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Assessment of global sensitivity analysis methods for project scheduling

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ABSTRACT

Product development requires scheduling that considers the interdependence between activities. The definition of the interdependencies and duration of activities, communication times and the level of overlap between activities is needed for project scheduling. However, these parameters have epistemic uncertainties that can affect project scheduling. In this work, different global sensitivity analysis techniques were applied to identify the parameters that had the greatest effect on project scheduling. It was concluded that standardized regression coefficients as well as the Morris and Sobol'–Jansen methods were the most appropriate. It was also found that global sensitivity analysis can help to focus resources based on the definitions and control the uncertainty of key activities. Furthermore, it was concluded that control of the uncertainty of key activities reduces the uncertainty and duration of projects.

1. Introduction

A profitable and effective product is the key to success in today's ever-changing and competitive market. As a result, strong competition in several industries has forced manufacturing firms to develop innovative and higher quality profitable products at an increasingly rapid pace (Kirshnan, Eppinger, & Whitney, 1997). The scheduling and management of large and complex projects is a difficult commission that requires effective tools (Herroelen, 2005). The dependency structure matrix, or design structure matrix (DSM), has been shown to be a powerful tool for the management of complex projects because (a) it can accurately represent the interdependence and/or relationships between different components of a system; (b) overcomes the size and complexity limitations of digraphs; (c) it is easy to understand and able to handle the processes in their entirety; and (d) the matrix format is suitable to program and calculate using computers (Chen & Lin, 2003). Chen, Ling, and Chen (2003) presented a project scheduling framework based on DSM to handle sequencing, monitoring, and control of a collaborative product development. Sosa, Eppinger, and Rowles (2004) investigated how the organizational and system boundaries, design interface strength, indirect interactions, and system modularity impact the alignment of design interfaces and team interactions. They used DSM to study complex product architectures in terms of component interfaces and to build statistical models for proper hypothesis testing using DSM data. The use of parameter-based DSM as a process modeling and system analysis tool for building design in the architecture/engineering/construc tion industry was proposed by Pektaş and Pultar (2006). Tang, Zhu, Tang, Xu, and He (2010) studied how to capture and trace the design knowledge through a single-domain and multi-domain DSM. They proposed a DSM-based design knowledge management system that allows for efficient knowledge capturing, searching, and tracing in product design.

Project scheduling is an important element of project management. The procedures range from the traditional models of CPM and PERT to sophisticated optimization models (Węglarz, Józefowska, Mika, & Waligóra, 2011), algorithms and heuristics based methods (Liang, 2009). Project scheduling research concentrates on the generation of a procedure that optimizes the scheduling objective, usually the project duration, and that should serve as a baseline schedule for executing the project (Herroelen & Leus, 2005). Research has been conducted for project scheduling using DSM where the interdependence of activities has been considered in the schedule as well, as DSM has been shown to be a powerful tool for the management of complex projects.

Project scheduling has considerable uncertainty because project activity parameters are also subject to uncertainties (Chtourou & Haouari, 2008; Dixit, Srivastava, & Chaudhuri, 2014). These

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uncertainties are usually epistemic (due to lack of knowledge) and not aleatory (inherent randomness of the system). Examples of epistemic uncertainties are activities that can take more or less time than originally estimated, such as material arriving behind schedule, unavailable resources, and incorrect estimation of activity overlap. There are some aleatory uncertainties, such as weather conditions or natural events that cause delays. From the viewpoint of project management, little can be done to control aleatory uncertainties, but actions can be taken regarding epistemic uncertainties. In addition activity durations and overlap factors can have different values by allocating different monetary resources to its execution (Zamani, 2013). However, what are the key uncertainties that require more control or study?

Herroelen and Leus (2005) define five approaches for dealing with uncertainty in the scheduling environment: reactive scheduling, stochastic scheduling, scheduling under fuzziness, proactive scheduling, and sensitivity analysis. The first four approaches are related to uncertainty analysis, and, therefore, use different methods to represent and address uncertainty. Sensitivity analysis has recently emerged in the project scheduling environment, but the "what if ...?" type of questions have been addressed to in most of the work published (Herroelen & Leus, 2005). Recently, Gálvez, Ordieres, and Capuz-Rizo (2015a) applied the Sobol method for the identification of the significant/insignificant input variables in project scheduling. Sensitivity analysis can be useful in scheduling modelling to classify the input variables starting from the most influent (the ones that most contribute to the variation of the output) to the least influent, and to detect the interaction between input variables or group of input variables. This information can be useful to decide which input variables to control or which input variables might eventually be considered as deterministic or which input variables might require additional research to improve their estimation. However, there are several sensitivity analysis methods that need to be explored in the scheduling environment to provide some advice about their use.

The objective of this work is to assess global sensitivity analysis (GSA) methods for project management. The DSM-based project duration is used as an example. The focus of this study is the use of GSA to identify key input uncertainties for the reduction of uncertainty in the project duration.

2. DSM-based project duration

DSM has been used for project scheduling in the past. Browning (1998) used DSM to enable critical path calculations by defining the amount of effort or work as the duration of the activities. Wang and Lin (2009) developed an overlapping process model to analyze the impact of the process structure on the lead-time of a development project with multiple activities. A DSM was used to represent the complex interaction patterns between the development activities. A triangular distribution was used to represent the uncertainties in the activity duration and reworks. Srour, Abdul-Malak, Yessine, and Ramadan (2013) provided a method to automatically generate a fast-track design schedule without violating the dependency information. They also extended the basic DSM method to construction projects. Maheswari and Varghese (2005) developed methods for the estimation of project durations including the communication time and natural overlaps between activities. The dependency between the activity duration, communication time, and overlap time factors were used to estimate the project duration. Uncertainty was not considered in the work of Maheswari and Varghese, which motivated the development of different studies to represent uncertainty in the input parameters. Gálvez, Capuz-Rizo, and Ordieres (2012) studied the effect of the uncertainty associated with task programming using DSM and grey theory, or interval arithmetic. Shi and Blomquist (2012) extended the DSM method proposed by Maheswari and Varghese using fuzzy numbers.

The methods of Gálvez et al. (2012) and Shi and Blomquist (2012) allow for representation of the uncertainty in the input parameters and calculation of the uncertainty in the project duration. One of the drawbacks of these methods is the need to characterize all the input factors, which are typically defined through an expert review process. Definition of the distribution that characterizes the epistemic uncertainty in the duration of activities and the time overlap factors can be one of the most important parts of uncertainty analysis because these distributions can determine the uncertainty in the project duration. These distributions must be defined through an expert review process, and their development can constitute a major analysis cost. The process of extracting expert knowledge about an unknown quantity or quantities and formulating that information as a probability distribution is known as elicitation (Meyer & Booker, 2001; O'Hagan et al., 2006). The scope of elicitation can vary widely depending on the purpose of the analysis, size of the analysis, and resources available to perform the analysis. One possible analysis strategy is to perform GSA with crude definitions of the distribution functions for the input factors (i.e., activity duration and time overlap factors) to identify key input factors and to understand the behavior of the project duration uncertainty. Then, resources can be concentrated where they are needed.

As previously mentioned, the objective of this work is to survey GSA methods for project management. An example using both the traditional method (sequential: an activity starts once its predecessors are completed) and phased method (some amount of overlap occurs between pairs of activities) is used to illustrate and assess the GSA methods. The example is given below.

The example consists of five activities from *A* to *E*. The DSM representation of the example is given in Fig. 1. The DSM is a square matrix containing a list of activities in the rows and columns in the same order. The order of activities in the rows and columns in the matrix indicates the sequence of execution. Values on the diagonal are the mean duration of the activities (days). For example, Fig. 1 shows that the mean duration of activity *A* is 2 days. The marks in the off-diagonal cells indicate that these activities are information predecessors, with activity inputs in its row and activity outputs in its column. For instance, activity *B* needs information from activity *A* and provides information to activity *D*.

In Fig. 1, the traditional, sequential method of project scheduling is shown. In this method, an activity starts once its predecessors have been completed. Based on the mean duration of the activities, the conventional project duration was estimated to be 14 days (Fig. 1). Note that activity *C* has no effect on the project duration, and all other activities are shown in the order of execution with no time between activities. The conventional project duration is estimated using the following equations:

$$(EF)_i = (ES)_i + A_{ii} \qquad 0 < i \leqslant n \tag{1}$$

$$(ES)_j = Max[(EF)_i] \qquad 0 < i \leqslant n,\ 0 < j \leqslant n \tag{2}$$

$$Conventional\ project\ duration = Max[(EF)_j] \qquad 0 < j \leqslant n \tag{3}$$

where n is the number of activities, i denotes all the immediate predecessors of activity j, j is the current activity chosen in the order identified by the DSM, ES means early start, EF early finish, and A_{ii} denotes the diagonal values of the DSM (duration of the activity).

The values in Fig. 1 correspond to the expected values of the activity durations. Two situations were analyzed. First, a variation of ±1 day in the activity durations represented by a uniform distribution (all the activity durations were equally likely) was