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Towards an Integration of Systems Engineering and Project Management Processes for a Decision Aiding Purpose

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Abstract: This article proposes an integrated process that combine Systems Engineering processes and Project Management ones. These processes are defined according to the industrial standard processes existing in the literature. The main idea is to define a common information model enabling the federation of all the points of view of the different actors with regards to Systems Engineering, Project Time Management, Project Cost Management and Project Risk Management. The resulting integrated project graph encompasses all the scenarios established after defining all the coupling points between those processes. The definition of the graph is based also on the available knowledge and the capitalized experiences resulting from experience feedback on previous projects. The scenario selection optimization is then performed using a decision-aided tool that aims to build a panel of Pareto-optimal solutions taking into account uncertainties on project objectives (cost and duration). This tool will also enable the decision-maker to select one scenario according to an acceptable level of risks. The integrated process, the optimization tool based on Ant Colony Optimization (ACO) and the method for decision making are described in the paper.

Keywords: Project Management, Systems Engineering, Processes Integration, Risk, Uncertainty, Ant Colony Optimization, Decision Aiding.

1. INTRODUCTION

The conception and the generation of new systems are industrial activities that are very complex to manage within an increasing competitive market. The high-risk nature of systems engineering projects and the difficulties to make efficient links between systems engineers and project managers are factors that increase this complexity. A trade-off between systems engineers' activities and project managers' responsibilities is necessary in order to efficiently meet customer requirements in terms of cost and time while controlling risk. In such a context, both systems engineers and project managers need an efficient risk management process to cope with different technical and programmatic risks that might be faced during projects (SEBOK (2014)). Some previous studies have defined the interactions between system design and project planning processes for better controlling and monitoring them. In these works, a structural interaction making bijective connections between project and system structures has been defined in (Abeille et al. (2010) and Coudert et al. (2011)). Then, a behavioral interaction model has been proposed in (Vareilles et al. (2015)) enabling a synchronization of system design and project planning by defining specific integrated models and rules. Moreover, the SEBOK Guide (SEBOK (2014)) highlights the necessity to have an overlap between systems engineering and project management by considering all the common concerns between both disciplines. In fact, the PMBOK Guide

(PMBOK (2013)) describes the project management processes considering the technical aspects as an input of the project. Moreover, the risk management is an important aspect in these standards. However, it is not performed during the earliest phases when uncertainties occur. It is rather performed during activities such as duration estimation and scheduling (see the description of the Project Time Management (PTM) process in sub-section 2.1). The structure of the system is well known and all the activities that are necessary to design, produce and deliver have to be defined with their resources. In this context, our contribution is to define an integrated process where systems, projects and risks' analysis are early and conjointly built using ad hoc coupling mechanisms and tools.

Risks exist whenever uncertainty exists (Better et al. (2008)). In some studies, the risk management processes are considered as project uncertainty management ones (Ward et al. (2003)). In other works, the risk is considered as uncertainty on the durations of tasks (Sobel et al. (2004), Creemers et al. (2012) and Bourne et al. (2014)). In our approach, uncertainty is considered as the effect of the occurrence of unknown situations on project objectives (cost and duration) and should be taken into account to make decisions on the structure of systems and projects. Then, the management of uncertainties during decision making can be seen as a way to take into account risks. This necessity to optimize very early the technical choices conjointly with the project ones was emphasized in previous studies performed

in (Pitiot et al. (2010)). A multicriteria evolutionary optimization method based on a knowledge-based evolutionary algorithm was proposed. It enables the optimization of project scenarios selection taking simultaneously into account the technical choices (design choices) and the PTM ones. A scenario is a set of tasks with precedence constraints which have to be planned. The goal was to obtain a set of Pareto-optimal scenarios in a two-dimension objective space (global cost and duration). However, in order to improve this method, a third dimension can be integrated: the risk one. In (Baroso et al. (2014)), the integration of risk as a third objective to minimize has been first proposed. A multi-objective Ant Colony Algorithm (MOACO) has been developed for this problem for its ability to solve such relevant combinatorial optimization problem in a reasonable amount of time. First results provided by this algorithm were presented in (Lachhab et al. (2016)). Following on these works, an important improvement is to define a decision-aided tool, based on the optimization model, that integrates the standard industrial processes (the systems engineering process (SEBOK (2014)) and the project management one (PMBOK (2013))) in the early first phases.

Thus, this article aims at defining an approach where Systems Engineering (SE) and Project Management (PM) (including cost and risk management) processes are articulated together efficiently. The coupling of these domains and their principal interactions will be carried out and are supported by a multicriteria decision-aided tool based on a multi-objective ACO algorithm. The decision-aided tool is integrated within the processes cited above to select scenarios in a project graph that gathers all possible alternatives and choices of design and realization of a new system. It also allows to minimize the project objectives in terms of cost, duration and risk. The risk is considered as a third objective to optimize and represents the uncertainty on project duration and cost. The SE and PM processes are fed up by a knowledge/experience base to control uncertainties about project cost and duration. The tool enables to generate a panel of Pareto-optimal scenarios (solutions). From this panel, one scenario can be selected in order to be scheduled and realized under the control of the project manager.

In the next section, the industrial standard processes related to Project Management and Systems Engineering scopes are described. The purpose of these depictions is the proposition of an integrated process that takes into account the different interactions between all the processes and the sub-processes belonging to PM and SE processes. In section 3, the PM and SE processes interactions are formulated, the definition of project scenarios is given, an algorithm of the multi-objective ACO is described, and then a multicriteria decision-aided tool is presented. Finally, conclusions and perspectives are given in section 4.

2. INDUSTRIAL STANDARD PROCESSES

2.1 Project Management Process

The project management encompasses all project activities, techniques and tools in order to meet the customer

requirements in terms of cost, time, quality, performance, etc. According to the Project Management Institute (PMI), the Project Management comprises five process groups defined in the Project Management Book of Knowledge Guide (PMBOK (2013)): Initiating, Planning, Executing, Monitoring/Controlling and Closing process groups. The "**Initiating**" process group includes two main processes that perform the stakeholders' identification. The "**Planning**" process group integrates all planning management activities that are necessary for developing a project management plan in accordance with the key stakeholders. The "**Executing**" process group allows to carry out all the necessary activities to reach the initial stated objectives of the project. The "**Monitoring and Controlling**" process group involves the control of the executed activities and the measurement of project performance. They also involve risk register updates and risk response plans. Finally, the "**Closing**" process group allows to capitalize all the lessons learned from the project realization and to evaluate the customer satisfaction.

Three main domains of knowledge of the PM process are then presented according to the PMBOK Guide (PMBOK (2013)) to highlight, in the section 3, the possibility of coupling them together and with other existing standard processes. These processes are ordered as follows: Project Time Management, Project Cost Management (PCM) and Project Risk Management (PRM).

- **Project Time Management Process**

The PTM process allows to manage the completion time of a project by means of six processes that interact with each other. The processes are: Define and Sequence Activities, Estimate Activity Resources and Durations, Develop Schedule and finally Control Schedule. The process "**Define Activities**" identifies the actions to be achieved to meet project goals taking into account constraints, assumptions, environmental factors, the scheduling methodology and lessons-learned from previous projects about similar activities listed in a knowledge base. The Working Breakdown Structure (WBS) is a decomposition technique carried out to structure the project into sub-projects by defining all the components of the project deliverable. The expert judgment is necessary to take profit from previous experiences in the activities definition process. Each activity has its own attributes that characterize them together with their schedule development (activity name, predecessor and successor activities, etc). After defining the list of activities and their associated attributes, the process "**Sequence Activities**" is realized. It allows to define the logical relationships between activities. During this step, the updating of activity lists, activity attributes and the risk register is necessary. The process "**Estimate Activity Resources**" is subordinated by the "Estimate Cost" process that will be defined in the Project Cost Management process part and it requires to know all information about resources to perform project activities like human resources, equipment and material. The process "**Estimate Activity Durations**" gives an approximation about the amount of work periods that is required to perform activities in accordance with estimated resources. Thus, the duration of activities is

modulated by the estimated resources affected to these activities (lower or higher skilled resources for example). There are many tools and techniques for estimating activities' durations such as historical duration information from existing databases (some datamining techniques and algorithms can be used from that (Bharati et al. (2010)) and expert judgment especially in the early phases of complex projects where few detailed information are available. In this case, the estimation of project duration is done by analogy with other previous similar project parameters. The process "**Develop Schedule**" creates the project schedule by analysing activity sequences, resource calendars, activity resource requirements, activity durations and constraints schedule. Finally, the "**Control Schedule**" process is a monitoring step that consists in managing the changes compared to schedule baseline and updating project progress. Corrective and preventive actions are required depending on schedule variation degree. Lessons learned from project control schedule and the causes of the variances and their corresponding corrective actions are then updated.

- **Project Cost Management Process**

The PMBOK Guide (PMBOK (2013)) describes the PCM process according to three processes: Estimate Costs, Determine Budget and Control Costs. The PCM is mainly based on the cost of the resources (labour, materials, equipment and services) required to perform project activities. The process "**Estimate Costs**" gives an estimation and a prediction about the costs of the different alternatives to realize project activities. They can be modified during the project progress whenever additional information is available and known. A risk register should be updated to consider negative or positive events that have effects on the project cost. Some methods are used to estimate costs. For example, the expert insight about project environment and the usage of historical information from previous analogous projects can be used. The process "**Determine Budget**" aggregate all the estimated costs for each project activities according the WBS. Finally, the "**Control Costs**" process is the process of supervising project budget status, managing actual changes when they appear to create changes in the costs baseline. All the measurements are communicated to the stakeholders and project documents are updated depending on the lessons learned from project cost control (causes of changes, chosen corrective and preventive actions, etc).

- **Project Risk Management process**

The PRM process includes six main processes: Plan Risk Management, Identify Risks, Qualitative Risk Analysis, Quantitative Risk Analysis, Plan Risk Responses, Monitor and Control Risks. The "**Plan Risk Management**" process gives a clear visibility about the necessary resources and time to conduct risk management activities. The process "**Identify Risks**" consists in identifying risks that may impact iteratively the project during its life cycle. The "**Qualitative Risk Analysis**" process is the process of prioritizing risks according to the combination of their probability of occurrence and their impacts on project objectives. The levels of risks are then identified and risks are rated in a probability

and impact matrix that distinguish high-risk zones from moderate and low-risk zones for a further quantitative analysis. The "**Quantitative Risk Analysis**" process gives a numerical analysis about the risks that have been prioritized in the previous step to make decisions in the presence of uncertainty. The "**Plan Risk Responses**" process provides some strategies to avoid, transfer, mitigate or accept negative risks or threats. Other strategies are used to exploit, share, enhance or accept positive risk or opportunities. Finally, the "**Monitor and Control Risks**" process include the following activities: risk response plans execution, identified risks control, new risks identification and residual risks monitoring and finally, the risk process evaluation.

2.2 Systems Engineering Process

The process described in the SEBOK Guide (SEBOK (2014)) unifies the existing systems engineering process representations. The SE process activities are: System Definition process, System Development process, Production and Utilization processes, Support process, and finally Dismantling, Recycling and Renewing process. The "**System Definition**" process defines the mission of the future system and all the requirements needed for its implementation. The "**System Development**" process consists in analysing the requirements formalized in the previous step to define the functional, performance, security and reliability characteristics of the system. The logical architecture of the system is defined by describing the structure (decomposition in sub-systems). The physical architecture is in line with the logical one by describing the components and/or the physical interfaces. Finally, the activity analysis allows a quantitative analysis of the realized technical choices. The "**Production**" process allows creating and testing the system versions already specified in the previous step. Verification and validation activities are performed to ensure that the resulting system is in accordance with the physical and logical architectures but also with the requirements. The "**Utilization**" process is the exploitation phase where all the developed functionalities are implemented. In the SEBOK Standard, the **Support** process assists the Production process and the Utilization process. Finally, the "**Dismantling, Recycling and Renewing**" process comprises all the activities that are carried out at the end of the life cycle of the system when it becomes obsolete or unprofitable economically.

3. PROPOSITION OF AN INTEGRATED PROCESS

3.1 PM and SE Processes Interactions

In the previous section, PM and SE processes have been defined according to the existing standards. Each process includes some sub-processes that are dependent and may interact with each other. However, the problem with these standards is the difficulty for the different managers (project manager, cost manager, risk manager, engineers...) to make concerted and collaborative decisions. As a result, additional risks may arise which will affect widely the project objectives

and its successfulness. In addition, in the PTM process, the activities are scheduled without taking in consideration the different possible alternatives of design and realization of project activities. That is why, our contribution, based on (PMBOK (2013)) and (SEBOK (2014)) guides, consists in the integration of PM processes and SE ones in a general framework that takes into account the potential risks and uncertainties that may affect the overall project goals. As can be seen on Fig.1, the decision-aided tool is mainly positioned in the early phases of the project. Nevertheless, other phases can enrich the model for later use (for instance during the closing sub-process, collected information can improve knowledge/experience bases).

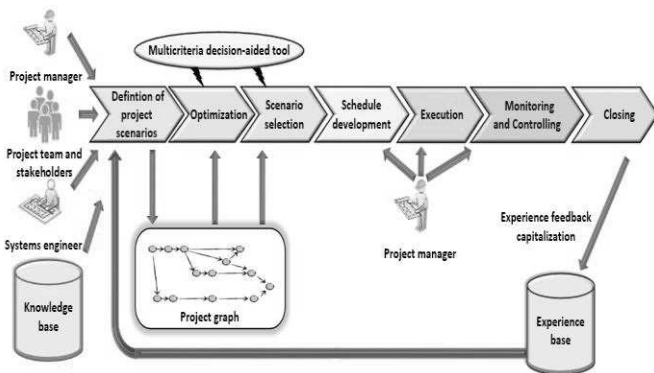


Fig. 1. General framework and integrated process.

The Fig.1 gives a general view of PM and SE processes integration. The proposed approach is based on an integrated process that allows to conduct collaboratively technical and project choices, in the early phases of a systems engineering project. The process includes 7 main processes groups: Definition of project scenarios process, Optimization process, Scenario selection process, Schedule development process, Execution process, Monitoring and controlling process, and finally the Closing process.

The integrated process is mainly based on the processes of PM/SE, and on the sub-processes of PTM, PCM and PRM. The definition of project scenarios is made by the project manager, the systems engineer, the project team, the stakeholders, etc. All these actors work collaboratively on the same resulting project graph and could be involved in all the other project phases for risk assessment and mitigation. In fact, they participate jointly on the project graph construction by taking into account all costs' resources estimations, the duration of tasks and the uncertainty information about these project objectives. These estimations may originate from the analysis of past experiences (Villeneuve et al. (2016)). The knowledge base enables to capitalize all the rules, models and standards that are suitable for PM and SE. For instance, in order to build the project graph, some parts of it can be selected in the knowledge base if they match with routine design elements. Some other parts can be designed from scratch if they are totally innovative. Therefore, from this project graph where all the information about PM and SE has been centralized, the proposed approach allows to select optimal solutions using an ACO algorithm. A better

integration of experience feedback process accelerates then the Optimization process (Pitiot et al. (2008)). The Optimization process includes a multi-objective ACO tool that provides a range of Pareto-optimal solutions and minimize the total cost, duration and risk of the SE project. The uncertainties about project goals (cost and duration) are modelled using single intervals (Lachhab et al. (2016)). The lower bounds correspond to nominal values and the upper bounds to the maximum possible values (estimated). In the Scenario selection process, a solution is then selected by decision-makers according to risk levels related to project objectives. The Optimization and the Scenario selection processes contributes in the constitution of a decision-aided tool that helps decision-makers to choose one scenario which needs to be scheduled. The developed scenario is then realized by a project manager in the Execution process by performing all its activities. The Monitoring and Controlling process consists in supervising the executed activities, defining corrective actions, and finally conducting performance measurements. The experience corresponding to this execution is formalized in the Closing process and is capitalized in an Experience base in order to be used in later projects.

3.2 Definition of project scenarios

In section 3.1, the integrated process that gathers PM and SE processes has been defined. In this section, the definition of project scenarios process is explained in detail to show how the resulted project graph is built from processes integration. Project manager, systems engineers, risk manager, the project team and stakeholders work together through pre-scheduled meetings to define an acyclic and oriented project graph. The graph is defined by a set of nodes (task nodes, logical operators (AND , \overline{AND} , XOR and \overline{XOR} nodes)) and a set of arcs (to represent the precedence constraints between these nodes) where the first and the last nodes are fictive (they represent the beginning and the end of the project). Each task node is associated with a triplet (cost, duration, risk). In our work, only "negative" risks are considered (i.e. those who have negative outcomes (impacts) by opposition to "positive" risks often called opportunities). These risks are defined as uncertainties and are related to the occurrence of unwanted events whom impacts will affect badly the project objectives in terms of cost and duration.

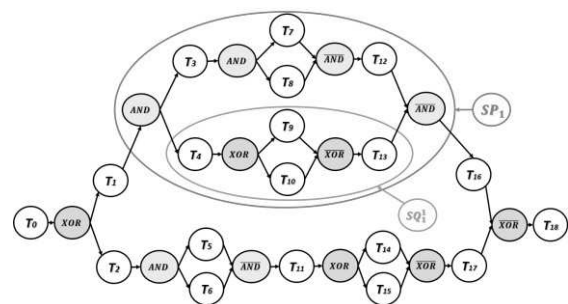


Fig. 2. Example of an integrated project graph.

A project graph may include other sub-graphs. A sub-graph is a sub-project (SP_1 for example in Fig. 2) defined between a divergence \overline{AND} node and a convergence \overline{AND} node as shown in Fig. 2. In this figure, for example, the project graph contains two fictive nodes (T_0 and T_{18}). At the beginning, there are two possible choices (T_1 and T_2) separated by the divergence \overline{XOR} node and then assembled by the convergence \overline{XOR} node. A sub-sequence (denoted by SQ_1^1 in the example of Fig. 2) is defined between a divergence \overline{AND} node and a convergence \overline{AND} node. A project graph may include other sub-projects depending on the system to perform and its complexity. The construction of optimal scenarios (project paths) is made using a multi-objective ACO algorithm that will be described in section 3.3. A detailed view of the definition of project scenarios process is given in Fig. 3. This figure includes all the actors, processes and sub-processes interactions to define the project graph (its scenarios). The description of the sub-processes is already done in section 2.



Fig. 3. A detailed view of the Definition of project scenarios sub-process.

First, the definition of the project graph results from coupling the "**Define Activities**" process with the "**System Development**" process by considering all the opinions of project manager, systems engineer, project team and stakeholders. Then, all the system design activities and their corresponding realization tasks are sequenced in the Sequence Activities process. The estimations of activities durations, resources and costs are performed according to project manager, systems engineer and knowledgeable expert in a specific field. The expert may work jointly with a risk manager to define uncertainties about project objectives. They can use a Knowledge base and/or an Experience base to get information about these uncertainties and perform the PRM process. In fact, the project actors should be involved in the identification of risks and their response actions. The experiences capitalized during past project realizations allows to the risk manager and the expert to evaluate the risks' probability and their impact. This information is then used to define the uncertainties by means of the cost' intervals and

durations for each task (i.e. the risk representation). Preventive tasks can also be added to the project graph as well as the possible alternatives when some sub-sequences will become impossible to accomplish because of risks occurrence. In order to consider the risk globally on the project, a third specific objective has been introduced that consists in the aggregation of all the local risk estimations on tasks. To do so, the GOWA operator was used (Yager (2004)). This operator can be tuned from minimum ($\beta \rightarrow -\infty$) to maximum ($\beta \rightarrow +\infty$) by means of β . Let R_{T_j} be the global uncertainty linked to the task T associated with the node j . Let O_{\min}^T (resp. O_{\max}^T) be the nominal (resp. maximum) value of the criteria O ($O \in \{C, D\}$, i.e. Cost and Duration). The risk associated with the task T is given by:

$$R_{T_j} = \left[\frac{1}{2} \left(\frac{C_{\max}^{T_j} - C_{\min}^{T_j}}{C_{\min}^{T_j}} \right)^\beta + \frac{1}{2} \left(\frac{D_{\max}^{T_j} - D_{\min}^{T_j}}{D_{\min}^{T_j}} \right)^\beta \right]^{\frac{1}{\beta}} \quad (1)$$

3.3 The multi-objective ACO algorithm

This section gives a brief description of the multi-objective ACO (MOACO) (Dorigo et al. (2006) and Stützle et al. (2011)) algorithm that constitutes our decision-aided tool (Fig. 1). This algorithm enables the optimization of scenarios selection on the project graph (section 3.2). The algorithm is based on a single colony that constructs solutions in the project graph by simultaneously minimizing the global values of the triplet (cost, duration, risk). The ants build their solutions independently in each iteration. For each criterion, a quantity of pheromone is deposited on the arcs belonging to the ants' paths. The first node of the project graph is associated with the initialization step. Each ant makes choices about the next node to reach according to a probability formula which is a function of local attractivities and global attractivities in terms of cost, duration and risk. In our model, in each iteration, the ants learn from their past constructed paths by changing dynamically the weights of project objectives integrated in the probability formula. At the end of the iterations, a Pareto-front of optimal scenarios is built in order to help a decision-maker to select one scenario that is about to be further developed and realized. In Lachhab et al. (2016), first experiments were conducted and shown that the MOACO algorithm gives better results using a learning mechanism (denoted MOACO-L). The MOACO-L algorithm has given efficient solutions in terms of cost, duration and risk and has improved the mean performance of the MOACO algorithm with almost a difference of 8.84%.

3.4 Multicriteria Decision-Aided Tool

In the last section, a brief description of the MOACO algorithm was given. The objective of this algorithm is to

provide a set of optimal scenarios of the resulting integrated project graph. This step is done in the Optimization process of the Fig. 1. That enables to define a decision-aided tool that helps the decision maker to select a scenario from a range of Pareto-optimal solutions. The idea is to cut the objective space according to the level of risks and look for a solution in the lower level of risk that allows a trade-off between the global cost of the project and its total duration. If the decision-maker finds a solution, he/she selects it. If not, he/she seeks a solution in a higher level of risk until he/she finds a trade-off between all the project objectives (cost, duration and risk) according to its preferences about budget and time.

4. CONCLUSIONS

The aim of this article was to provide an integrated process between SE processes and PM ones, based on existing industrial standards, by defining all the interactions between those processes. The resulting project graph includes all the alternative choices of system design and project activities towards scenarios definition. The selection of optimal scenarios is performed via a decision-aided tool based on a multi-objective ACO algorithm that takes in consideration the uncertainty about project objectives. In our model, the representation of uncertainty was given by a single interval which is rather simple, but it is the base of more advanced representation that will be integrated in the future (i.e. a multi-interval associated to a weight that enable fuzzy subset and even belief functions representation).

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