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DESIGN PROJECT PLANNING, MONITORING AND RE-PLANNING THROUGH PROCESS SIMULATION

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ABSTRACT

Effective management of design schedules is a major concern in industry, since timely project delivery can have a significant influence on a company's profitability. Based on insights gained through a case study of planning practice in aero-engine component design, this paper examines how task network simulation models can be deployed in a new way to support design process planning. Our method shows how simulation can be used to reconcile a description of design activities and information flows with project targets such as milestone delivery dates. It also shows how monitoring and re-planning can be supported using the non-ideal metrics which the case study revealed are used to monitor processes in practice. The approach is presented as a theoretical contribution which requires further work to implement and evaluate in practice.

Keywords: Design process simulation, design project planning, project metrics

1 INTRODUCTION

A key aspect of delivering profitable new product development projects is ensuring that project deliverables are produced within the available time and budget, while ensuring that they are of adequate quality. This is undertaken through the mechanisms of planning, monitoring and re-planning when progress falls behind schedule. This paper introduces a new approach to support these three process management (PM) activities through process simulation modelling. The research draws upon a case study of aero-engine component design which is used to identify some of the key challenges faced by design process planners in practice. The case study is also used to develop a simplified model of design process planning which clarifies the specific aspects of PM on which this paper focuses. We propose that the challenges we identify can be addressed by a novel methodology based on design process simulation.

The paper is presented as a theoretical contribution to the literature on using process simulation to support design planning. It contributes three main insights to this literature. Firstly, we highlight the need to consider not only initial planning, but also monitoring and re-planning when developing approaches to support planning practice. Secondly, drawing on the case study, we identify the need for model-based planning support methods to account for the limited fidelity of process models, the limited knowledge of project participants when plans are constructed, and the lack of ideal metrics for monitoring project progress. These issues are not considered in detail in the existing literature. Thirdly, we introduce a simulation-and-selection methodology to support design planning, showing one way in which these issues could be resolved.

The paper proceeds as follows. Section 2 sets the context of our ideas through a brief overview of the literature proposing model-based approaches to support design planning. Section 3 reports on a case study of aero-engine component design. Based on this study, we present a simplified view of design process planning which highlights the key challenges of PM. This is used to identify requirements for support methodologies which are not thoroughly addressed in the existing literature. In Section 4, an approach to planning support is proposed which shows one way to address these limitations. Section 5 reflects upon the contributions of the paper and identifies opportunities for further research. Section 6 concludes.

2 BACKGROUND

Many model-based approaches have been proposed to support PM in general. Perhaps the most well-known is the PERT chart and related critical path analysis, which aims to assist managers by identifying those activities which have greatest impact on overall project duration, and which must therefore be carefully managed [1]. Pritsker extended this approach, introducing GERT simulation models which allow incorporation of iteration cycles [2]. A number of model-based approaches to support design project management in particular may be found in the literature, where most focus on developing improved process configurations or optimised plans through analysis of a task network model. For example, Eppinger shows how a dependency structure matrix (DSM) indicating the information flows between activities in a project may be used to identify an order of attempting tasks (*i.e.*, a plan) which minimizes information feedback and hence iteration [4]. Browning and Eppinger [6] extend this work to show how simulation can be used to evaluate different sequences of tasks to find the best plan, accounting for the durations of tasks and the likelihood and impact of different rework scenarios. Cho and Eppinger [5] propose a framework for project management based on a similar simulation model. O'Donovan et al. [7] use Signposting simulation models to develop plans which offer 'optimal' guidance by expressing which task should be prioritised in any reachable process state. One limitation is that all these approaches assume that detailed, high-fidelity process models exist from the outset of a project, when planning is undertaken. In practice, however, such models are not easily constructed up-front for highly complex, one-off or innovative projects.

The need to support re-planning is often discussed in this model-based planning literature. For instance, Lévárdy and Browning explicitly consider re-planning by proposing that activity plans may be dynamically modified in response to the emerging state of the project to reach cost, schedule and technical performance targets [10]. However, in the design process planning literature most authors do not directly consider the problems of monitoring, *i.e.*, determining when and what to re-plan.

One well-known approach which does assist monitoring is the critical chain methodology. This aims to help managers protect the critical path of a project through explicit recognition of possible delays and the placement of appropriately-sized buffers at the end of scheduled chains of tasks [3][21]. These buffers are then gradually used up as tasks within their chains are delayed; the rates of reduction can be used to predict when the critical path will be compromised and thus when re-planning or other corrective actions will be necessary. While this is effective for complex projects involving streams of interdependent work, the critical chain network cannot be constructed if task sequencing is uncertain. This is the case for the highly iterative component design processes considered in this paper.

In summary, therefore, relatively few approaches support the management of design plans throughout their entire lifecycles, *i.e.*, in the stages of plan development, project monitoring and re-planning. Design planning approaches that do consider whole plan lifecycles include PlanWeaver [8], Plexus Modeller (no academic publications available), and ProNavigator [9]. However, these approaches focus on planning from a high-level product development perspective and do not address the difficulties of modelling, planning, monitoring and controlling processes at the component design level considered in this paper. The characteristics and specific PM challenges of such processes are discussed in more detail below through a case study of design planning practice.

3 CASE STUDY: DESIGN PLANNING CHALLENGES IN INDUSTRY

The research reported in this paper was motivated by a case study in which the first author spent eight months on-site at a large UK aero-engine manufacturer between March and October 2004 [18]. The study was undertaken in the detail design phase of a fan blisk (a major aero-engine component) in which it had been previously found difficult to decompose the highly iterative design process into a detailed programme of work against which progress could be monitored. The objective of the case study was to explore how a task network model of the blisk design process could be used to help the project manager maintain a more accurate and up-to-date picture of progress, such that any schedule slippage could be quickly identified and mitigating actions taken in good time to ensure success.

Throughout the study the researcher observed meetings and conducted informal interviews with design and management personnel. Twenty-one interviews were scheduled and documented, and more discussions were held on an opportunistic and undocumented basis. Most of the individuals who were interviewed either worked in the engineering-focused business unit responsible for the technical component design or in the customer-focused unit responsible for project delivery. A number of regularly-scheduled and one-off meetings were also observed to supplement the interviews.

The focus of data-gathering during the first two months of the study was to understand the characteristics of the component design process and to elicit the key challenges in planning and managing this process, from both engineering and PM perspectives. Key findings are described below.

3.1 Overview of the component design process as observed during the study

From the mechanical design perspective, the blisk design process observed during the study involves iterative refinement of the parameters which define the blisk through four main activities, each of which can be further decomposed into a greater level of detail. Each activity can be attempted at different resolutions, or with different amounts of effort, according to the maturity of the design data and the perceived importance of the corresponding objective at that time. In general, the effort devoted to each activity increases over time to reflect increasing design maturity. Activities may be performed concurrently to compress project schedules.

To summarise, the study revealed that blisk design can be modelled in terms of the iterative application of design and analysis tools used to perform specific activities. Such a model was constructed using the ‘Applied Signposting’ approach and is reported in [18]. The tools and their possible interactions through the transfer of data are well-defined, although in general the sequence of activities during design is difficult to describe as this is determined by in-situ decisions. Further uncertainty in activity sequencing arises since changes in design constraints may be required at any time to accommodate emerging issues in other engine components, or changes to the customer requirements (for instance, increases in airframe weight may require greater thrust from the engine and hence modifications to the highest-level fan requirements). Such redesign may occur several times during a single development project and could involve revisiting all design activities.

3.2 A simplified model of design process planning

The case study was used to develop a simplified model of design process planning, illustrating the roles of key stakeholders in the planning activity and the key problems they face. The aspects of planning captured in this simplified model led to development of the new planning support methodology described in Section 4.

Roelofsen et al. [11] argue that planning takes place on multiple levels of abstraction, including the project level and the operational level. Our model uses a similar concept, arguing that project-level planning involves reasoning in terms of project performance-level objectives, and that operational reasoning is conducted in terms of plan-level objectives. We then consider three key components of design planning observed during the case study. These are respectively *planning* design tasks, *monitoring* progress as the project proceeds and *re-planning* in response to unexpected or adverse events, thereby controlling the project and guiding it to a satisfactory outcome. In our simplified model of design planning, the relationships between these three planning activities and two levels of representation are:

- **Planning.** Project targets are typically defined in performance-level terms such as the rate of accumulating cost and the dates at which milestones must be delivered. However, although setting performance targets, for instance via EVMS [13], is part of planning, this does not identify how – and whether – the targets can be met. A schedule of work must also be expressed in plan-level terms by decomposing the design process into tasks, identifying a sequence for attempting those tasks, and scheduling the times at which they should each be completed.
- **Monitoring.** As the project proceeds, progress may be monitored by comparison with a schedule stated in terms of the performance-level objectives. For instance, has the expected resource been spent, and does the total value of milestones delivered match the value stipulated in the plan? It may also be evaluated against a plan-level representation: have the planned tasks been completed on schedule?
- **Re-planning.** When monitoring reveals a project is running significantly behind schedule, a new schedule may need to be developed to identify how the design work can be completed within acceptable time and budget. Re-planning involves finding a way to do more work in the same time, which might involve re-assignment of resources, re-prioritisation among the multiple design objectives, and/or conducting fewer or shorter iterations to refine the design. As with planning, the results of re-planning must be expressed in plan-level representations.

These three planning activities, two levels of representation and their interrelationships form our simplified model of design process planning. The model is intended to highlight the need to maintain consistency between the performance and plan levels of description. This can be challenging when planning engineering design processes such as that observed in the case study, because such processes are characterised by uncertain task ordering and many design iterations and require frequent re-planning to respond to unexpected issues.

3.3 Design planning challenges highlighted by the case study and simplified model

In this section, the case study and simplified model are analysed to highlight some key challenges of design planning in practice. The approach introduced in Section 4 aims to address these challenges.

Incorporating iteration in planning and monitoring

Iteration was identified as a defining aspect of the design process during the case study. Furthermore, the ubiquity of iteration in design is a recurring theme across much of design literature [14]. However, the planning methods in use today are ill-equipped to help planners account for iteration in the design process. For instance, during the case study the Gantt chart-based scheduling package used by the company did not provide any way of expressing iteration, other than listing tasks in multiple rows to indicate that they would be revisited on known dates. The uncertainty associated with the occurrence of design iteration, with the effort expended on revisited tasks and with their ordering could not easily be indicated or accounted for. Furthermore, these tools do not assist in identifying and scheduling the knock-on consequences of unplanned rework when it is discovered during the process. Since unplanned rework is almost inevitable and can lead to significant knock-on consequences, such support could greatly reduce the effort associated with re-planning.

Another planning and monitoring system used in the company was earned value management, a standard project management approach which aims to support progress monitoring by providing simple metrics to identify when a project is behind cost or schedule. The EVMS approach requires a project to be decomposed into discrete deliverables whose value is ‘earned’ at the time they are completed [13]. This provides a simple way to monitor progress in terms of how much capital has been spent for what fraction of the expected progress. However, accurate monitoring using this approach requires that deliverables are spaced evenly throughout the project and that they cannot be invalidated by later work. These assumptions are often inaccurate for engineering design, since it is a process of iterative refinement in which few deliverables are finalised prior to completion.

To summarise, accounting for iteration in monitoring and scheduling are key challenges in design PM. Although it is possible to schedule an iterative process using today’s planning tools, these tools do not recognise the significance of design iteration and do not provide language for describing its different behaviours [14]. Therefore, although planners may understand the iterative behaviour of their processes, it can nonetheless be difficult for them to reason about the limitations of the available scheduling tools and techniques and hence to use them effectively by working around their limitations.

Monitoring in the presence of uncertainty

In an uncertain environment, timely project delivery requires effective progress monitoring, so that delays may be identified and corrective actions – re-planning – can be taken in good time to avoid adverse consequences. Monitoring should ideally be based on indicators which may be reliably and regularly estimated and which highlight potential problems well ahead of time. However, this is often not possible in practice. The underlying reasons are discussed below in terms of the difficulties associated with tracking individual task completion and those associated with other progress metrics.

Identifying the current state by monitoring tasks completed

At any time during a project, tasks may be classified into five categories: 1) those which have not yet been attempted; 2) those which have been completed and will never be revisited; 3) those which are in progress, but once completed will not be revisited; 4) those which have been completed but which may be re-attempted in future; and 5) those which are currently in progress and which may be re-attempted following completion. During design, accurately categorising tasks in this way is usually not possible due to the uncertainty surrounding design iterations. This leads to the situation in which tasks are assumed to be complete and the project on schedule, but unexpected rework is discovered later. Cooper uses a simulation model to show that such hidden rework can have significant adverse effects on project predictability [15]. To avoid these consequences, task-based monitoring requires a detailed knowledge of which tasks are being performed and whether they may be revisited in order to determine whether or not the project is behind schedule. This requires comparison of current progress to a plan-level schedule. However, the required level of fidelity is usually unavailable in planning documents due to the uncertainty about the design process at the time the plans were set down. For example, if additional, unplanned analyses are performed to address emerging concerns about the design, or if the sequencing of activities does not exactly follow the plan, it may not be possible to directly compare the work completed against the activities which were originally planned. Therefore, the simplest monitoring approach of ‘ticking off’ tasks once complete is difficult to apply to monitor iterative design processes, due to the complexity and uncertainty of task sequencing within them.

Identifying the current state by monitoring other metrics

Although plan-level schedules can be expected to be inaccurate for the reasons outlined above, it is still useful to maintain a detailed activity plan while acknowledging that it is not fully representative of the design process. Progress monitoring can then be based on metrics that are not expressed in terms of tasks completed. Examples of such metrics include aggregate performance-level measures such as earned value and work completed to date. More subjective measures such as experts’ confidence in design completeness and the inversely-related measure of ‘perceived risk’ can also be used to monitor progress [7]. However, these concepts are difficult to define and quantify in practice. Even when aggregate metrics are well-defined, they suffer from a number of limitations such as bias and inaccuracy, as discussed in [18]. Therefore, although aggregate metrics may be more practical than plan-level monitoring, they also provide a less certain picture of progress. In practice, managers must reason about project progress qualitatively, by considering a set of different observations whose exact values and relationship to project completion are difficult to quantify. Assisting progress monitoring in a way which recognises non-ideal metrics is thus a key requirement for design PM support.

Identifying the ‘best’ schedule

Often, multiple schedules offer plausible routes to complete a project. In such situations it is necessary to identify the alternatives, consider the trade-offs made between design and management objectives within them and select the ‘best’ plan for implementation. To illustrate such trade-offs, consider the choice between 1) focusing effort to optimise the design for one objective early in the process and 2) releasing preliminary information and moving on quickly to address another problem. In this case, the desire to minimise schedule risk suggests that deliverables should be produced as early as possible so that time is saved to buffer against problems which may arise later. However, spending more time on refining the early design could reduce the risk of more expensive rework later. Since different personnel are often responsible for managing these different risks, such trade-offs can be difficult to identify. In summary, an important aspect of supporting PM is to help planners identify schedules which make appropriate trade-offs between quality- and schedule-focused risks.

Adapting schedules to the dynamic project context

Since most participants in a design process do not have a clear overview of the work which is undertaken during design [12], it is usually not possible to construct a detailed schedule which captures all tasks in the process. Furthermore, due to the complexity and large numbers of factors which influence iterative behaviour in practice, no single model or modelling approach can fully reflect the complexity of iterative dynamics [14]. It is therefore infeasible to construct a plan prior to beginning work which accurately encompasses all possible outcomes of a design project – even if uncertain events are incorporated. In practice, this necessitates that PM is based on incomplete and potentially inconsistent representations of the plan. Programme managers therefore expect to adapt their working schedules frequently in response to the dynamic project context. However, this can be difficult as support for re-scheduling is not incorporated in most planning tools used today. It is therefore necessary for the planner to reason manually through the implications of a change to the plan, for instance to identify tasks that might require rework, and then to manually update schedules on a task-by-task basis. Computational support for re-scheduling has potential to significantly reduce the effort involved, allowing more frequent re-scheduling and thereby enhancing plan fidelity.

3.4 Summary

The key issues highlighted by the case study were the uncertainty and complexity of design processes in practice, the difficulty of understanding that practice to construct a model which can be used for planning, and the difficulty of monitoring progress due to the lack of ideal metrics. It was also identified that approaches proposed to support design planning in the literature largely focus on a sub-set of the planning activity – the development of an initial schedule. These approaches do not directly support the aspects of monitoring and re-scheduling, which the case study revealed are significant aspects of planning practice.

4 SUPPORT FOR DESIGN PLANNING, MONITORING AND RE-PLANNING

A design process simulation model enables planners to translate between the performance- and plan-level descriptions used in design project management – and thereby to address the challenges outlined above. However, a problem which must be resolved in order to use simulation in this way is that the programme management process requires identification of the best means to meet performance targets, *i.e.* conversion of performance-level targets into plan-level schedules, whereas process simulation provides the reverse – prediction of the performance of a given process.

In this section, we show that this problem can be solved through an iterative process of *generating* many candidate plans and *analysing* these candidates to select the single most suitable option. In overview, the simulation-and-selection methodology introduced here supports this process as follows:

1. **Simulation**. A set of candidate schedules is generated by discrete-event simulation of a plan of work, which is expressed as a stochastic process model that can incorporate uncertain events such as the possibility of unplanned iteration and of unexpected delays in task completion.
2. **Selection**. Each candidate schedule is evaluated according to whether it meets project performance objectives and whether it is possible at all – given current estimates of progress alongside the activities and time remaining. The single candidate which is possible to achieve and meets all objectives while incurring the least schedule risk is selected computationally.
3. **Iteration.** The selection step immediately reveals if no schedules are possible given the current plan and estimated progress. If this occurs, the human planner can consider the best way to modify the plan – or may allow the project objectives to slip. By iteratively repeating the generation and evaluation steps, alternative re-planning options may be evaluated.

Through this structured process our approach is intended to help planners maintain schedules which are updated more often and therefore have, on average, higher fidelity. It also provides a systematic method to account for uncertainty in the design process and non-ideality in progress metrics, thereby showing one way to address all the planning challenges identified in Section 3.

The following sub-sections discuss the details of the approach under seven headings which reflect its main steps: Model the design process; Simulate the design process; Select acceptable outcomes; Resolve conflicts; Identify a schedule of work; Monitor progress and re-schedule; and Re-plan.

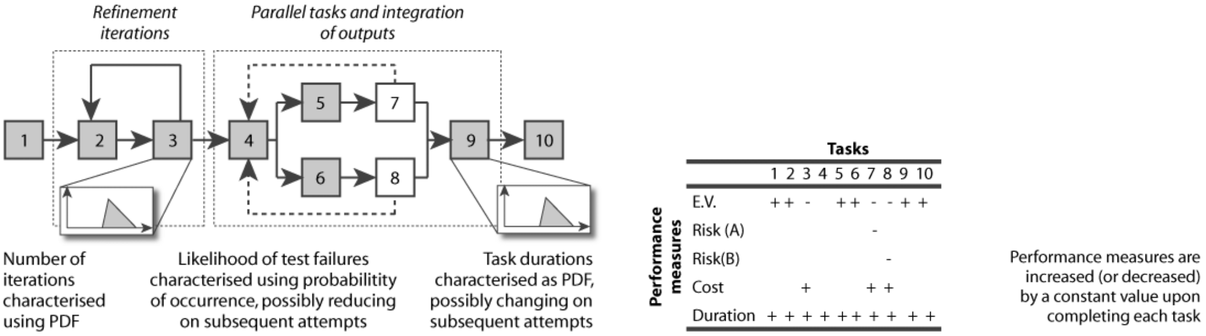
4.1 Step 1: Model the design process

In the first step of our approach, a process model is developed to represent tasks and iterations which comprise the technical design process, alongside key project deliverables resulting from these tasks. Modelling is based on a formal task network model which allows stochastic simulation. The modelling framework is not critical to the planning support approach; for instance, DSM-based (*e.g.*, [5][6]) or PERT-based (*e.g.*, [2][18]) approaches could be used. The steps of constructing such a model are:

- **Decompose the process into tasks and estimate their characteristics.** The model should decompose the process to a level of detail suitable for goal-setting and progress monitoring. Thus, tasks should typically represent several hours' to several days' work. Within the model, the expected duration of each task, the numbers of convergence/refinement iterations which are planned and any resource limitations which might cause bottlenecks must be specified. Primary sources of uncertainty must be identified and their characteristics estimated. For example, tasks' durations may be specified using probability density functions (PDFs). Convergence/refinement cycles may be parameterised with a PDF characterising the number of iterations required, and design evaluation tasks with the estimated likelihood of revealing rework which would require previous tasks to be revisited.
- **Describe the contribution of each task to each performance-level metric.** The model must include the metrics used to determine process performance and those used to monitor project progress. All such metrics must be expressed in terms of contributions from individual tasks in the process model. Browning et al. [16] argue that many useful measures may be linked to activities in this way. For example, commonly-used process performance measures include total cost expended and value of schedule milestones delivered, both of which must meet or exceed specified profiles of accumulation. These metrics may be respectively modelled as increasing

when cost-accumulating tasks are completed or when design releases are made. In the latter case, the earned value should be removed if those activities are later invalidated by the discovery of rework. Another metric observed during the case study is technical risk, which Lévárdy and Browning [10] propose can be modelled as reducing when testing activities are performed. Figure 1 illustrates how metrics can be incorporated in a process simulation model, by tabulation against the tasks which affect their values.

Models constructed in this way include many uncertain events distributed throughout the schedule. When multiple uncertainties are manifested, for instance as delays in multiple tasks, their consequences on project delivery are not independent. Depending on the structure and parameters of the model, delays could potentially interact to affect the project outcome in difficult-to-predict ways. For example, such interactions can arise from queueing behaviour resulting from resource bottlenecks; test failures, which may cause rework to propagate through many tasks in the schedule in a manner dependent upon the tasks attempted prior to the failure; and any interdependent behaviours which are explicitly incorporated, such as tasks requiring different amounts of effort on subsequent attempts. However, although the behaviour of models constructed for planning may be difficult to understand through inspection due to the large numbers of tasks and sources of uncertainty, the case study revealed that models of component design processes are likely to be organised such that combinations of the uncertain events do not cause significant unexpected consequences. In other words, in the types of model we consider the variability in simulation outcome is derived from an essentially linear accumulation of many small uncertainties rather than through complex interactions between them. (This is an important finding of the case study, since it follows that human planners can identify possible ways to influence simulation results, *e.g.*, to reduce total process duration, by direct inspection of the model; the implications for our method are highlighted in Section 4.4).



Performance measures	Tasks 1	2	3	4	5	6	7	8	9	10
E.V.	+	+	-		+	+	-	-	+	+
Risk (A)							-			
Risk(B)								-		
Cost			+				+	+		
Duration	+	+	+	+	+	+	+	+	+	+

Figure 1. A process simulation model and associated metrics

4.2 Step 2: Simulate the process

Monte Carlo simulation of the stochastic process model reveals a sample from the set of possible outcomes. Each outcome represents the effect of a particular sequence of task-level events upon the project-level metrics. The profile of outcomes represents the open-loop response of the project, since it is assumed in the model that participants do not respond to counteract accumulating delays or other adverse events which occur during the process. As it does not capture this active guidance towards acceptable outcomes, the model may exhibit greater variability than the project it is used to support.

Any process simulation can only represent a subset of the possible outcomes due to the large number of events affecting the process and the requirement for parsimony. For example, a model may only incorporate the possibility of failure modes which are considered most likely to occur, or those which cannot be easily absorbed by the project. Most component design processes comprise a number of high-level iterations to refine multiple design objectives, each through a well-defined framework of lower-level tasks. Although the task framework can usually be modelled, it is not possible to predict the order of addressing the objectives and the time expended on each high-level iteration using a task network model, because these decisions are made in-situ by considering the current state of the design and of the project. This type of high-level design iteration must therefore be ‘unrolled’ into a planned process involving distinct, increasingly detailed applications of the task frameworks.

As any model-based approach can only consider possibilities which are represented in the model, if unanticipated events do occur guidance will be invalidated. For example, the fidelity of a model incorporating unrolled iterations is contingent upon the planned sequence occurring in practice. The simulation model is therefore a form of plan. In common with other plans it should be optimistic in outlook; and re-planning will likely be necessary to account for unexpected adverse events. Re-planning is discussed further in Section 4.7.

4.3 Step 3: Select acceptable outcomes

To choose a plan of work the set of acceptable processes must be identified from the profile revealed through simulation. The definition of acceptability can encompass multiple criteria. For example, as discussed above it is usually necessary to meet a cost accumulation profile, deliver intermediate project milestones on time and complete all work by a certain date. The method requires these performance-level success criteria to be codified as constraints on the values of the metrics derived through simulation. In this case, meeting the cost accumulation criteria may be modelled using multiple constraints, each requiring the *total cost* metric to be below a threshold on a given date. Similarly, milestone constraints may be incorporated by requiring certain tasks to be completed, *i.e.*, their outputs delivered, in advance of the milestone dates.

A *process selector* is used to identify the set of processes which meet or exceed all acceptability criteria. The Process Selector as introduced in this paper is a new concept based on the Engineering Selector discussed by Ashby et al. [17]. Process selectors consist of a number of stages, each of which represents a filter that passes only those processes which satisfy a single constraint. The sub-set of processes which meet all criteria may be identified by applying each selection stage in turn; this identifies the intersection between the sets of outcomes which satisfy individual constraints (Figure 2). Configuring and applying the process selector does not require an explicit understanding of the model or the circumstances under which criteria are met. This is a critical point; the *simulation-and-selection methodology* introduced in this paper provides an intuitive approach to identify acceptable means of reaching the desired goals, even if the plan contains too many variables for suitable schedules to be identified by direct inspection. The selector thus allows human planners to overlay high-level project objectives onto the constraints on project execution which arise from the interactions between technical design activities, without requiring the planner to have a detailed understanding of the activity network.

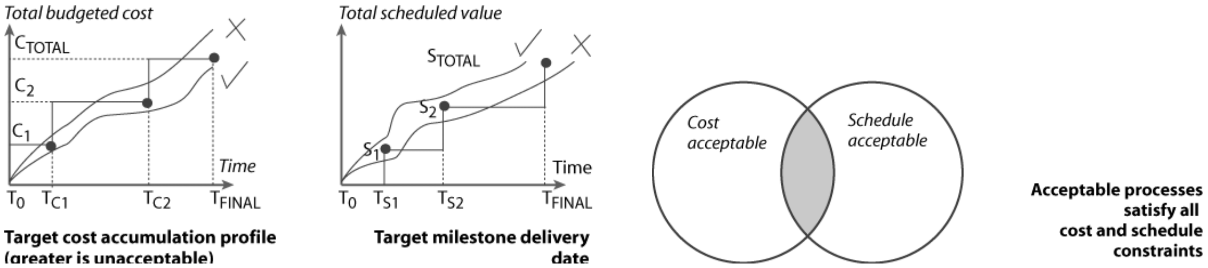


Figure 2. A selector identifies the set of outcomes which meet all acceptability constraints

4.4 Step 4: Resolve conflicts

It may occur that no acceptable processes can be immediately identified using the selector, because one or more constraint-satisfying sets are empty or do not intersect. This indicates a conflict between individual project targets or between one or more targets and the plan of work. For example, the sum of desired durations for each task might exceed the permissible total, given the resource constraints and any possibilities for concurrency which arise from the project structure.

Prior to generating a schedule, any conflicts must be resolved by relaxing the constraints of the simulation model and/or the selection stages which represent programme targets. In this example, this could be achieved by some combination of: reducing the planned duration of individual tasks; reducing the number of planned convergence/refinement cycles; increasing resourcing levels; or removing ‘non-critical’ tasks altogether. In the mostly non-concurrent process observed during the case study, it is possible to resolve conflicts simply by inspecting the model to identify tasks whose duration might be reduced. Additional guidance would be required where planning is based on a large model incorporating significant concurrency and/or many possibilities for concurrent rework (such that the critical path cannot be easily identified) and/or many project success criteria (such that the effect of a proposed resolution on all the criteria cannot be easily seen). Opportunities for further work to provide such guidance and reduce the frequency with which conflict resolution is required are discussed in Section 6.

4.5 Step 5: Identify schedule

Application of the process selector results in a sample from the set of possible processes which satisfy the stage constraints. The method then requires that a single process is then chosen from this sample, rendered as a Gantt chart and used as the plan of work. This schedule provides a decomposition of the process into individual task durations which, if achieved, would satisfy the performance-level targets. The approach therefore converts performance-level targets into a detailed, incremental checklist of plan-level sub-goals described in terms of engineering activities. The schedule may then be used to support progress monitoring and assist in guiding the project towards a satisfactory outcome.

The sample revealed by the selector may comprise multiple processes which indicate alternative acceptable routes. (To illustrate, consider a very simple model comprising one task with duration of either one or two days and which is attempted either once or twice. In this case, two alternative processes can result in a total duration of two days). To identify the most effective schedule from the sample of acceptable outcomes, a simple heuristic is used which aims to minimise the likelihood that re-planning will be required, i.e. to minimise the schedule's volatility with respect to delays in individual tasks. This is achieved by identifying the single simulation outcome for which the total scheduled duration risk is most evenly distributed amongst its constituent tasks such that the likelihood of any one task over-running is minimised. To achieve this, the n^{th} scheduled task's duration risk is defined as the likelihood that that task's actual duration will exceed its scheduled duration, which may be calculated from the task's duration probability density function *f(t)* as shown in Equation 1. The least volatile schedule in a given set can then be expressed as the one that minimises the sum of squared task duration risks, which is defined in Equation 2. This volatility metric is arranged to penalise schedules in which risk is concentrated in a small number of tasks.

$$\chi_n = 1 - \int_{t=0}^{T} f(t).dt \tag{1}$$

$$\chi^2_{TOTAL} = \sum_{n=0}^{N} \chi^2_n \tag{2}$$

4.6 Step 6: Monitor progress and re-schedule

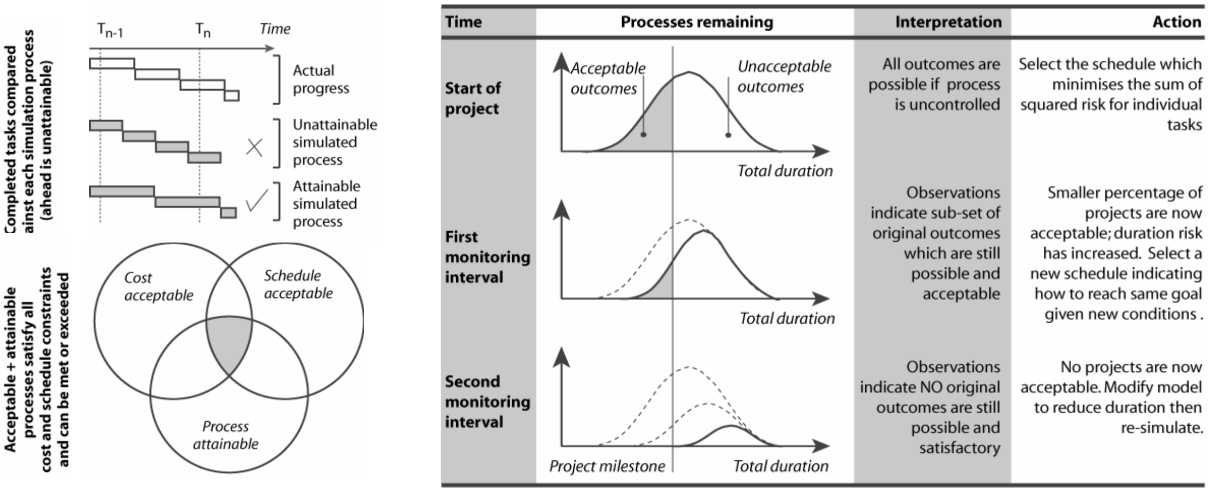
We assume that schedules may provide continuous guidance but that progress is monitored at discrete intervals. This reflects the practice of regular project review meetings observed during the case study. At the outset of the project, the schedule resulting from Step 5 provides a detailed Gantt chart indicating which activities should be complete by the end of the first monitoring period. However, the Gantt chart is both an imperfect prediction and a non-contingent representation. It can therefore be expected that reality will quickly deviate from the detail of this schedule, and that when the first monitoring interval is complete the schedule for future intervals will no longer be valid. When this occurs, a revised schedule may be generated by constructing additional selection stages which represent the estimated state of the project at the current time. These stages must select those processes which are equally- or less complete than the estimated state at the current time. This may be achieved using any combination of plan- and performance-level metrics:

- **Plan-level metrics** may be incorporated by creating a new selection stage that selects only those processes where all presently-uncompleted tasks have not been completed at the current date. This concept is illustrated graphically in Figure 3 (left).
- **Performance-level metrics** which are incorporated in the simulation model as discussed in Section 4.1 may also be used to estimate the project state. For each observation, a new selection stage must be created to select only those processes for which the metric lies in the estimated range at the current date. For example, to estimate the current state given the observation that 'technical risk' is between 40% and 60%, a stage would be created to select only those processes for which that metric lies within the observed range at the current date.

After re-applying the selector, the remaining sub-set contains processes which are both acceptable *and still attainable* following any adverse events which have already occurred. The size of this set relative to the total number of simulation runs represents the risk of not meeting all acceptability constraints, given the planned activities and the current state of the project. In other words, high schedule risk indicates a high likelihood that the remaining work will not be delivered according to specified milestones, even with rescheduling. The schedule risk measure helps highlight the trade-off between technical and project objectives – as the project becomes progressively more delayed, increasing schedule risk highlights the likelihood of problems arising from ‘shoehorning’ same design process into less time. The rate at which schedule risk increases with each re-schedule provides an up-front indication of when re-planning will become necessary. This is similar to buffer monitoring in critical chain ([21]; Section 2) but additionally accounts for the possibility of iteration and re-scheduling.

4.7 Step 7: Re-plan

In the context of our method, re-planning refers to the modification of the simulation model and/or the selection stages representing project acceptability constraints. Re-planning is necessary when the project diverges from the plan sufficiently that no acceptable and attainable processes can be immediately identified using the process selector. As indicated in Figure 3 (right), this may follow an accumulation of delays whose possibility was incorporated when the process simulation model was developed – for instance, as uncertain durations of tasks in the model or as the possibility of evaluation tasks revealing unplanned rework. It could also be caused by events whose possibility was not anticipated and/or not incorporated in the simulation. Re-planning may also be necessary if activities which were not considered during planning are required during the project, or if activities must be re-sequenced for any reason. Regardless of origin, all conflicts must be resolved using the procedure discussed in Step 4 above.



Time	Processes remaining	Interpretation	Action
Start of project		All outcomes are possible if process is uncontrolled	Select the schedule which minimises the sum of squared risk for individual tasks
First monitoring interval		Observations indicate sub-set of original outcomes which are still possible and acceptable	Smaller percentage of projects are now acceptable; duration risk has increased. Select a new schedule indicating how to reach same goal given new conditions .
Second monitoring interval		Observations indicate NO original outcomes are still possible and satisfactory	No projects are now acceptable. Modify model to reduce duration then re-simulate.

Figure 3. Re-planning is necessary when no acceptable processes are acceptable and still attainable

5 DISCUSSION

To recap, the approach described above was developed to meet requirements identified through an extended industry case study. Although it therefore has an empirical grounding, it has not yet been possible to undertake a formal evaluation in an industry setting. The paper is thus presented as a theoretical contribution to the ongoing discussion regarding how design planning can be supported through process modelling.

The approach presented in this paper can be described as supporting planning through two interlaced strategies. Firstly, our approach provides a way for planners to express not a single schedule as shown in a Gantt chart, but a space of possible plans – as a simulation model which encompasses the possibility of adverse events such as task delays and rework. Such models can represent a wider space of possibilities than the Gantt chart, and thus allow planners to more accurately express their reasoning about risk and uncertainty in projects alongside their expectations of what would happen if these uncertainties were manifested – for instance, which tasks would be revisited if a certain rework scenario occurred. However, in comparison with Gantt charts these models are biased towards description – capturing what *could* happen – rather than prescription - what *should* happen, and when. The second strategy in our approach is thus to ‘collapse’ the multiple possibilities expressed by the simulation model into a simple approximation appropriate to current circumstances and requirements – a Gantt chart suitable for prescriptive planning. From this point of view re-scheduling is made straightforward, requiring application of the same procedure to identify a different approximation which better reflects a change in circumstances – in other words, by re-setting the Gantt chart to a new baseline. Unlike conventional methods, this approach requires very little effort to re-schedule even if the new schedule involves a significantly different task sequence, as often occurs following rework in engineering projects. This should be true for any case where the planner was able to anticipate the risk of project delay and incorporate it into the model from which schedules are derived.

A number of opportunities for further work have arisen from the research presented in this paper:

1. **Resolving conflicts.** Section 4.4 indicated the need to identify ways to reduce the expected duration of a given process network. This is known as "crashing" in the project management literature. For our approach to be applied in practice, methods are needed to assist in the identification of crashing strategies.
2. **Selecting schedules.** There is a related need to investigate alternative ways for selecting the 'best' schedule from the set of acceptable outcomes identified through simulation. The simple heuristic proposed in Section 4.5 should provide acceptable results if the subset of acceptable outcomes is clustered such that a small deviation from one satisfactory plan usually leads to another which is not significantly less acceptable. However, if the set includes significantly different process trajectories, and if similar trajectories can be found both inside and outside the set, it may be important to identify a schedule that is robust to the risks of delay which are captured as uncertainties in the simulation model. Such robust schedules could reduce the risk of needing to crash a project. Another approach which could potentially be used to incorporate uncertainty in choosing the best schedule from the set of selector results is the Benefit Asset Pricing Model proposed by Schabacker [20]. This method uses the theory of financial instruments to evaluate the total 'benefit yield' of projects under uncertainty.
3. **Integration with critical chain.** A possible extension to the approach would be to automatically incorporate buffers within schedules generated using the selector, thereby allowing managers to use critical chain techniques [21] to manage delays in these schedules. Such an approach would restrict the need for re-scheduling using the selector to cases of significant delay or unplanned rework. The method would then more effectively complement existing tools and ways of working with plans and schedules, and could thus be more easily accepted in practice.

6 CONCLUSIONS

Delivering engineering projects on time and budget is critical to companies' success – and the effective management of design schedules is therefore of major concern in industry. Based on insights gained through a case study of an aero-engine component design process and observations of the planning practice associated with this process, this paper has introduced an approach which shows how a task network simulation model could be applied to support design process management by increasing the fidelity of plans and reducing the cost of re-planning. The approach provides a way to reconcile a description of the technical design activities and information flows between them with project targets such as milestone delivery dates, and shows how monitoring and re-planning can be supported using the non-ideal metrics which are available to monitor processes in practice. More generally, our methodology also demonstrates – in a theoretical sense – one way in which process simulation models could support planning in a manner which recognises their limited fidelity alongside the complexity and uncertainty of design practice. By highlighting the need to explore how design process simulation models can be used effectively despite their known limitations, this insight has potential to enhance the utility of process simulation-based methods to improve design processes in practice.

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