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The impact of design uncertainty in engineer-to-order project planning

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ABSTRACT

A major driver of planning complexity in engineer-to-order (ETO) projects is design uncertainty far into the engineering and production processes. This leads to uncertainty in technical information and will typically lead to a revision of parts of the project network itself. Hence, this uncertainty is different from standard task completion uncertainty. We build a stochastic program to draw attention to, and analyse, the engineering-design planning problem, and in particular, to understand what role design flexibility plays in hedging against such uncertainty. The purpose is not to devise a general stochastic dynamic model to be used in practice, but to demonstrate by the use of small model instances how design flexibility actually adds value to a project and what, exactly, it is that produces this value. This will help us understand better where and when to develop flexibility and buffers, even when not actually solving stochastic models.

1. Problem description

We consider a project production system following the engineer-to-order (ETO) approach where design, engineering and production do not commence until after a customer order is confirmed (Rudberg & Wikner, 2004). This approach is used to create products that are tailored for each customer and is used in, for example, shipbuilding and off-shore oil and gas installations. A typical feature of ETO projects, especially in the case of complex orders such as offshore ships, is a continuous dialogue with the customer after the order has been received.

This often leads to specification changes after the design phase of the project has started, sometimes even far into the engineering and production phases.

While the flexibility is good for the customer, for the producer it represents a source of uncertainty in the technical information, which often leads to uncertainty in the project network itself. This leads to continuous adjustments in procurement, engineering and execution (Emblemsvåg, 2014), and suggests that we are dealing with a stochastic dynamic planning problem with uncertainty at two levels. Firstly, we have that task completion times are uncertain and usually correlated for any fixed design. Secondly, design uncertainty is added to this. And this latter layer is not merely a scaling of the first, but can change its structure substantially. Consequently, the resulting dependencies become very complicated.

Design uncertainty is, therefore, a major driver of planning complexity in ETO projects where advanced design and engineering is taking place concurrently with production. Obviously, concurrency is challenging only when design is uncertain. Despite this, design is most commonly separated from project scheduling (Eckert & Clarkson, 2003; Emblemsvåg, 2014), leading to plans that lack the flexibility necessary to handle the true uncertainty.

In general, what is lacking in the classical project scheduling *models* is the possibility to have decisions that are conditioned on arriving information (in our case the progress of tasks and changes in design) as well as future decisions. The major difficulty is that there *is* no arrival of information in these models. However, even though the models do not consider re-planning, this is of course performed in reality, normally by rerunning the existing models based on all new information, that is, *reactive planning*.

It is, however, well established, see for example King and Wallace (2012), that such a sequence of decisions (plans) from static models, often referred to as rolling horizon modeling, can lead to arbitrarily poor decisions. The reason is that each individual plan is inflexible; it assumes the future (in terms of decisions) cannot be changed. And a series of inflexible decisions remains inflexible.

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Contrary to reactive scheduling, *proactive scheduling* would imply a scheduling that takes into account both arrival of information and future decisions that might unfold. This is discussed in Jørgensen and Wallace (2000), and might lead to plans (and decisions) that are very different from those stemming from static (non-dynamic) models. The main reason is that dynamic models will suggest decisions that are much more flexible, and that lead to future situations that are much easier to handle when something goes wrong; they include options, see Wallace (2010).

There are very few proactive approaches that discuss the two main issues, arrival of information and future decisions (see details in Section 2), and in any case, these are not very practical. As practitioners increasingly recognize the shortcomings of classical project scheduling models, these are often replaced by team-based judgemental decision processes that automatically open up for behavioral challenges (Vaagen & Aas, 2014). Dealing with the described complexity without model-based decision support is obviously not easier when we lack guidelines on where, when and how to develop flexibility and buffers. Although buffer management is commonly used to hedge against uncertainty (Van de Vonder, Demeulemeester, Leus, & Herroelen, 2006), the optimal solutions in stochastic dynamic environments are not 'the static solution plus something'. Rather, the two solutions are normally structurally different; see Wallace (2010) for a detailed discussion.

This is intuitive if we consider, for example, changing an offshore shipbuilding process from an originally planned cable-layer to a fire-fighter, far into the production process. A fire-fighter requires specialised solutions throughout the bow of the vessel, which implies activity sequencing substantially different from other design solutions. Late adaptation to such complex outfitting designs cannot be handled by fixed schedules for other design solutions, plus some slack, as they require extensive rework.

A second, and probably less intuitive example, is uncertainty in the design of strategic components, e.g., size, technical specifications or supplier of the engine for sea exploration operations. The alternative designs often require very different piping and electro solutions, with different tasks and sequencing. Handling this type of change by adding time buffers to the design-dependent tasks is certainly possible, given that the uncertainty is identified and the buffers are sufficiently large. But with many low-probability/high-impact changes throughout the project life-cycle, in an environment where short delivery time is critical for competitiveness, adding time buffers is obviously a sub-optimal countermeasure.

This leads to our main concern: handling the uncertainty and dynamics generated by frequent design changes, where a particular technical solution may be selected/de-selected by the customer, even far into the production. For a given design, task durations are inherently uncertain and often assumed to follow known and rather simple distributions, e.g., uniform or exponential (Lambrechts, Demeulemeester, & Herroelen, 2010), and are frequently handled by time buffers in proactive-reactive approaches (Van de Vonder et al., 2006). But design uncertainty differs from uncertainty in task durations, as it affects the choice (and technical sequencing) of the tasks to be executed. This suggests that the most critical variation is actually caused by design uncertainty. Obviously, this poses challenges when the managerial objective of reducing delivery times triggers concurrency in engineering and execution activities, in projects with frequent low probability/ high impact design changes. This is the case we study.

The purpose of this paper is, therefore, to understand better how engineering design uncertainty affects project planning complexity and how this uncertainty leads to different plans and decisions when taken explicitly into account in the decision models. This will help us understand better where and when to develop flexibility and buffers, even when not actually solving stochastic models. In real projects these models will be far too heavy. We do this by solving small model instances, showing how design flexibility adds value to a project and what this flexibility actually comes from. Within this framework, we seek a methodology that captures the value of future choices on design alternatives. Stochastic programming is, in our view, a good approach for this task, despite its complexities. As we deal with a stochastic dynamic problem not yet solved in the literature, the challenges in formulating and solving the problem necessarily have to be discussed, but that is not the message of this paper. Our main concern is what we can learn about the impact of design uncertainty on planning, by analyzing small model instances.

The paper is organized as follows. Section 2 discusses relevant attempts to handle uncertainty in the engineering design process, with particular focus on project management and scheduling. The stochastic modeling approach is described in Section 3. The following two sections present and analyze two test cases. The first is a design-engineering planning case that focuses on the value of flexible (two-step) design strategies. The second test case is set up to help us characterize good plans when these flexible design strategies are not available. Insights from analyzing the test cases come in Section 6, before we conclude the paper in Section 7. The detailed mathematical formulation of the stochastic dynamic project scheduling model, needed for our analysis, is given in the appendix.

2. Existing literature

The engineering design process connects the phases of basic (preliminary) design with detailed design and project planning and scheduling, where one design alternative normally excludes other alternatives. Most commonly, design planning and project scheduling are treated as separated stages. This separation is problematic in an uncertain world where speed to market drives competitiveness, and design activities are necessarily performed concurrently with planning and execution (Eckert & Clarkson, 2003; Emblemsvåg, 2014).

Decision-making trends in project management and advances in scheduling techniques are reviewed in Rolstadås, Pinto, Falster, and Venkataraman (2014), highlighting the need for increased use of analytical approaches to handle project uncertainty. That said, the number of model-based approaches to support project planning is substantial, but with important shortcomings in handling uncertainty, dependencies and dynamics (Herroelen, 2007; Vaagen & Aas, 2014; Van de Vonder et al., 2006). Most importantly, a large share of the research assumes a static and deterministic environment, while real project activities often are subject to substantial uncertainty, leading to schedule disruptions.

But also approaches developed to handle uncertainty fail to properly handle project uncertainty and dynamics, e.g., proactive or reactive scheduling dealing with a sequence of decisions from static models. For important work on generating robust (deterministic) baseline schedules that are sufficiently protected against (anticipated) uncertainty, and reactive policies deployed to adjust the baseline schedules after uncertainty is revealed, see Van de Vonder et al. (2006) and Herroelen (2007). Here, statistical information about possible disruptions is used to create baseline (deterministic) schedules, which are revised/reoptimized when necessary. The underlying idea is to create a 'solution robust' baseline schedule, normally by adding time buffers (Herroelen & Leus, 2005), or by developing multiple baselines before and during the project execution, and responding to anticipated events by switching to the schedule that corresponds to the event that occurred (see, e.g., Artigues, Billaut, & Esswein, 2005). The latter is also called *contingent scheduling*, as it focuses on alternatives. These solutions are, however, not flexible, despite the alternatives provided, as the approach applied consists of a series of inflexible decisions.