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# A robust bi-objective model for concurrent planning of project scheduling and material procurement

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ABSTRACT

Simultaneous planning of project scheduling and material procurement can lead to the project execution costs improvement. Hence, the issue has been addressed in this paper by a robust mixed-integer programming mathematical model, which aims to minimize the corresponding costs and maximize the schedule robustness. The given approach is able to control the degree of solution conservatism, in regard to probabilistic bounds on constraint violation. The proposed model takes the uncertainty issue into account from both viewpoints of activities duration time and execution costs. The NSGA-II and a modified version of multi-objective differential evolution algorithm have been applied as the solution methodologies. Moreover, the principal factors are calibrated by the Taguchi method to provide robustness to the obtained results. Finally, the performance of the solution methods is compared according to a varied set of instances to test their applicability and efficiency.



## 1. Introduction

This paper deals with procurement of required materials in construction projects scheduling. In traditional planning methods, project scheduling and material ordering issues were treated as separated problems. In other words, the appropriate schedule was determined first and material ordering plan was decided considering the given baseline, afterwards. This approach yielded to neglect trade-off consideration of corresponding costs of the project. These costs mainly consist of the ordering, holding, and penalty (reward payments) costs for late (early) project completion (Okubo & et al., 2015). The aforementioned trade-off can be interpreted such that earlier procurement of resources can increase the holding cost but decrease the ordering costs, if the required resources are ordered in larger amounts. On the other hand, smaller procurement amounts leads to the ordering cost increase, in return for the holding cost decrease. Therefore, taking the trade-off influence into account highlights the necessity of project scheduling and material procurement integration.

To the best of our knowledge, Aquilano and Smith (1980) introduced the integrated problem for the first time by developing a hybrid model of the critical path method with material requirement planning. Afterwards, Smith-Daniels and Aquilano (1984) addressed an improvement for the problem by a heuristic scheduling for large-sized projects based on the least slack rule. They considered the precedence constraints and variation in activities duration for a network with both renewable and nonrenewable resources. Smith-Daniels and Smith-Daniels (1987) considered fixed duration for the activities and found that the latest starting time schedule could lead to an optimal solution. It was shown that the problem could be solved optimally while it is decomposed into a derivation of the ordering plan and a derivation of the project schedule. Their proposed objective function (OF) included minimization of total costs pertaining to the inventory holding, material ordering, completed activities holding, and project delay.

Dodin and Elimam (2001) developed the problem by total costs minimization under activity crashing possibility, rewards for early completion, and materials quantity discounts. They showed that variable activity duration, and crashing possibility as a consequence, provides more flexibility to the project scheduling. Moreover, the intensive influence of the network structure and size on the computation time was taken into consideration. Schmitt and Faaland (2004) proposed a heuristic algorithm for scheduling a recurrent construction to the net present value maximization of cash flows, in which an initial schedule is constructed and worker teams are dispatched to the tasks for backlogged products. They optimized a series of maximal closure problems to find material release times.

In another research, Sheikh Sajadieh, Shadrokh, and Hassanzadeh (2009) applied a genetic algorithm (GA) to solve an

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extended version of the Dodin and Elimam's model (2001). However, the crashing cost had been assumed to follow a constant slope for every activity. One the other hand, the resources requirement had been considered to be independent of the activity duration, which may seem impractical for some circumstances since the completion of an activity within a shorter time period is associated with more resources requirement. Hence, Fu (2014) proposed a multi-mode resource constraint project scheduling problem to address the relevance of activity duration with the resources requirement with respect to different modes. They applied a combined solution methodology based on an adaptive harmony search and GA to find near-optimal solutions.

Schedules quality plays a significant role in successful execution of a project. Thus, Icmeli-Tukel and Rom (1998) regarded the necessity of dealing with the schedule quality as a crucial criterion. They stated that a quality solution should be investigated through three aspects including performance, conformance, and robustness of the schedule. The first two aspects point to the makespan minimization (or the given OF optimization), in terms of the precedence and resource constraints. However, the third aspect goes back to accommodation of potential uncertainties threatening the project execution, compared with the preplanned schedule. This issue can take place because of different events such as un-forecasted accidents, employee elements, equipment break down, delays in materials' arrival, and so on, affecting the activities duration. In other words, the project delivery is depended on a varied set of uncontrollable factors whose oversight can affect the schedule. Without loss of generality, the robustness is traced to quality-robustness when it is measured according to the project duration. However, the robustness is addressed by solution-robustness, once it is measured by deviation between the planned and realized start times of the projected schedule.

According to the resource constraint project scheduling problem (RCPSP) literature, the aforementioned uncertainties have been treated by different approaches such as reactive, stochastic, fuzzy, proactive (robust) scheduling, and sensitivity analysis. A baseline schedule must be generated for each of the approaches selected, without regarding the variability, at the outset. Thereafter, different rules or heuristics may be applied in order to modify the occurrence of potential disruption (Artigues & Roubellat, 2000; Calhoun et al., 2002). In this respect, simple right shift of disruption-affected activities to complete rescheduling can be taken into consideration as extreme points of the corrective rules spectrum. For instance, the reactive scheduling functions such that it re-optimizes the baseline schedule in occurrence of an un-expected event. Herroelen and Leus (2001) highlighted some drawbacks of this approach because of oversimplification of the RCPSP reality, though it is very popular in different optimization fields.

Project scheduling with stochastic-based approaches mainly treat the RCPSP as a multi-stage decision process, associated with a priori knowledge about the distribution of the activity time duration (Ashtiani, Leus, & Aryanezhad, 2011). However, this approach may be impractical for circumstances, where there is no precise knowledge on the proper probability distribution function. On the other hand, the lack of possibility to provide a baseline schedule can be accounted for another chief deficiency of a stochastic-based method.

The other uncertainty management approach, namely fuzzy project scheduling, addresses the concept of fuzzy activity duration and produce fuzzy schedule, consequently. Application of such an approach is highly depended on the use of membership functions to define the activity duration distributions (Wang, 2004). However, the difficulty in uncertainties estimation makes its application less efficient, from a practical point of view.

The generated schedules in the proactive category account for variability. Thus, the approach is referred to as robust scheduling, as well (Wang & et al., 2015). This methodology is mainly based on time buffers insertion into an appropriate schedule to enhance its quality-robustness. Finally, the sensitivity analysis approach pertains to the "what if ..." questions, originated from parameters changes.

Amongst the above mentioned approaches, the robust optimization (RO) techniques have received much attention within the last years, due to their efficiency and applicability. As a rule, they aim to find the best solution feasible for any realization of the data in the given uncertainty set. RO provides the flexibility to control the solution quality, rather than only resulting in the worst-case scenario solutions. Moreover, it does not suffer from the exponential increase in the computational complexity because of the uncertain parameters rise up (Pishvaee, Rabbani, & Torabi, 2011; De Rosa, Hartmann, Gebhard, & Wollenweber, 2014; Moreira, Cordeau, Costa, & Laporte, 2015).

In the support course of RO models, different formulations and techniques have been developed for distinctive problems. For instance, Mulvey, Vanderbei, and Zenios (1995) proposed an integrated approach composed of the goal-programming formulation and a scenario-based explanation of the problem data. They took the solutions that remain close to optimal and those that remain 'almost feasible' into account and used the 'solution robust' and 'model robust' terms, respectively. Ben-Tal and Nemirovski (1999, 2000, 2002) obtained robust solutions to convex optimization problems with ellipsoidal data sets. However, the proposed approach could result in non-linear models, in spite of constraints satisfaction. Bertsimas and Sim (2003, 2004) addressed data uncertainty for discrete optimization problems (i.e., the network-flow problem), considering the degree of solution conservatism. The issue yielded to reducing the 'price of robustness' in return for lower protection level. Lin, Janak, and Floudas (2004) and Janak, Lin, and Floudas (2007) developed the RO theory framework for general mixed-integer linear programming problems, considering both bounded and several known probability distributions. A comparative theoretical and computational study on robust counterpart optimization was further investigated by Li, Ding, and Floudas (2011).

This paper aims to develop a mathematical model to address simultaneous planning of the project scheduling and material procurement, regarding the aforementioned notes. The extant papers have just concentrated on the ordering issue, according to the best knowledge of the authors. However, there are significant differences between material ordering and procurement. In a broader sense, procurement accommodates a wider set of issues relevant to acquisition strategies rather than the mere purchasing. Moreover, both aspects, i.e., project scheduling and material procurement, are taken into consideration under the presence of uncertainties. In other words, both project activities duration and different costs of material usage can be affected by variation and fluctuation, respectively. The model novelties can be concisely counted, as follows.

- Developing a bi-objective mixed-integer programming model which can deal with the robustness criterion from two distinctive aspects associated with activities duration and resources cost uncertainties.
- Considering the possibility to procure required materials from different suppliers each proposing a specific all units-discount opportunity.
- Application of calibrated meta-heuristics to solve the model for large-sized instances, in particular.

The rest of the paper is organized as follows. The mathematical model is described in Section 2, in addition to its robust counterpart. Section 3 discusses the solution methodologies application and the individual generation method. The robust experimental