A decision support system for project portfolio management in construction companies

Article

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A DECISION SUPPORT SYSTEM FOR PROJECT PORTFOLIO MANAGEMENT IN CONSTRUCTION COMPANIES

ABSTRACT

Project portfolio management requires a systematic process that comprises assessment of portfolio risk and expected profitability, as well as strategic fit of individual projects with company objectives. After a needs analysis based on literature findings and surveys with experts, in this study, a process model and a tool, COPPMAN (COnstruction Project Portfolio MANagement), were developed to support project portfolio decisions in construction companies. COPPMAN was developed in collaboration with construction professionals. Different from previous studies, it incorporates a portfolio risk and strategic fit assessment model considering project dependencies and integrates knowledge of previous, on-going and potential projects to estimate value of alternative project portfolios. COPPMAN was implemented in a construction company and evaluated as a useful tool due to its features such as knowledge integration, forecasting of portfolio profitability and recommendation of strategies as well as its visualization features. Research design and findings can be used for development of similar tools in other project-based industries.

Keywords: Construction management; decision support systems; project portfolio management; risk management.

1. Introduction

A portfolio is a collection of projects and programs that are managed as a group to achieve strategic objectives (1, 2). Companies need to decide which projects to include in their portfolio considering their strategic targets as well as their resource constraints. In a project-based industry such as construction industry, in order to ensure project success, companies enhance their project management skills over time, which is mainly about execution and delivery of projects right. On the other hand; project portfolio management (PPM), which focuses on doing the right projects at the right time, requires completely different techniques and perspectives than project management (3).Traditional project management routines and decision-making at “project level” may not satisfy the needs of simultaneous management of multiple projects considering limited resources/capabilities and the need for strategic integration to achieve company objectives (4,5,6). PPM as an approach is different than multi-project management in that it is based on a strategic perspective rather than tactical/operational concerns. PPM provides the link between the permanent organization and its temporary projects by extending the capability of management by combining operational and business strategies. It serves for both levels to derive short-term and long-term benefits, which may help not only effective management of projects within the portfolio but also implementation of enterprise strategy (6,7,8,9,10,11,12,13). It is strongly advocated in the literature that successful implementation of PPM helps achievement of sustainable competitive advantage within project-based industries (13,14,15,16,17,18,19). There is a growing need for effective PPM solutions that would meet the specific requirements of these industries (4,14,18). On the other hand, traditional project management approach is still dominating the construction sector (20,21,22) whereas studies on PPM in the construction industry have been very limited (23,24,25,26,27,28,29).

This study presents the results of a research and development project aimed at developing a process model and a tool for PPM in construction companies. The study aims to structure a complete process model for adopting portfolio management initiatives that can fill the identified research gaps in the literature. Moreover, research follows a methodology that enables close collaboration with construction professionals to identify and meet the needs of the industry. Research findings demonstrate that the tool can provide a knowledge-based support for decision-making and has potential benefits with its information visualization features and easy-to-follow processes.

2. Research Objectives and Methodology

The research objectives are;

1. Exploratory objective: to specify the need/requirements for portfolio management applications in construction companies — identifying problems either anticipated by researchers (by literature survey) and/or perceived in practice (by surveys with company professionals),

2. Constructive objective: to generate a process model and a solution as a tool, and

3. Empirical objective: to test feasibility of the generated solution by its potential users - utilizing usability testing and real applications in construction companies.

The research methodology utilized in this study is given in Fig. 1. Triangulation has been used to avoid possible bias originating from subjectivity in qualitative assessments. Opinions of different professionals were collected at various levels of the study progress. Evaluation forms were structured through ratings for pre-defined statements to control extent of the evaluations and open-ended questions to reveal their understanding and expectations. Needs analysis was structured based on literature review and “focus group” study that was undertaken to assess the practical needs and test validity of the initially identified requirements found as a result of literature review. The “focus group” consisting of three professionals (as summarized in Table 1) from a large global engineering and construction company was consulted to learn their needs and later, to get their feedback for the process model. Then, process model was developed based on findings of needs analysis and data obtained from a questionnaire survey administered to construction professionals operating in the international market. Preliminary functions of the tool were identified by a survey responded by 108 Turkish company professionals experienced in international markets (where 38.57% return rate was achieved). Profile of the respondents is provided in Table 2. After, consulting the “focus group” for their comments on the process model, the model was finalized by generation of numerical examples in two iterations. This paper prototype of the tool was used for illustrating a sample case before its codification. Tool was generated in an iterative process (within five sprints) to re-assess the architectural details in each iteration and address problems in each run. Verification process of the finalized tool was conducted by the research team by black-box testing methods (i.e., requirements testing, positive and negative testing, compatibility testing, and performance testing) and comparison of the obtained results with the numerical example considering hypothetical projects. The first released version (alpha version) was evaluated by an “expert panel” consisting of two academicians and two industry professionals (one from construction and the other from software company), who are competent in both portfolio management and information technologies. Expert panel conducted direct investigation of the tool where the hypothetical case was considered as the base model to simulate the overall process. Trial utilization of the updated alpha version was performed by two different company professionals (from large and medium-scale construction companies) by “pilot testing” of the tool in a simulated use environment. They established their own sample portfolios, which provided evaluation of the initial test results and readiness of the tool for further testing. This study mainly confirmed the transition between the process testing with “demonstration” of the tool and testing with its “utilization by actual users”. More performance-oriented testing was held by usability testing with six external participants to eliminate interface or flow-related errors that might be detected in its actual trial. It was carried out in two sessions in a lab environment (in Human-Computer Interaction Research and Application Laboratory at METU) by graduate level civil engineering students. Finally, beta testing was executed by implementing the tool by the "focus group" to evaluate its usability and possible benefits as a result of its utilization in its actual environment. The process model and tool have been developed with the contribution of various professionals, roles of which are summarized in Table 1.

3. Needs Analysis

The needs analysis comprises of two steps, mainly literature review to understand requirements for PPM depicted in literature and consultation with professionals about their needs. The research gap is identified and fundamentals of the process model and the tool have been determined considering this gap.

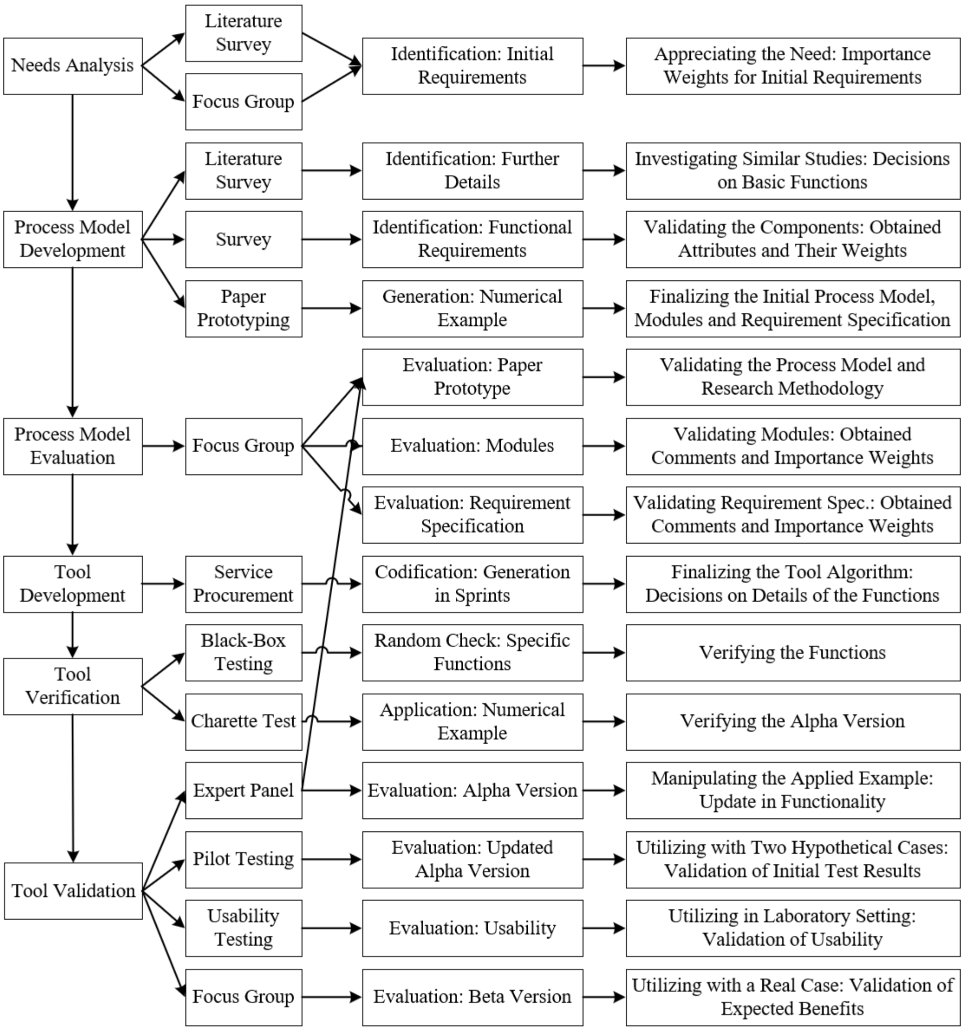

Fig. 1. Research methodology

3.1. *Literature review*

PPM requires assessment, selection, and management of the projects considering their strategic value in the portfolio, contribution to the organizational objectives, and their interrelationships/dependencies (30). Construction Industry Institute (CII) (31) highlighted the need for a comprehensive and objective method for PPM that is capable of directing the project selection process considering company objectives, ensuring the resource and budget constraints of the company as well as taking into account global risks are still some challenges about PPM in the construction industry (32). Cooper *et al.* (33) claim that the main challenges are resource balancing, prioritizing projects against one another, and making go/no-go decisions in the absence of solid information (34). Artto (35) argues that PPM challenges relate to questions of relevant information content, information sharing, and aspects of learning. Thus, PPM requires a successful knowledge integration and management process. Levine (36) defines assessment of impact of uncertainty on projects and portfolios as a problem associated with PPM. A review of the literature also highlights that handling dependencies between projects while giving portfolio decisions is another requirement but also a challenge (21,37,38). Simultaneous execution of projects requires investigation of the interactions among projects originating from shared resources, technical requirements, physical locations, contractual agreements, and external environment. Successful identification and evaluation of project dependencies by efficient, practical and user-friendly methods is required so that strategies for PPM can be formulated effectively (7,11,21,30,37,39,40,41,42,43). On the other hand, there is limited number of studies that tackle these dependencies and incorporate them into the decision-making process at the portfolio level (38,40,42,44,45,46,47).

There are various models and tools addressing PPM in various project-based sectors where most of the studies focus on the project selection process. Solutions are ranging from simple multi-criteria scoring methods to complex portfolio optimization (48,49). Optimization techniques for portfolio selection stand out amongst others with significant importance in the overall share. However; these methods have been criticized for failing in getting user acceptance due to limited room for incorporating user judgement/experience in portfolio selection process (40). Ghasemzadeh and Archer (40) underlined the importance of decision support systems (DSSs) as an integrated framework for PPM. DSSs increase the user acceptance potential of the provided solution due to its capabilities such as flexibility (allowing adaptation for company's environment, i.e., its strategies, models, procedures) and interactive system support (capturing and presenting users' actual preferences in decision-making through a user-friendly interface) (10,40,50). The initial idea in this research was to develop a DSS that may support challenging tasks of PPM, particularly knowledge integration, risk assessment and modelling project dependencies to facilitate decision-making at the portfolio level. It may help the user assess their current portfolios and may aid user's decision by comparatively presenting possible portfolio alternatives prior to selection (51).

3.2. *Needs of construction professionals*

Interviews with the "focus group" (Table 1) regarding their current approach on portfolio management and requirements of an ideal solution revealed the need of a systematic and strategic support considering interrelations among projects and contributions of projects to the overall success of a portfolio as well as strategic priorities of the company. Experts reported that they had been utilizing different tools at the project level by different departments and making decisions at the portfolio level (e.g., project selection) considering outputs produced by these tools and trying to integrate individual outputs manually. They laid emphasis on an integrated system design that combines all departments within the company on a common platform for PPM, which includes a database of all the critical information required for portfolio decisions. They emphasized that the system should convert data into knowledge through supporting mechanisms for collecting the right data at the right time and conveying it to the right person while also serving for corporate learning. A responsive reporting mechanism is also needed, which is supported with real time, numerical and visual data, in addition to forecasting and learning abilities. Some other requirements mentioned by the "focus group" are listed as follows:

- It should be construction industry specific responding to needs, expectations and requirements of construction companies.
- It should assist in management of group of projects considering the interrelations/dependencies between these projects.
- It should conduct a comprehensive risk analysis at the portfolio level considering related risks stemming from project, market, and country factors.
- It should have an effective similarity assessment function to learn from completed projects (such as, major risks encountered, deviation between as-planned and actual performance levels) and forecast project performance by making comparisons with previous projects.
- It should be flexible to be used by companies having different portfolios (large or small, involving similar or diverse projects, etc.).
- It should be dynamic to track and respond to the changes in projects and markets.

Table 1. Profile of professionals

Group	Participation	Title	Company / University	Experience (years)	Knowledge in IT	Knowledge in PPM
Focus Group	Needs Analysis Process Model Real Application	Business Development Director	Construction Company A	23	High	High
		Business Control and Risk Management Director		21	High	Medium
		Enterprise Systems Manager		11	Medium	Medium
Expert Panel	Process Model Alpha Version	Professor	METU	26	High	Medium
		Assistant Professor	METU	3	High	Low
		Executive Assistant to CEO	Construction Company B	6	Medium	High

		Product Manager	Software Company	10	High	Low
Pilot Testing	Alpha Version	Director of Procurement	Construction Company C	15	Medium	Medium
		Director of Business Development	Company D	14	High	Low
Usability Testing	Alpha Version	Research Assistant / PhD Candidate (6/6)	METU (6/6)	-	Medium (5/6)	Low (4/6)

Note: Names of the companies are withheld due to confidentiality reasons. Usability testing group consists of 6 participants where (n/6) represents the number of participants (n), who apply for the presented result.

These findings motivated development of a knowledge-based decision support tool that would integrate various systems and establishment of a web-based system for capturing and retrieving knowledge. After the needs analysis, current DSS depicted in the literature have been reviewed and the process model was developed considering research gap.

Table 2. Profile of survey respondents

Characteristic	Category	Percentage (%)
Education	MSc	59
	PhD	7
Title	Director	24
	Technical Office Staff	17
	Planning Department Employee	16
	General Managers	14
Experience	At least 11 years	52
	At least 21 years	16
Level of Knowledge / Experience on PPM	Low	29
	Medium	42
	High	29

3.3. *Evaluation of current tools for PPM*

The commercially available tools for PPM are usually structured on a "database" where projects are categorized according to their types and "prioritization" of projects is done using scoring models. "Bubble diagrams", "pie charts", "bar charts", and "dashboards" are the common visualization methods at "project" and "portfolio" levels. "Strategic prioritization", “project selection”, “risk analysis”, and “scenario analysis (considering effect of a project on portfolio in terms of benefits, time and cost analyses)” are the major capabilities of the existing tools. These tools help with establishing and visualizing portfolios for all types of projects; however, decision-making with particular types of projects may require specific considerations. Solutions provided in the literature are mainly optimization-based models with limited visualization capabilities where dependencies are generally considered at the constraint level. Table 3 presents a representative set of DSSs that were mainly developed for identification of optimal portfolio (also referred as most attractive (or “best”) portfolio or highest value for money). As underlined by Stummer *et al. (54)* optimization approaches (i.e., converting projects to a single utility value for the portfolio) dominates portfolio selection models; however, decision-maker should be supported with visual displays that enable visibility of the process and self-learning of the issue/case. Although integration and visualization capabilities have been identified as required features by many researchers (57,58,59), there are limited studies in literature that address these features, which are mainly in the IT sector. As an example, Newton and Girardi (60) proposed a knowledge-based and ontology-driven tool that investigates similar software projects in the portfolio to handle resource optimization. In another study, Rahmouni *et al (61)* analyzed the similarity between IT projects and integrated visualization of the relationships between projects to the process. As summarized, dependencies between projects have hardly been considered during assessment of risk and benefits. Additionally, integration of knowledge to portfolio analysis has been very limited in previous studies. Optimization may not be fully possible/reliable with limited number of projects and it may not represent the ultimate aim while making portfolio decisions. Therefore, this study aims at structuring a portfolio perspective with the objective of enhancing project and portfolio visibility by considering the interactions between projects, predictions for projects, and lessons learned.

Table 3. DSS studies in PPM literature

Reference	Portfolio	Parameters	Dependency Analysis	Visualization	Method
Chu *et al.* 1996 (52)	Product research and development projects	Resource constraints, uncertainty estimation (probability of success), and decision criteria on cost and time (monitoring of actual values for reassessment)	Task level learning effects are incorporated to probability of success	-	Time-cost tradeoff analysis, strategic selection algorithm
Ghasemzadeh and Archer 2000 (40)	All projects	Strategic fit, financial constraints, resource constraints, timing, project interdependencies, balancing criteria, and other constraints	Constraint-based	Portfolio matrix displays, Gantt Chart	AHP for assessment of objectives, optimization and adjustment of portfolios
Lin and Hsieh 2004 (10)	All projects	Strategic focus, resource constraints, implementation time or cost, expected profit, and user-defined evaluation criteria	-	Scatter plots	Fuzzy integer linear programming model
Hu *et al.* 2008 (53)	Manufacturing projects	Company benefits, total cost, resource constraints, diversity constraint, and management limit constraint	Modeling integrated benefits considering project interactions	Pareto frontier chart, bubble charts, histograms	Multi-objective integer programming model
Stummer *et al.* 2009 (54)	Research and development projects	Required human competencies, ideal work time, working time periods, economic objectives, and strategic objectives	-	Heatmaps, parallel coordinate plots, column charts, mapping	Multi-criteria mathematical programming approach
Lourenço *et al.* 2012 (47)	All projects	Project's cost and value scores on the benefit criteria, user-defined constraints, uncertainty domain	Constraint-based	Pareto frontier chart	Multi-criteria mathematical programming approach, hierarchical value model, and sensitivity analysis
Mira *et al.* 2013 (55)	Power generation projects	Contribution to controlled risk, total cost and schedule of each project	-	Charts for costs and risks	K-random risk greedy heuristics (kRGH)

Gade *et al.* 2018 (56)	Building renovation projects	User-defined renovation criteria, criteria weights, building status, estimated renovation costs	-	Histograms	AHP for assessment of weights, value-based prioritization

4. Process Model

Based on the findings of needs analysis, the initial process model has been developed. It is based on scenario analysis where the portfolio alternatives are visualized with project/portfolio level representations. For integrating knowledge, similarities between projects are quantified and utilized to retrieve previous projects that can be used for prediction, as the average values and deviations from expectations. "Overlap similarity measure" as defined by Boriah *et al.* (62), which is basically investigation of categorical data similarities, was adopted by representing projects with several attributes. Project similarity is also used as a reference for dependency calculations (i.e., financial and resource dependencies). Dependencies are visualized by dependency network maps. Density of this map is defined as an indicator of uncertainty originating from complexity (due to dependencies of projects), which is further reflected in the portfolio risk score. To differentiate the projects with considerable learning opportunity, "learning potential" is defined as a measure to be used in strategic assessment of the projects/portfolios. Dissimilarity of the project in question with the other projects is used to assess the potential of organizational learning due to new lessons learned, whereas it indicates a higher risk. "Portfolio strategic fit" is measured as a score based on the compliance of the portfolio with the identified strategic factors and targets. "Portfolio risk" is defined as a source or event that involves uncertainty and may have a negative impact on project outcomes. "Portfolio risk" score is also quantified by evaluation of a factor set, whereas dependencies are incorporated as a coefficient to this score. "Portfolio value" reflects the contribution of each project to the portfolio, which is related with portfolio strategic fit score and portfolio risk score (as an indicator of portfolio success potential). The initial process model was constructed based on these structured definitions, whereas more detailed information can be found in Bilgin *et al.* (63) Then, a questionnaire survey was conducted for its functional requirements. It mainly investigated preliminary functions of the tool considering assessment of strategic fit, risk, and similarity between projects in three sections.

- First section identified strategic factors for a construction company and their importance weights for determining value of a project/portfolio. It also included the factors and their weights for calculating learning potential/opportunity.

- Second section was about risk assessment. It investigated risk factors and their weights to assess their potential impact on a construction project (in terms of duration, cost) if they occur. This section further analyzed the importance weights while assessing dependencies during risk assessment.
- Third section addressed the criteria and their importance weights for measuring the similarity of construction projects.

The default importance weights were obtained which are also editable for company specific use. Results of the questionnaire survey were utilized to analyze a portfolio of 25 hypothetical projects (5 of which are summarized in Table 4). This hypothetical portfolio was set up with the information that would exemplify the intended calculations (project data, risk and strategic evaluations, and lessons learned) and the process in the form of a "numerical example". This example summarizes the required data load for starting a typical portfolio analysis. This paper prototype was carried out mainly in Excel for handling project data and making required calculations. Dependency maps was generated in "ORA" tool provided by CASOS (Computational Analysis of Social and Organizational Systems) center of Carnegie Mellon University. This initial model was evaluated by the research team and current model was refined in codification and retrieval of data, especially replacing the initial design of lesson entry forms. Generation and evaluation of the paper prototype led the research team to further structure and finalize the process model details.

Table 4. Representative projects from the hypothetical project portfolio

Project No	P2	P10	P20	P21	P24
Project Status	Completed	Completed	Completed	On-going	Potential
Project Name	High-Rise Residential Building	Tunnel	Hotel	Highway	Shopping Mall
Project Type	Building	Tunnel	Building	Road	Building
Project Scope	Construction of 6 blocks of 30 story buildings	Construction of 5 km long tunnel	Construction of a 5-star hotel with outdoor sports facilities	Construction of 20 km concrete road	Construction of a 5-story shopping mall
Client	Company V	Company TA	Company R	Company TG	Company V

Country	Russia	Azerbaijan	Turkey	Greece	Russia
Project Delivery System	Design-Bid-Build	Design-Build	Design-Bid-Build	Build-Operate-Transfer	Design-Build
Contract Type	FIDIC	-	-	-	FIDIC
Contract Payment Type	Unit-Price	Unit-Price	Unit-Price	Unit-Price	Unit-Price
Currency	US Dollar	Euro	Turkish Lira	US Dollar	US Dollar
Start Date	2009	2006	2005	2015	2016
End Date	2012	2008	2007	2017	2018
Critical Resource Type	Machinery and Equipment	Machinery and Equipment	Material	Personnel	Personnel
Critical Resource Name	Tower Crane	Tunnel Boring Machine	Curtain Wall (window film)	Planner (Dep1)	Mechanical Designer (Dep3)
Partnership Type	Joint Venture	Joint Venture	-	-	Consortium
Partner Company	Company M	Company A	-	-	Company K
Planned Project Duration	840	600	460	730	730
Completion Percentage	100%	100%	100%	60%	0%
Contract Price	$95,000,000	€ 40,000,000	75,000,000 TL	$60,000,000	$75,000,000
Expected Cost	$85,000,000	€ 35,000,000	70,000,000 TL	$51,000,000	$67,000,000
Outcome Dependency	-	-	-	-	P22
Construction Technology	Self-Climbing Formwork	Tunnel Boring Machine	Tunnel Formwork	Concrete Road	Pre-stressed Concrete
Actual Project Duration	900	620	470		
Extension of Time	30	0	10		
Delay	60	20	10		
Actual Cost	$89,100,000	€ 35,500,000	71,300,000 TL		
Change in Contract Price	$3,000,000	€ 0	0 TL		

Delay Cost	$3,600,000	€ 500,000	500,000 TL
Delay Penalty	-	-	-
Early Completion Incentive	-	-	-
Claimed Duration	30	-	10
Duration Awarded	30	-	10
Claimed Payment	$3,000,000	-	-
Payment Awarded	$3,000,000	-	-
Critical Delay Cause	Scope change, Unavailability of qualified labor	Unavailability of machinery – late delivery of TBM machine	Unforeseen ground conditions
Critical Actor	Company V, Company G	Company G	Company G
Critical Work Package	Interior Wall, Fire System Installation	Boring	Foundation

Finally, modules of the tool (as groups of the related functions) were structured to organize the process into manageable tasks. Thus, the system was formalized under five main modules on "System Management", "Knowledge Management", "Risk Assessment", "Strategic Assessment", and "Portfolio Analysis" where fifteen main requirements were set out to fulfil the intended design principles as presented in Table 5. Following the approval of the "focus group" on the finalized "paper prototype", "requirements" and "modules", a tool, entitled as COPPMAN (Construction Project Portfolio MANagement) was developed to test possible benefits of the system. COPPMAN was developed as a cross-browser compatible single page web application developed on top of "ASP.NET MVC" framework where server-side components were programmed with "C#" and client-side components were programmed with "JavaScript". Development steps of COPPMAN are given in Figure 1.

5. Architecture of COPPMAN

As a knowledge-based tool based on the developed PPM process model, COPPMAN utilizes the previous projects of a company to generate company specific knowledge-base that would be used to form portfolios in accordance to the company's strategic objectives. There are three categories of projects in COPPMAN, which are "completed projects" (used as the basis of company knowledge), "on-going projects" as the projects currently being executed, and “potential projects” that the company is considering to bid (where optional project statuses are also provided as “suspended”, “eliminated”, and “cancelled” to enrich the codified project information). During scenario analysis, COPPMAN establishes various portfolio alternatives by grouping the current/active projects (i.e., “on-going” and “potential projects”) with different “potential project alternatives”.

Model has been structured with approaches of weighted averages, similarity measures, and principles of network analysis. Prediction results are presented through average values or modes of different types of data. Warnings are mainly provided as comparison results with threshold values, which are editable through user preferences. The tool automatically calculates the “dependencies” between projects, draws “dependency network maps”, and numerically integrates them into portfolio analysis process. The impact of any potential project to the existing portfolio is evaluated within the context of scenario analysis by considering different types of dependencies. “Resource dependencies” highlight the shared resources between projects and facilitate management of resources. “Financial dependencies” underline the same/similar financial resources and may improve risk assessments and portfolio profitability. “Learning dependencies” reveal similar content of new experience with the projects and may foster learning considering both the risk and the potential. “Outcome dependencies” indicate any specific relationship between projects that needs to be tracked in the process (e.g., phased projects, market entry, etc.). The tool provides “portfolio dependency map”, calculated “dependencies” between the projects and “warnings” on how this specific portfolio can be managed to the potential decision-makers. Identification of “critical dependencies” as well as “critical projects” and “critical portfolios” in comparison to others is also possible using COPPMAN. A dependency that has a magnitude over the limits (/threshold) is to be identified as the “critical dependency” between all dependencies within the portfolio and may indicate the dependency that needs attention. For example, the tool can help the user schedule the projects “A”, “B” and “C” considering resource dependencies, to concentrate on the effective transfer of lessons learned between the projects “D” and “F”, and to consider the projects “E” and “G” together in developing the risk management plans. Portfolio alternatives are shown visually to the users with quantitative scores indicating their “risks”, “strategic fits”, and “expected profits”. As previously mentioned, an attribute-based weighted similarity calculation is followed for dependency calculations (64). Overall dependency between the projects $\{X, Y\}$ as $D(X, Y)$ are calculated according to the following formulae:

$$D(X,Y)\ [0,100\%] = \sum_{i=1}^{4} D_i\ (X,Y) * w_i \quad i = \{dependency\ types\} \tag{5.1}$$

$$D_i(X,Y) = \sum_{k=1}^{n_k} w_k * S_k(X_k, Y_k) \tag{5.2}$$

$$S_k(X_k, Y_k) = \begin{cases} 100\% & if\ X_k = Y_k \\ 0 & otherwise \end{cases} \quad k = 1, \dots, n_k \tag{5.3}$$

where; X and Y are projects, $D_i\ (X,Y)$ is the dependency measure for dependency i, w_i is the overall weight for dependency i, w_k is the attribute weight for attribute k, $S_k(X_k, Y_k)$ is the per-attribute similarity, and n_k is the maximum number of the attributes for measuring dependency i. Attributes used for calculation of dependencies are as follows:

- Financial Dependency Attributes: “client” and “currency”,
- Resource Dependency Attributes: “personnel”, “manpower”, “machinery and equipment”, and “material”,
- Learning Dependency Attributes: “country”, “project type”, “client”, “technology”, “contract type”, and “partnering company”,
- Outcome Dependency: user directly identifies through entering a value between [0,100%].
- Based on dependency analysis, the critical projects and the intensity of dependency network map are quantified by using the below formulae:

$$P_C(X)\ [0,100\%] = \frac{\sum_{i=1}^{n_p} D(X,Y_i)}{\sum_{i=1}^{n_p} D(X,Y_i) + \sum_{i<j} D(Y_i,Y_j)} \quad Port = \{X, Y_1, \dots, Y_{n_p}\} \tag{5.4}$$

where; $P_C(X)$ is the centrality of the project X, $\sum_{i=1}^{n_p} D(X,Y_i)$ is the total dependency of the Project X, $\sum_{i=1}^{n_p} D(X,Y_i) + \sum_{i<j} D(Y_i,Y_j)$ is the total dependencies between the projects of the portfolio $\{X, Y_1, \dots, Y_{n_p}\}$.

$$Port_{ND}\ [0,1] = \frac{\sum_{i<j} D(X_i,X_j)}{\binom{n_p}{2} * 100\%} \quad Port = \{X_1, \dots, X_{n_p}\} \tag{5.5}$$

where; $Port_{ND}$ is the network density of the portfolio, $\sum_{i<j} D(X_i,X_j)$ is the total of dependencies between the projects of the portfolio $\{X_1, \dots, X_{n_p}\}$ and $\binom{n_p}{2}$ is the possible dependencies of the network as binary combination count of the projects in the portfolio.

Table 5. Requirement specification

Requirement	Design Principle	Module
Identification of different users in tool with different accessibility options to the tool menu/operations.	Multi-users	System Management Module
Menu for entry of different types of projects, together with view and query options.	Multi-projects	Knowledge Management Module
Identification of ready-to-use project inputs.	Pre-defined Attributes	Knowledge Management Module
Calculation and presentation of predictions for the on-going and potential projects through use of information of completed projects.	Post Project Appraisal	Knowledge Management Module
Menu for entry of lessons learned, together with view and query options.	Lessons Learned Management	Knowledge Management Module
Tagging system for entry of lessons learned, including editing options for the tag tree and tag-based query.	Lesson Classification	Knowledge Management Module
Calculation and presentation of learning potentials for the on-going and potential projects.	Learning Potential Assessment	Knowledge Management Module
Establishment of project similarity-based search and calculation capabilities.	Similarity Assessment	Knowledge Management Module
Establishment of filtering-based search and calculation capabilities.	Filtering Capability	Knowledge Management Module
Menu for evaluation of risk and strategic fit factors, including editing of the factors and calculation of scores.	Risk and Strategic Fit Analysis	Risk and Strategic Assessment Modules

Calculation of dependencies between projects and visualization of dependencies with a dependency map.	Dependency Assessment	Portfolio Analysis Module
Development of a project symbol to be used in visualizations.	Visualization of Projects	Portfolio Analysis Module
Automatic formation of the portfolio alternatives through addition of potential project combinations to on-going projects.	Portfolio Formation / Scenario Analysis	Portfolio Analysis Module
Calculation of portfolio attributes and depiction of results through tables, bubble diagrams and bar charts.	Visualization of Portfolios	Portfolio Analysis Module
Establishment of an automatic warning system for current portfolios.	Warnings	Portfolio Analysis Module

A similar procedure to given dependency calculation is also applied for similarity calculation for the projects where the attributes of "country", "project type", "client", "technology", and "contract type" are matched while user is allowed to assign gradual similarity ([0,100%]) between the different attributes of "country", "project type", and "client". Learning potential is based on dissimilarity of projects; therefore, same calculation procedure through use of attributes "country", "project type", "client", "technology", "contract type", "project delivery system", "partner company" is adopted with the difference of subtraction of the obtained similarity score from a maximum value (which is "100").

Portfolio strategic fit is assessed considering contribution of a portfolio to the company's strategic objectives. For risk and strategic fit assessments of projects, weighted averages are calculated following scoring of each identified evaluation factor (factor set). Project risk (P_R) and strategic fit (P_{SF}) evaluations are obtained as total of multiplication of factor evaluation score (Fs) [0,100] and factor weight (Fw) for each factor in the risk/strategic fit evaluation set. Thus, the average values for the projects in the portfolio constitute the basis of portfolio risk and strategic fit calculations.

$$P_R\ [0,100] = P_{SF}\ [0,100] = \sum_{i=1}^{n} Fs_i * Fw_i \quad i = \{evaluation\ factors\} \tag{5.6}$$

$$Port_{RA}\ [0,100] = \bar{X}(P_R) \tag{5.7}$$

$$Port_{SF}\ [0,100] = \bar{X}(P_{SF}) \tag{5.8}$$

where; $Port_{RA}$ is the portfolio risk average and $\bar{X}(P_R)$ is the average risk score of the projects in the portfolio while $Port_{SF}$ denotes the portfolio strategic fit through $\bar{X}(P_{SF})$ as the average strategic fit of the projects in the portfolio.

Dependencies are considered while calculating portfolio risk scores and portfolio success potential is calculated using risk scores. Following identification of the critical dependencies, projects and networks; the accumulated/total effect of dependencies is integrated to portfolio risk assessment by multiplying with the factor originating from density of the dependency map. The effect is reflected to the average risk scores ($Port_{RA}$) obtained by individual risk assessments carried out for each single project in the portfolio.

$$Port_R\ [0{,}100] = \bar{X}(P_R) * \frac{1+Port_{ND}}{2} \tag{5.9}$$

where; $Port_R$ is the portfolio risk and $\bar{X}(P_R)$ is the average risk score of the projects in the portfolio.

Portfolio success potential ($Port_{SP}$) is regarded as a risk-free value and quantified through subtraction of the portfolio risk ($Port_R$) from a maximum value (which is “100”) and calculated as follows:

$$Port_{SP}\ [0{,}100] = 100 - Port_R. \tag{5.10}$$

Portfolio value is defined as the sum of portfolio strategic fit and success potential and previous project data is used to calculate expected portfolio profitability. Portfolio value ($Port_V$) is based on maximizing portfolio strategic fit and minimizing portfolio risk; therefore, simply quantified as total of portfolio strategic fit ($Port_{SF}$) and success potential ($Port_{SP}$):

$$Port_V\ [0{,}200] = Port_{SF} + Port_{SP}. \tag{5.11}$$

Portfolio profit ($Port_P$) is the total of expected profit of the projects in the portfolio (P_P) based on selection of a common currency for the analysis:

$$Port_P = \sum_{i=1}^{n} P_{P_i} \quad i = \{portfolio\ projects\}. \tag{5.12}$$

To ensure functionality, COPPMAN is equipped with dynamic features where all data entries are provided in an updatable or re-definable format. Some numerical figures used in calculations and evaluation criteria used in the process are provided as default but can be changed by the user.

Regarding utilization of this system, typical operations can be grouped under main stages of “data input”, “evaluation” and “analysis”. Initially the user should set required parameters to reflect company/project specific preferences (e.g., specified factors, evaluation scale for assessments, weights, attributes). Following that, user should define the “completed projects” and the information to be used in the evaluation of the projects for “post project appraisal” and "lessons learned". Information on the active/current projects should also be entered. Once the project level assessments (risk and strategic fit assessments for each of the current/active projects) are completed, COPPMAN becomes ready for portfolio analysis where the user is able to examine different portfolio alternatives and select a portfolio that would be best for the company by taking into account the calculated ratings, visual aids and warnings about strategies. Fig. 2 presents the flowchart of main inputs and outputs of COPPMAN, whereas Fig. 3 presents the use case diagram of COPPMAN.

6. Testing of COPPMAN

Following the first release, as summarized in Fig. 1, expert panel delivered a retrospective evaluation on the model by the numerical example (hypothetical case/paper prototype) where it also served as the base model for alpha version of the tool. They had a week's time to navigate within the tool, and the following meeting was aimed at introducing the methodology, model and the alpha version of the tool for open discussion with the panel members. During the discussions, the tool was found successful in the promise of guiding project selection with the support including automatic measurement of dependencies, codification of data, presentation of numerical past project data, useful visual graphics, and provision of warnings with a functional user interface. Findings demonstrate the tool's "functional" and "operational" capabilities as well as its "usability" (Table 6). As a result, alpha version required minor improvement in its visual and searching capabilities (e.g., interactivity with graphics, enhancement in data entry, presentation and retrieval). The "updated alpha version" was tested by two different company professionals based on their own sample portfolios. The strengths of the tool were identified as "web-based tool", "algorithm to calculate portfolio value" and "user-friendly interface design and visual outputs — specifically the dependency network map", "automatic creation of portfolios by gradual inclusion of the potential projects", "flexibility and extent of the risk and strategic fit assessment processes", "comparison of different alternatives by different measures and graphics", "project selection process supported with predictions" and "flexibility of the tool". It was commented that the tool helped selection of a portfolio of projects with a comprehensive reasoning and was flexible enough to adapt changes according to company preferences and objectives. In "usability testing" participants performed pre-defined tasks (under 14 scenarios) in laboratory setting. This performance-oriented testing through eye-tracking technology provided evaluation of micro-level behaviors as the indicator of the success of the process design and the related interface. An analysis software (Tobii Studio) was used in the process whose outputs were supported with post-task and post-test questionnaires and session audit results (i.e., critical and non-critical errors, task completion rates). Performance (quantitative) and preference (qualitative) data were collected through "Think Aloud" testing session including visual (i.e., clusters, gazeplots, heatmaps etc.) and numerical outputs (i.e., total fixation duration/time on task, mouse click count) (65). All of the data provided successful and complementary results, which eliminated the potential update requirement. This final version of the tool was accepted to be the "beta version" which was further tested with a "real application".

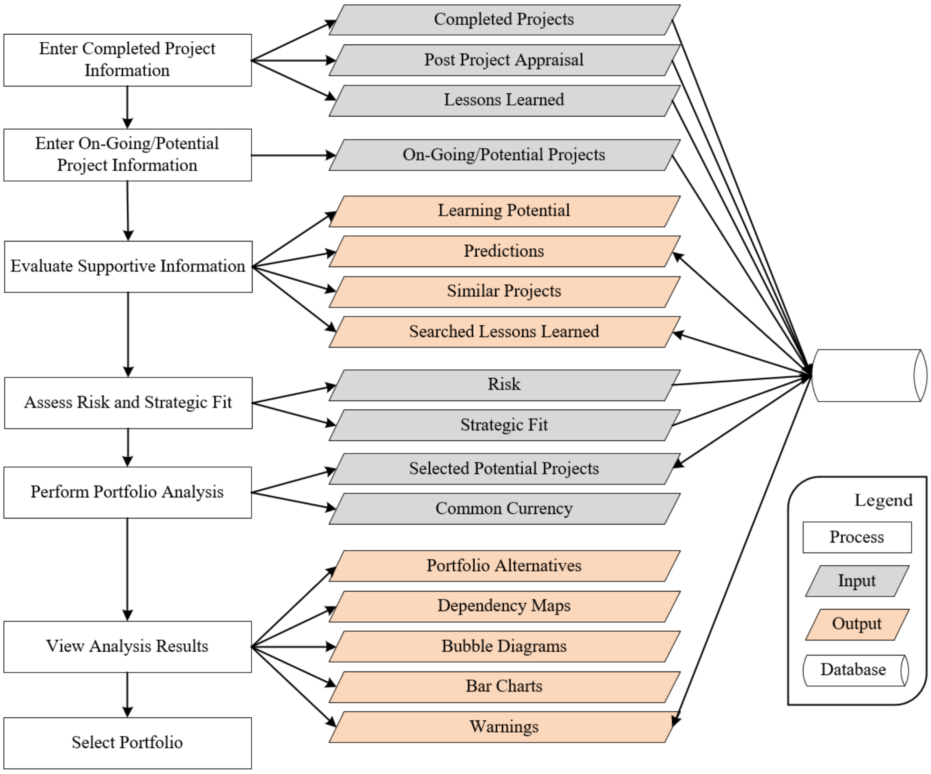

Fig. 2. Flowchart for main inputs and outputs

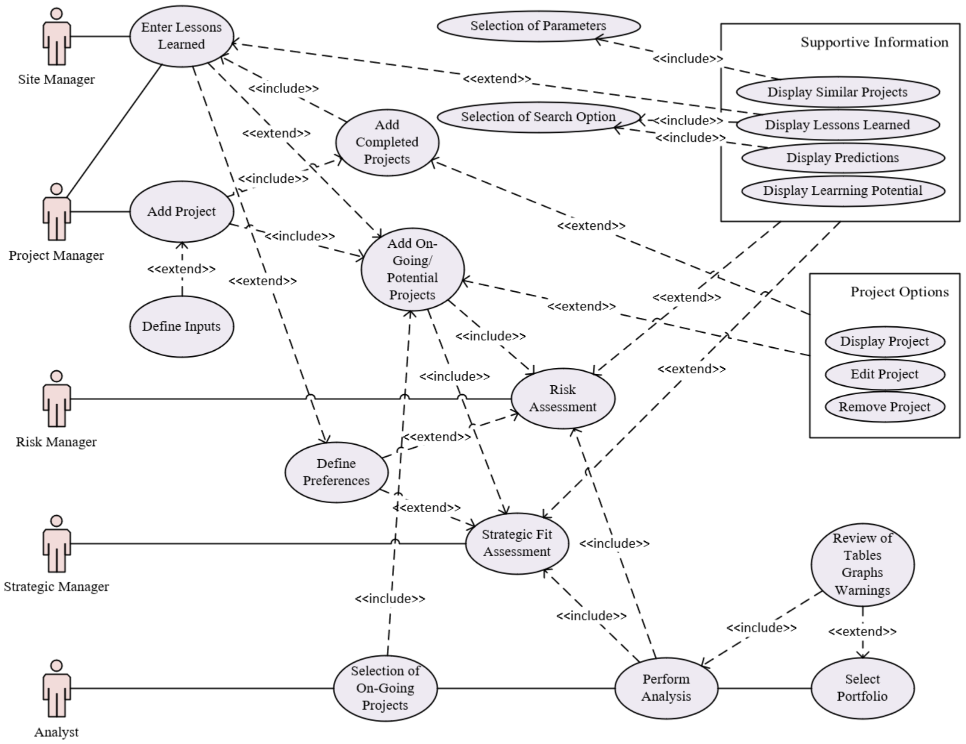

Fig. 3. Use case diagram

Table 6. Survey results for expert panel

	Completeness / Coverage	Suitability / Accuracy	Usefulness	Usability	Receptiveness	Overall	Average
Expert 1	5.64	5.75	6.00	5.67	5.80	6.14	5.833
Expert 2	6.14	6.50	7.00	6.00	6.00	6.14	6.297
Expert 3	6.36	5.92	7.00	6.44	6.80	6.14	6.443
Expert 4	5.64	5.67	5.80	5.89	5.20	5.43	5.605
Average	5.945	5.960	6.450	6.000	5.950	5.963	6.045

Evaluation on seven-point Likert Scale ranging from “strongly disagree (1)” to “strongly agree (7)”

7. A Practical Application

The construction company involved in this research mainly undertakes turnkey power generation projects in diverse locations around the world as the Engineering, Procurement and Construction (EPC) contracting arm of a holding. It owns several companies that are involved in the construction of power plants, refinery, cement, petro-chemical and gas plants, factories, high-rise buildings, water treatment plants and transmission lines, bridges and other infrastructure projects. The following sections present the details of the study undertaken in the company by the "focus group" (test group) to investigate COPPMAN's possible benefits/drawbacks.

The "focus group" utilized COPPMAN on its web address http://www.coppman.net (username and password is available from the corresponding author upon request). They built up a sample project portfolio consisting of mainly "combined cycle power plant projects" which are summarized in Table 7. They identified five "completed projects" with five "lessons learned" in these projects where two "on-going projects" and two "potential projects" were also included in the portfolio. Information about the projects were protected by coding arbitrary "project names" and "actor names" as well as changing financial information by adjusting numerical figures using a similar ratio for all projects. They appreciated the default inputs, and defined only some additional attributes such as; actors of the company (individual/company), strategic preferences, technologies, critical delay causes and work packages, etc. Factors for strategic fit and risk assessment were considered to be sufficient. Integration of project significance, critical milestones, and project specific notes were the suggestions for improvement related with data entry process. On-going projects were suggested to be enriched with information of achieved status (i.e., current performance) and checkpoints addressing change management initiatives. Focus group also underlined the requirement of a project level codification of the actual risk and strategic fit scores for quick summary of the project performance. Prior to risk and strategic fit assessments, supportive information such as the similar projects to on-going and potential projects, their lessons learned, predictions for these projects and their learning potentials were assessed. Similarity assessment was found successful in refining the important projects with respect to the project in question. Additionally, they appreciated that the similarity results also reinforced the sources of similarity. They advised an improvement on similarity calculation as in selection of the attributes and integration of country information to calculations. They found the lesson learned management system successful to retrieve the related cases, where an additional free-text search of lessons might be integrated. Forecasting was found valuable to provide insight to the user but experts suggested a possible improvement in process/milestone-based predictions in addition to project outcome figures. Portfolio alternatives were generated by COPPMAN and further details about the portfolios were explored at both project and portfolio levels. Table 8 represents the summary of portfolio alternatives assessed by COPPMAN. They first investigated the portfolio level outputs, which are the summary table (Table 8), bubble graph for strategic fit vs. risk of portfolio alternatives, bar chart of portfolio values as stack columns of success potential and strategic fit, portfolio change graphs indicating the relative profit and value of the alternative with respect to current portfolio, and portfolio level warnings. They further investigated the specific portfolios where project level outputs are provided. Fig. 4 exemplifies the project symbols of “Alternative 4” and Fig. 5 presents the screenshots of the project level outputs for this portfolio alternative. Project level outputs include tables that summarize some project characteristics, bubble graph for strategic fit vs. risk scores of projects in the portfolio, dependency map of the portfolio projects, and project level warnings as in Fig. 5. They found the visual outputs and warnings very helpful for the decision-maker since they were revealing the important criteria. They commented that reporting abilities might be enhanced by organizing reports according to specific need of different users. Finally, they ranked the portfolio alternatives according to different selection criteria. They found ranking useful and pointed that there might be automatic elimination of the alternatives according to user-defined limits on different criteria. Focus group evaluated COPPMAN as a reliable portfolio management tool since it encapsulates and integrates several systems (such as strategic and risk assessment, lessons learned, etc.), and has successful retrieval mechanisms, forecasting, benchmarking, visualization and quantitative reporting.

Table 7. General information about the projects in the sample portfolio

	Completed Projects					On-Going Projects		Potential Projects	
	Project K	Project Z	Project R	Project B	Project H	Project A	Project P	Project N	Project R2
Short Code	PK	PZ	PR	PB	PH	PA	PP	PN	PR2
Project Type	Combined Cycle Power Plant	Combined Cycle Power Plant	Combined Cycle Power Plant	Simple Cycle Power Plant	Thermal Power Station Rehabilitation	Combined Cycle Power Plant	Electromechanical Installation	Combined Cycle Power Plant	Combined Cycle Power Plant
Project Scope	840 MW	390 MW	420 MW	750 MW	200 MW	1800 MW	1800 MW	500 MW	450 MW
Client	Client K	Client Z	Client R	Client B	Client H	Client A	Client P	Client Z	Client R2
Country	Turkey	Russian Federation	Latvia	Algeria	Iraq	Bahrain	Saudi Arabia	Russian Federation	Tunisia
Project Delivery System	EPC	EPC	EPC	EPC	Construction / Contractor	EPC	Construction / Contractor	EPC	EPC

Contract Type	FIDIC Silver	FIDIC Silver	FIDIC Silver	FIDIC Silver	FIDIC Silver	FIDIC Silver	Client Specific	FIDIC Silver	FIDIC Silver
Contract Payment Type	Lump Sum	Lump Sum	Lump Sum	Lump Sum	Lump Sum	Lump Sum	Lump Sum	Lump Sum	Lump Sum
Currency	USD	EUR	EUR	USD	USD	EUR	USD	EUR	EUR
Start Date	30/12/2013	1/4/2014	11/10/2010	21/10/2013	19/04/2016	4/8/2016	2/7/2015	1/4/2018	1/12/2017
End Date	30/12/2016	29/06/2017	30/07/2013	1/9/2017	29/09/2017	1/4/2019	6/12/2018	1/4/2021	1/9/2020

Table 8. Summary of portfolio alternatives

Portfolio Name	Potential Projects in the Alternative	Average Risk Score (%)	Average Strategic Fit Score (%)	Network Density	Portfolio Risk	Portfolio Success Potential (%)	Portfolio Value	Portfolio Profit (€)
Alt1		38.970	46.695	0.000	19.485	80.515	127.210	4,146,791.60
Alt2	PN	38.337	52.587	0.095	20.990	79.010	131.597	2,480,124.93
Alt3	PR2	35.210	52.943	0.074	18.912	81.088	134.031	5,646,791.60
Alt4	PN, PR2	35.675	55.800	0.122	20.009	79.991	135.791	3,980,124.93

Fig. 4. Visual outputs showing the projects in Portfolio Alternative 4

Direct utilization of the tool for introducing and analyzing a complete set of real projects helped in-depth evaluation of the tool. Experts provided live feedback throughout the processes of data entry, analysis and output. The built-in capabilities were appreciated to be successful for handling project portfolios where possible improvements can be made in “ease of information entry”, “flexibility in calculations”, and “reporting abilities”. Experts highlighted the requirement of a “geographical map” as a visual aid where all projects of the company and alternative portfolio options can be observed and all project symbols can be visible on the same frame. More flexibility in the calculation of “portfolio value”, identification of “exceptional projects” to provide an option for excluding these projects from the portfolio analysis process and also identification of “strategic hold points” were the other remarks made by the experts. Knowledge integration, realistic numerical forecasting and lessons learned database were evaluated among the strengths as well as its visual features and recommendations about strategies. All the respondents achieved consensus on its potential benefits in “strategic planning and strategic achievement”, “project selection and portfolio optimization”, “knowledge management and organizational learning”, and improvements in “communication, documentation and reporting” where other potential benefits were identified as “risk minimization” and “long term profitability”.

8. Discussion of Findings

Needs analysis findings demonstrate that a PPM process is necessary to integrate estimation of portfolio value by assessing risk and strategic fit considering project dependencies and learning from previous projects. The process model developed in this study mainly includes a scenario analysis where possible portfolio alternatives are visualized with project/portfolio level representations. “Portfolio value” that reflects the contribution of each project to the portfolio is quantified by considering portfolio strategic fit score and portfolio risk score between projects. Portfolio risk is calculated by considering project dependencies (resource, financial, learning and outcome dependencies) and dependency network maps are drawn for each alternative scenario to assess criticality and complexity. Portfolio strategic fit is assessed considering strategic targets where “learning potential” is defined as a measure in strategic fit calculations. Similarities between projects are also quantified and incorporated to retrieve previous projects that can be used for prediction. Portfolio analysis is made easier by incorporating the knowledge about previous and on-going projects (using the lessons learned database) while making predictions about the future and assessing risk, strategic fit and expected portfolio profitability considering dependencies between projects in the portfolio.

Based on this process model, COPPMAN has been developed and following are the major strengths of COPPMAN:

- Dependency assessment: Considering the main drawbacks in available tools, COPPMAN has a strength in integrating a model for measurement of dependencies for quantifying portfolio risk and strategic fit. It further adopts visualization with a dependency network map where different types of dependencies are represented by their magnitudes.
- Knowledge management and organizational learning: Unlike the majority of the previous studies, the process model depends on the idea of integrating knowledge management to portfolio management process by introducing project similarities, learning potential of projects, related lessons learned and predictions to assist user in risk and strategic fit assessment. Construction companies can establish a customized information management system and corporate memory to support their portfolio decisions. The corporate memory structure developed as a part of this study can be found in Eken *et al.*[66] Continuous use of the tool may result in a knowledge-base that may successfully support portfolio decisions of the company.
- Visualization: Visualization is enabled at two levels. Portfolio level visualization enables comparative representation of the alternative portfolios. Details of a specific portfolio can be investigated by visualization at project level as well as at the portfolio level, including a dependency map.
- Scenario analysis: Scenario analysis is facilitated by evaluation of a portfolio with assessment of its contribution to strategic targets, risk, profitability, and its effect on portfolio value. Similarity assessment utilizing lessons-learned database is used to make predictions for the future.
- Intelligence: The provided functions are encapsulated within an intelligent decision support system where the user can obtain warnings/recommendations for portfolio selection and management based on the calculated dependencies and project/portfolio measures. Thus, it provides decision support in the management of risks and resource allocation, also enhances learning opportunity between the projects based on the identified similarities and dependencies.

Based on above information, COPPMAN reflects the portfolio details through different aspects that need to be taken into consideration by the user for complete/accurate decision-making, rather than presenting an "optimal portfolio" as in most of other approaches. Testing results demonstrate that COPPMAN has a practical value for construction companies as it enhances tasks of “strategic planning”, “business development”, “organizational learning”, and “knowledge management”. It is equipped with functions that have been generated under the control of construction professionals, and it contains default preferences obtained through the questionnaire study. As a result, this study proposes a solution for construction companies in adopting portfolio management principles and selecting their projects based on portfolio value, which may transform management focus of the companies from success of individual projects to overall success of the company.

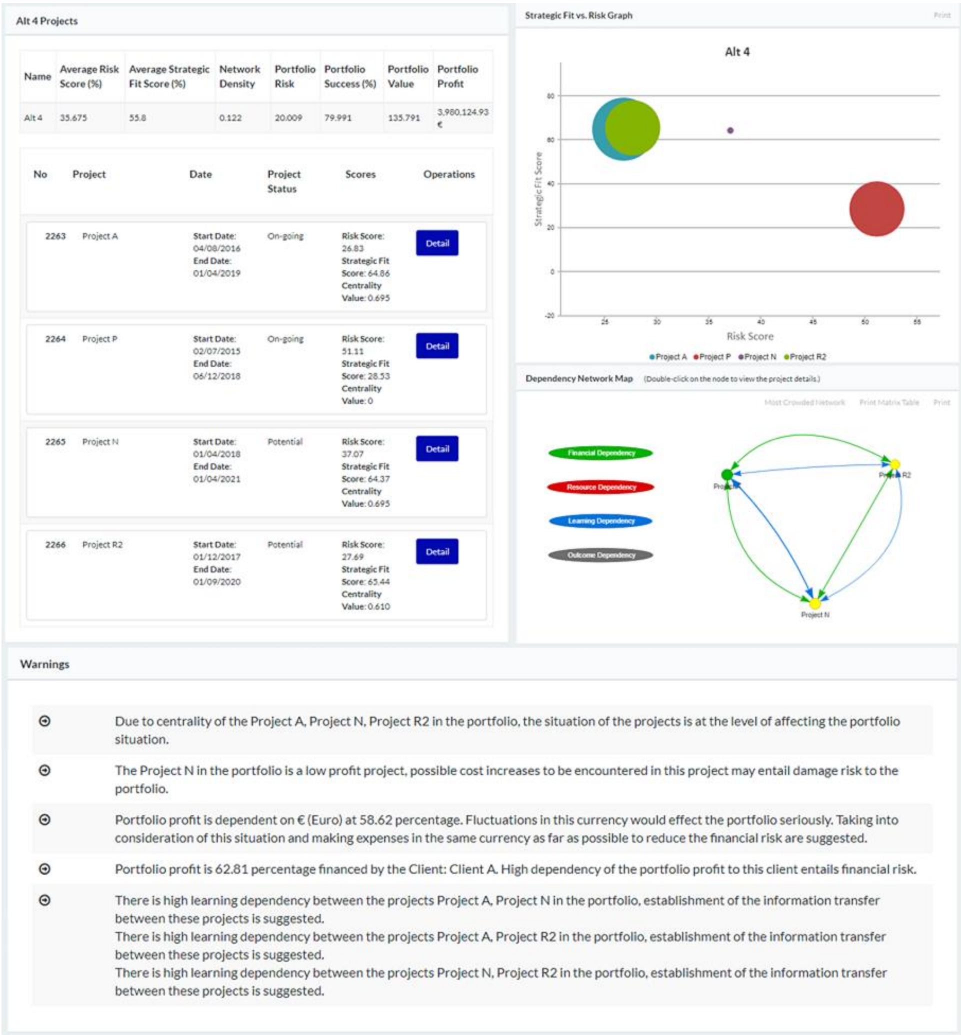

Fig. 5. Project level outputs for Portfolio Alternative 4

9. Conclusions

In this study a process model and a decision support tool, COPPMAN were developed to support decision-making at the portfolio level in construction companies. The major contribution of this study to PPM body of knowledge is framing the need for “portfolio management in construction companies” and development of a formalized process model and a DSS in line with the identified need. The process model and algorithms used to calculate portfolio value can be used by other researchers to develop similar tools. The process model has been structured upon the idea that first, information about project attributes is defined and then, project level risk and strategic fit are assessed. Then, user can run the analysis following setting the editable preferences for the analysis. The structure of the process model and the analysis method can easily be adapted for their utilization in other project-based sectors. The methods used for calculation of “portfolio risk”, “strategic fit” and “project similarity” may be used in other studies on PPM as well as the “dependency network map” that is used to assess criticality as well as complexity in a portfolio. The visual representations (as given in Fig. 4 and Fig. 5) may also be used in similar studies and their effectiveness may be tested in other companies.

COPPMAN, as a decision support tool was developed in collaboration with construction professionals. The process model has been developed as a result of a comprehensive needs analysis and COPPMAN has been developed in an iterative process (within five sprints). Verification process of the finalized tool was conducted by black-box testing methods and comparison of the obtained results with the numerical examples considering hypothetical projects. It is believed that research design and DSS development methodology used in this study can contribute to literature as they may provide a good example for generation of similar process models and DSS in different contexts.

It is believed that the developed tool can be an innovative initiative especially for medium to large-sized construction companies operating in international markets that have to manage complex portfolios. Successful utilization of this knowledge-based portfolio management system may help construction companies enhance their organizational learning abilities and improve quality of their project selection decisions.

In addition to discussed potential benefits, there are some drawbacks of the system that should be considered before implementing in construction companies. First of all, in order to effectively use COPPMAN, companies need to consider that strong coordination between different divisions might be needed since they would work on the same platform. Data collection and refining issues would be under control of a unique department/professional, which might be a possible barrier for full utilization of COPPMAN. Moreover, company culture would be a major factor affecting the success in generation/utilization of knowledge across projects. The process requires minimum information for each project to run the analysis. However, to establish the knowledge support, retrospective identification of previous projects is needed. The effort and time that would be required in to generate the portfolio of projects that includes all of the previous projects of a large-scaled company should also be considered before its utilization.

It has to be noted that as a major research limitation, although various experts contributed to the development of the process model and DSS by responding to questionnaires, participating in expert panels, pilot studies, and usability testing; the findings of research reflect opinions of a limited number of experts, mainly working in Turkish construction companies. The actual implementation has been tested in a single large-scale construction company that is operating in international markets. The limited number of experts and companies involved in the research study can be listed as the major research limitation.

Some built-in features can be improved in forthcoming studies. Although COPPMAN provides warnings on resource management; it lacks a complete "resource management system", which may be integrated into the tool. Additionally, "schedule" information of the projects may be included for an automatic update in "dependencies" and "risks" of the projects/portfolios. Instead of subjective assessment and manual assignment of "attribute similarities" and "country grouping", clustering analysis may be incorporated in the tool. To increase decision support ability of COPPMAN, optimization methods can be introduced into the process to select optimum portfolio considering risk, profitability and strategic fit. Finally, "portfolio selection histories" may be captured and this knowledge can also be utilized during forthcoming portfolio selection decisions.

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