Engineering Applications of Artificial Intelligence 72 (2018) 310–326

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

A risk-based approach applied to system engineering projects: A new learning based multi-criteria decision support tool based on an Ant Colony Algorithm

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ARTICLE INFO

Keywords:
Project management
System engineering
Uncertainty
Risk
MONACO
Decision support
Learning

ABSTRACT

This article proposes a multi-criteria decision support tool fully integrated within system engineering and project management processes that allows decision makers to select an optimal scenario of a project. A model based on an oriented graph includes all the alternative choices of a new system's conception and realization. These choices take into account the risks inherent to perform project tasks in terms of cost and duration. The model of the graph is constructed by considering all the collaborative decisions of the different actors involved in the project. This decision support tool is based on an Ant Colony Algorithm (ACO) for its ability to provide optimal solutions in a reasonable amount of time. The model developed is a multi-objective new ant colony algorithm based on an innovative learning mechanism (named MONACO) that allows ants to learn from their previous choices in order to influence the future ones. The objectives to be minimized are the total cost of the project, its global duration and the risk associated with these criteria. The risk is modeled as an uncertainty related to the increase of the nominal values of cost and duration. The optimization tool is a part of an integrated and more global process, based on industrial standards (the System Engineering process and the Project Management one) that are widely known and used in companies.

1. Introduction

Whenever complexity exists, risks exist too. The difficulty to make concerted decisions between all the actors of a Project Management (PM) process and a System Engineering (SE) one increases the complexity of a SE project. For this purpose, an integrated process that takes into account the interactions between the PM and the SE sub-processes is a good way to make collaborative decisions and meet the customer needs by satisfying the different requirements and project objectives especially in terms of cost, duration and risk. Some previous works done in our research team have defined coupling points between a system design process and a project planning process (Coudert et al., 2011; Vareilles et al., 2015). These works have shown that both processes need to be controlled and executed in parallel with strong synchronization mechanisms which allow meeting the requirements of the customers. A centralized information model (represented by an oriented graph) is useful to consider all the decisions of these project actors about all the possible tasks and their associated project objectives values. Making good decisions among all these possible choices needs to select the optimized ones. In our work, the objectives to optimize are the global cost of the project, its total duration and the global risk associated to these criteria. Risks are defined in this work as uncertainty about project objectives and are considered in the preliminary steps of a project graph construction. Uncertainty is modeled by using intervals to take into account the negative risks' impacts on tasks costs and durations. The idea is to provide to the decision makers a panel of Pareto-optimal solutions in order to select one good scenario to plan and then realize.

The proposed integrated process includes a multi-criteria decision support tool based on a multi-objective optimization method. It allows the generation of Pareto-optimal scenarios from the resulting integrated project graph that encompasses all the design and the project alternative choices of a new system to conceive and realize. For this matter, the standard Ant Colony Optimization (ACO) meta-heuristic (Dorigo and Stützle, 2010; Stützle et al., 2011) was adopted and adapted to develop a multi-objective new ant colony algorithm based on a learning mechanism denoted as MONACO algorithm.

The standard ACO algorithm performance is improved by a learning mechanism. That consists in modifying the standard probability formula used by every ant to reach a next node in the graph. It is modified taking

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https://doi.org/10.1016/j.engappai.2018.04.001
Received 7 July 2017; Received in revised form 8 January 2018; Accepted 3 April 2018
Available online 8 May 2018

into account the path that every ant has taken before the decision. The proposed learning mechanism learns from the past choices made by an ant in order to influence its future ones by changing dynamically the weights given to the three objectives (cost, duration, risk) in the probability formula of the MONACO algorithm. At the end of the algorithm, a Pareto-front is built and all the optimal scenarios are given to help the decision makers to select one scenario that has reasonable global values of cost, duration and risk.

A related works section is given in the next part (Section 2) to contextualize the problematic with regards to other works and to justify the use of an Ant Colony Algorithm. Then, a detailed description of the integrated SE and PM process is presented in Section 3 with the different project actors that may be involved in all the project phases. The problem formalization is described in the same section. The proposed multi-criteria decision support tool based on the MONACO algorithm is detailed in Section 4. The algorithm is developed by using Ruby language and some experiments have been conducted and presented in the results section (cf. Section 5). Finally, conclusions and future works are described in Section 6.

2. Related works

The design and the generation of new systems are industrial activities that are complex to manage in a very competitive market. In this context, system engineers and project managers need an efficient risk management process to face the various technical and programmatic risks that may arise during the project (SEBOK Guide, 2014). Previous works have defined the interactions between systems design and project planning processes to better control them. In Abeille et al. (2010) and Coudert et al. (2011), structural interactions to establish bijective connections between system and project structures have been defined. Another model of behavioral interaction has been proposed in Vareilles et al. (2015) allowing synchronization of system design and project planning by defining the rules that are related to a specific integrated model. The risk management process (PMBOK Guide, 2013) is not carried out during the early phases of the project elaboration. It is rather done during the project activity planning process to estimate the tasks costs and durations, as well as all resources related to design, production and distribution activities. That is why we propose an integrated process where risks are taken into account upstream.

Risk exists whenever there is uncertainty (Better and Glover, 2008). Many works in the literature provide the fundamental principles on how to manage, characterize and assess risk by giving the appropriate concepts and management tools to support the decision making in practice (Aven, 2016). Thus, many risk management methods use qualitative and quantitative approaches to assess the risk with some tools that are based on the probability and impact concepts (Fang and Marle, 2012). Recent directions of development to represent uncertainty in risk assessment are provided in Flage et al. (2014). In this article, many methods are used to handle the uncertainty but the predominant one is the probabilistic analysis method to handle both random and epistemic uncertainty. In Aqlan and Ali (2014), the uncertainty inherent in risks is performed by using lean principles and fuzzy bow-tie analysis to improve the risk management process in the chemical industry. In Villeneuve et al. (2016), the authors proposed to improve the risk assessment by using the theory of belief functions and statistical knowledge combined with the expert knowledge for aircraft deconstruction. In the case of supplier selection problem, the authors in Kaya and Karhaman (2010) developed a decision making tool that evaluates risks by using fuzzy logic models. In Ward and Chapman (2003), the authors considered the risk management processes as projects uncertainty management processes. For large engineering projects, a network theory based approach was presented in Fang et al. (2012) to deal with the interdependencies between negative risks and to better understand their potential interactions by using network theory indicators in project risk analysis. In Nguyen et al. (2013), the ProRisk methodology has been developed to provide to project managers a decision making tool to select the best risk treatment strategy. In the same context, in Fan et al. (2008) an analytical model based on a conceptual framework that describes the quantitative relationships between risk-handling strategy and the various project characteristics (technical complexity, project size, slack) has been proposed. Some works are based on an improved CPM (Critical Path Method—see Galloway (2006) for instance) because the durations values can be changed considering the multiple risk factors, such as, the use of Monte Carlo Simulation (MCS). However, MCS provides a project risk analysis on project objectives without considering the interdependencies between the different risk factors (Jun-Yan, 2012) which is not in accordance with real-life projects. Bayesian networks (Pearl, 1995) are appropriate to deal with the relationships between the risk factors. For example, in Khodakarami et al. (2007), uncertainty in project scheduling was modeled by means of Bayesian networks considering that the traditional inputs for each activity (cost, time, resources) are not deterministic.

In our approach, uncertainty is defined as the impact of undesirable events on project objectives (cost and duration). It must be considered while making decisions about the structure of the system and its associated project. The need to optimize each technical choice jointly with those related to project activities has been highlighted in previous works (Pitiot et al., 2010) where a multi-criteria optimization method based on an evolutionary algorithm guided by knowledge has been proposed. The method principle was to optimize the selection of project scenarios, taking into account design choices and project activities associated with them. A scenario is a set of tasks, with precedence constraints, that must be planned. The aim was to obtain a set of Pareto-optimal scenarios in a two-dimensional objective space (the total cost and the overall duration of the project). However, uncertainty was not taken into account. Thus, in order to improve it, a third dimension can be integrated: the risk one. In previous works done in our research team (Baroso et al., 2014), the integration of risk as a third objective to minimize was proposed using a multi-objective algorithm based on a standard ACO. The ACO meta-heuristic is selected for addressing the problem that this paper is dealing with because many works in the literature attest that the use of ACO is very promising in project management especially in providing near optimal solutions to handle issues that are too expensive computationally. In Fernandez et al. (2015), the authors have developed a hybrid approach based mainly on ACO meta-heuristic to handle many objectives in the case of portfolio problems. It provided high-quality portfolios compared with other powerful meta-heuristics that deal with Pareto-front solutions. Other works have proved the power of ACO algorithms for solving both deterministic and probabilistic networks such as CPM/PERT by providing good optimal and sub-optimal solutions (Abdallah et al., 2009). In Chen and Zhang (2012), the authors used an Ant Colony System (ACS) approach and Monte Carlo simulation (MCS) to maximize under uncertainty the expected net present value (NPV) of cash flows in the case of scheduling multi-mode projects. Another application of ACO and MCS technique was exploited in Aghaie and Mokhtari (2009) for stochastic project crashing problem under uncertainty. This method has shown the high performance of ACO approach especially on high scale networks.

Moreover, by building the solutions step-by-step within ACO algorithms, it is possible to design useful heuristics to direct the ants to avoid critical tasks as early as possible (Chen and Zhang, 2013). This characteristic is a key concept in our work. The improvement of the standard ACO for optimization consists in allowing the ants not only to learn from the previous paths taken by the other ants, but also by guiding each ant in its process of selecting the next node (task) in a project graph. This process is based on a new learning mechanism that considers the path of each ant to influence its next choice by favoring one criterion over another based on the capital consumed in terms of cost, duration and risk. This learning process is reflected in this article through the use of dynamic weights in the probability formula. Therefore, the choice of the ACO meta-heuristic is also driven by these