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Technical Paper

Makespan estimation of a production process affected by uncertainty: Application on MTO production of NC machine tools

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A R T I C L E   I N F O

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A B S T R A C T

In this paper we address the estimation of the duration of the production process of a complex product in a *Make-To-Order* (*MTO*) or *Engineering-To-Order* (*ETO*) environment, a common situation in the manufacturing sector, specifically when production operations are executed by human operators. The addressed products, due to their complexity and high degree of customization, are specifically designed for a customer, together with their production process. On the other hand, the uncertainty affecting the production problem must be considered due to the presence of operations executed by human operators, the high level of customization entailing the need to cope with new products and processes and the behavior of the production environment.

The proposed approach deals with the estimation of the duration of a production process modeled through a *project network* whose activities have an uncertain duration. It can provide support to a manager in the estimation of the *makespan* of the production of a product to provide a realistic and competitive *due date* to the customer, as well as to manage the scheduling of production and supplying operations and the resources assignment within the plant.

The proposed approach is described, validated and compared with existing approaches through an ideal case. Moreover, a real case application is provided, related to the assembly process of a NC machine, to demonstrate its industrial viability.

1. Introduction

The European industrial sector is evolving towards an increasing customization of the products to provide tailored solutions to the customers. Companies competing on the market have to design and produce products that can be easily customized and, consequently, also the associated manufacturing processes must be adapted accordingly. Hence, the series production paradigm is no longer viable being each product a new one with specific characteristics and its production process must be specifically tailored as well. All these factors make the production phase more complex to manage and plan.

To this aim, companies often adopt a *Manufacturing-To-Order* (*MTO*) approach, producing an item only when a customer place an order, without keeping any inventory of finished parts. In many cases, the *MTO* scheme is also extended to the upstream phases, i.e., the design, leading to the *Engineering-To-Order* (*ETO*) paradigm, where also part of the design as well as the procurement of components and/or raw materials are specifically linked to an order. At the planning level, a *MTO* or *ETO* organization entails a high level of uncertainty, because of the unpredictability of the production activities the company have to execute in the medium and long terms. An additional factor of uncertainty is incurred when production activities are executed by human operators, thus increasing the complexity of the production planning problem.

Strictly linked to the production planning phase is the definition of the due dates for the delivery of orders to the customers. The estimation of the due dates is inevitably affected by the intrinsic uncertainty at the production planning level. To support this phase, tools and methodologies are needed to assess the duration of the whole production process, the makespan, taking into consideration the stochastic characteristics of the problem. Moreover, these tools could be also used during the production phase, to estimate the probability to be late in relation to a given due date, thus triggering possible reactive approaches to reschedule the production.

Many approaches have been proposed in the literature to face these situations, most of them are based on *Project Evaluation and Review Technique* (*PERT*) and *Critical Path Method* (*CPM*) techniques. These approaches, described in the following Section, consider that

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all the production activities have a stochastic duration modeled through a random variable.

In this paper, we propose a method to estimate the distribution of the makespan of a generic set of production activities and the associated precedence constraints modeling a production process. This method can be used to estimate the lateness in relation to a *due date* as well as the scheduling of the entire process. In comparison to *PERT* and *CPM* techniques, the proposed approach can handle a wider range of stochastic distributions modeling the duration of the activities and solve general project networks in a reasonable time. Since no specific constraints are given for the distribution of an activity's duration, it can be shaped starting from the investigation of real activities in the manufacturing process (e.g. real assembling or machining activity) and, unlike the *PERT* method, avoid unnecessary and constraining hypotheses on the distribution type. The contribution of the proposed approach relies in the joint utilization of both analytical and simulation approaches already available in the literature. Moreover, the proposed approach is not affected by the typical limitations of available analytical techniques, requiring strong hypotheses on the stochastic distributions that can be used and, hence, is able to estimate the makespan of a generic process with performances that are better that pure simulation approaches.

In addition, we propose and demonstrate the exploitation of this class of approaches as a management tool, e.g., in the negotiation of delivery dates or to assess the most convenient scheduling policy. The relevance of this class of approaches is motivated by the application to specific manufacturing sectors, e.g., the production of machine tools, where production and/or assembling activities are often executed by human operators, thus entailing the need of adequately considering uncertainty.

To demonstrate the viability of the proposed approach, we provide the application to an ideal case as well as to an industrial case, provided by *MCM S.p.A.*, an Italian company that designs and produces *CNC* machines and *FMSs*. *MCM*, as many European machine tool builders, opted for a high level of customization for its machines and, hence, its production environment perfectly matches the capability of the proposed approach and provides an ideal application case.

In Section 2 we provide a survey of the related literature and, in Section 3, we formalize the addressed production problem. Section 4 contains a step-by-step description of the proposed approach. Section 5 provides a validation and testing of the proposed method on an ideal case: the results are analyzed and compared with a benchmark distribution to assess the quality of the estimation as well as the performance of the approach in terms of the time needed to solve the considered instances. In Section 6 an application to an industrial case is provided; the assembly process for the production of NC machines is modeled and the proposed approach is tested on a set of production orders. Additional details related to the production process under study are available in Appendix A.

2. State of art

The need to cope with the uncertainty affecting the execution of a project entails modeling the duration of the activities with a random variable. Stochastic project networks, also called *PERT* networks [16] can be used, traditionally modeled using a *Directed Acyclic Graph* $D = (N, A, p)$ where $A = \{1, 2, \ldots, m\}$ is the set of arcs representing the activities, $N = \{1, 2, \ldots, n\}$ is the set of nodes representing events, also called milestones and p is a vector of independent random variables, modeling the duration of the activities. The benefit of this technique stays in the estimation of the duration of complex projects: a very difficult activity, especially when all the activities are uncertain. The *PERT* technique grounds on few simple assumptions: (a) the process network is formalized with strictly rules concerning the representation and the precedence constraints between activities; (b) the stochastic characteristics of the activities are modeled starting from three different data, the optimistic, the pessimistic and the most likely values taken from a beta distribution modeling the duration of the activity.

As a result, the graphic formalization of *PERT* networks is a digraph in which each activity is represented with an arc and each project event is represented with a node; in this case, the digraph is called *AoA* (*Activity on Arc*), whose characteristics are described in Elmaghraby [7].

Grounding on this particular formalization of a project, several tools have been developed to calculate different characteristics of the problem, first of all, the duration of the entire project using the *CPM* technique. This technique exploits the formalization of the project network to estimate its duration by the identification of the most critical path and considering only deterministic durations.

The main advantage of the *CPM* and *PERT* techniques is the capability of considering the entire project but, on the other hand, it has some disadvantages. Firstly, the estimation provided is only a single value and not a probability distribution. The approach is able to take into consideration only one path and, in addition, the only distribution supported is the *Beta* distribution.

In order to have a better and more general estimation of the makespan of this class of project networks, it is desirable to:

- obtain an estimation of the whole probability distribution of the makespan, because some regions of the distribution (e.g. the last percentiles) are more critical, and the expected value is not enough to assess the impact of these situations;
- take into consideration all the paths in the network (and not only one), to capture the stochastic behavior of the whole process.
- be able to consider multiple type of probability distributions.

Several approaches has been proposed to address these limitations.

A first set of computational problems in the evaluation of stochastic project networks comprehends the identification of the critical paths and the critical activities and the estimation of the probability distribution of the project's completion time (or stochastic bounds for it). It must be noticed that, for a stochastic network, the duration of the entire project is also a random variable, critical paths can be more than one and, for each of them, the probability to be critical should be estimated.

Two methods for the estimation of the stochastic duration of the project have been developed exploiting the concept of simplification and reduction of a network. Martin [17] and Valdes and Tarjan [23] face this problem proposing methods to reduce a complex stochastic *AoA* graph to a network with only two nodes and a single arc by the iterative application of series and parallel reduction steps, grounding on convolution and point-to-point multiplication (respectively). The distribution of the duration of the remaining arc is the distribution of the makespan of the entire original network.

The proposed approaches can reach their goal only on series-parallel networks, i.e., networks where the series-parallel reduction can be completely executed. Two activities (edges) are in series if the sink node of the first activity is also the source node of the second activity and, in particular, this node has in-degree and out-degree equal to 1 (Fig. 1(a)). In this case it is possible to substitute a single activity to the original two, whose duration is the sum of the two durations, this is a series reduction. For example, given two activities i and j in series, with duration d_i and d_j, respectively, they may be reduced to a single activity k whose duration d_k is the sum of the two starting activities $d_k = d_i + d_j$. In the case of stochastic