frac{5.125 + 5.239 + 5.393 + 5.267 + 5.065}{5} = 5.218,$$

$$CI = \frac{\lambda_{\max} - m}{m-1} = \frac{5.218 - 5}{4} = 0.054,$$

$$CR = \frac{CI}{RI} = \frac{0.054}{1.12} = 0.049 < 0.1.$$

The obtained consistency ratio CR is less than the threshold value 0.1.

Description of candidate teams

A performance measure of the decision criteria for all consortium variants in the decision analysis requires precise description of candidate teams. Apart from information required to evaluate decision criteria, the presented method requires setting cost factors necessary for competency expansion costs. These cost factors were taken from 'Socrates-Minerva rules for participation' guide that provides cost factors for all EU countries.

Descriptions of candidate teams were gathered in Table 6.

Table 6
Characteristics of candidate teams.

	Team	Political status	Team size (men/ women)	Current workload of team members	$c^K(\alpha)$	$t^K(\alpha)$
z_1	FR1	EU member	2 (1/1)	1 p. 2 l.	$2.66 \cdot \alpha$	$7 \cdot \alpha$
z_2	FR2	EU member	4 (3/1)	2 p. 2 l.	$2.66 \cdot \alpha$	$5 \cdot \alpha$
z_3	ES	EU member	2 (0/2)	3 p. 1 l.	$1.97 \cdot \alpha$	$5 \cdot \alpha$
z_4	FI	EU member	4 (2/2)	3 p.	$2.26 \cdot \alpha$	$6 \cdot \alpha$
z_5	PL	EU candidate country*	6 (1/5)	6 l. 3 PhD	$1 \cdot \alpha$	$5 \cdot \alpha$
z_6	CH1	EU associated country	2 (0/2)	1 p. 1 l.	$3.18 \cdot \alpha$	$5 \cdot \alpha$
z_7	CH2	EU associated country	3 (2/1)	2 p. 2 l.	$3.18 \cdot \alpha$	$7 \cdot \alpha$
z_8	BE	EU member	3 (2/1)	3 a.	$2.60 \cdot \alpha$	$6 \cdot \alpha$

p. – project, l. – lecturer, a. – audit
* as for 2003

The coordinator of the e-quality project selected the following consortium variant:

$$v^R = (z_1, z_3, z_2, z_4, z_5, z_6, z_7).$$

Now, the decision made by the real coordinator can be compared with the result of the proposed method.

Pre-assignment of candidate teams

As it was described in previous sections of the article the complexity of the decision problem can be significantly reduced by verifying the possibility of team to work package assignment basing on the competence criteria. Namely, in case when a team does not have competences required to complete a given work package it means that the cost and time for such a assignment cannot be find, which results in rejecting the team to be candidate for this work package coordination. Outcomes of this verification are gathered in Tables 7 and 8.

Table 7
Competence expansion costs computed for every work package of the project – $c^{\mathrm{K}}\left(Sk(z_j), Tr(p_i)\right)$.

	$Tr(p_1)$	$Tr(p_2)$	$Tr(p_3)$	$Tr(p_4)$	$Tr(p_5)$	$Tr(p_6)$	$Tr(p_7)$
$Sk(z_1)$	11.28	7.71	7.18	n.a.	n.a.	n.a.	4.26
$Sk(z_2)$	n.a.	1.06	0.80	2.93	n.a.	n.a.	n.a.
$Sk(z_3)$	15.41	0.79	1.77	2.56	n.a.	n.a.	3.15
$Sk(z_4)$	n.a.	4.52	4.75	1.81	n.a.	n.a.	n.a.
$Sk(z_5)$	n.a.	n.a.	n.a.	n.a.	1.90	1.47	n.a.
$Sk(z_6)$	n.a.	n.a.	n.a.	n.a.	5.09	2.54	n.a.
$Sk(z_7)$	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.00
$Sk(z_8)$	n.a.	n.a.	n.a.	n.a.	1.82	3.12	n.a.

Table 8
Competence expansion times computed for every work package of the project – $t^{\mathrm{K}}\left(Sk(z_j), Tr(p_i)\right)$.

	$Tr(p_1)$	$Tr(p_2)$	$Tr(p_3)$	$Tr(p_4)$	$Tr(p_5)$	$Tr(p_6)$	$Tr(p_7)$
$Sk(z_1)$	29.68	20.03	18.90	n.a.	n.a.	n.a.	11.20
$Sk(z_2)$	n.a.	2.00	1.50	5.50	n.a.	n.a.	n.a.
$Sk(z_3)$	39.10	2.00	4.50	6.50	n.a.	n.a.	8.00
$Sk(z_4)$	n.a.	12.00	12.60	4.80	n.a.	n.a.	n.a.
$Sk(z_5)$	n.a.	n.a.	n.a.	n.a.	9.50	7.35	n.a.
$Sk(z_6)$	n.a.	n.a.	n.a.	n.a.	8.00	4.00	n.a.
$Sk(z_7)$	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.00
$Sk(z_8)$	n.a.	n.a.	n.a.	n.a.	4.20	7.20	n.a.

Using data gathered in Tables 7 and 8 it is now possible to find the reduced number of consortium variants taking into account the competence of every team to complete work packages of the project. Therefore, for the work package p_1 there are only two possible assignments (z_1 and z_3), for p_2 four, for p_3 four, for p_4 three, forp_5 three, for p_6 three and for p_7 three as well. Thus, now we have $2 \cdot 4 \cdot 4 \cdot 3 \cdot 3 \cdot 3 \cdot 3 = 2.592$ possible consortium variants, which is significantly less comparing to 2,097,152 initial variants.

Reduction of number of consortium variants

Despite the significant reduction of the number of possible variants on the pre-assignment phase, the number of all possible variants for setting up the consortium is still too large considering the possibility of applying the AHP method as it requires pairwise comparisons of all. Making 2592^2 decisions by the decision maker is not feasible in a reasonably short time. Therefore, it is necessary to further reduce the number of decision variants. This can be achieved by using the constraints presented in one of the previous subsections. The performed constraint analysis resulted in only 8 consortium variants that fulfill all 5 constraints. These variants are presented in Table 9.

The last step of the method is the decision analysis with the AHP method. Performance measures provided for all the decision criteria are gathered in Table 10. The Table contains data only for 8 variants eligible for decision analysis.

Table 9
Assignments in the reduced set of consortium variants.

	v1	v2	v3	v4	v5	v6	v7	v8
v(p1)	z1	z1	z1	z1	z1	z1	z1	z1
v(p2)	z2	z3	z3	z3	z3	z3	z3	z3
v(p3)	z3	z2	z2	z2	z2	z2	z2	z2
v(p4)	z4	z4	z4	z4	z4	z3	z3	z3
v(p5)	z8	z5	z5	z8	z8	z5	z8	z8
v(p6)	z5	z8	z6	z5	z6	z6	z5	z6
v(p7)	z7	z7	z7	z7	z7	z7	z7	z7
CK	19.21	19.70	19.12	17.97	19.04	19.87	18.72	19.79
TK	11.85	8.70	5.50	8.85	5.50	5.50	8.85	5.50

Table 10
Performance measures of eligible consortium variants.

	$e_1(v)$	$e_2(v)$	$e_3(v)$	$e_4(v)$	$e_5(v)$
v^1	19.21	11.85	2	1	11/13
v^2	19.70	8.70	2	1	11/13
v^3	19.12	5.50	1	2	9/14
v^4	17.97	8.85	2	1	11/13
v^5	19.04	5.50	2	7	10/10
v^6	19.87	5.50	3	5	9/14
v^7	18.72	8.85	6	4	11/13
v^8	19.79	5.50	6	9	10/10

Basing on data from Table 8 it is now possible to find the final ranking of consortium variants using AHP method of pair wise comparisons of all variants within every decision criteria and computing weighted sum of obtained utility vectors:

$$u = \sum_{m=1}^{M} w_m \cdot u^m = w_1 \cdot u^1 + w_2 \cdot u^2 + w_3 \cdot u^3 + \\ + w_4 \cdot u^4 + w_5 \cdot u^5 =$$

$$= 0.094 \cdot \begin{bmatrix} 0.073 \\ 0.050 \\ 0.108 \\ 0.327 \\ 0.157 \\ 0.024 \\ 0.227 \\ 0.034 \end{bmatrix} + 0.144 \cdot \begin{bmatrix} 0.040 \\ 0.104 \\ 0.183 \\ 0.062 \\ 0.183 \\ 0.183 \\ 0.062 \\ 0.183 \end{bmatrix} + 0.463 \cdot \begin{bmatrix} 0.147 \\ 0.147 \\ 0.269 \\ 0.147 \\ 0.141 \\ 0.088 \\ 0.030 \\ 0.030 \end{bmatrix} +$$

$$+ 0.248 \cdot \begin{bmatrix} 0.228 \\ 0.228 \\ 0.145 \\ 0.224 \\ 0.029 \\ 0.053 \\ 0.074 \\ 0.019 \end{bmatrix} + 0.052 \cdot \begin{bmatrix} 0.123 \\ 0.123 \\ 0.035 \\ 0.123 \\ 0.219 \\ 0.035 \\ 0.123 \\ 0.219 \end{bmatrix} = \begin{bmatrix} 0.144 \\ 0.151 \\ 0.198 \\ 0.170 \\ 0.125 \\ 0.084 \\ 0.069 \\ 0.060 \end{bmatrix}.$$

The aggregated utility vector shows, that the highest value of overall utility has the variant $v^3 = (z_1, z_3, z_2, z_4, z_5, z_6, z_7)$.

The decision received from the multiple criteria model is consistent with the decision of the real decision maker. Thus, it is possible to conclude the method is valid and provides effective results.

Summary

The paper presented the method for project consortium building. The method is based on multiple criteria decision modelling. In order to decrease the computational complexity of the problem the methods proposed two staged approach to reduction of possible decision alternatives. The proposed hierarchical model of decision criteria was preceded by an analysis of the current rules of participation in major European research programmes in order to reflect the real life situation of decision making. The biggest effort was made on modelling the competence criteria of the decision support model. Despite the proposition of compound set of decision criteria the authors do not intend to close the method only to these criteria. The proposed approach is rather a framework where depending on the application other decision criteria can be easily introduced.

One of the possible applications of the method was presented in the Case Study section of the article. The example shown there, use real date from the project run by the collaborative team consisted of 7 research teams. This example not only demonstrated all steps of the proposed method but also used as validation tool.

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