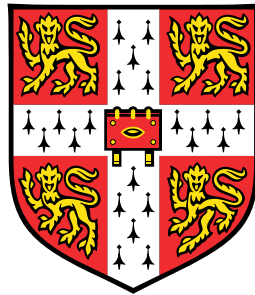# Modelling Resources in Engineering Design Processes

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This dissertation is submitted for the degree of
Doctor of Philosophy

Hughes Hall   November 2017

- To my family -

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification at the University of Cambridge, or any other university. Unless otherwise stated in the text, this dissertation is my own work and does not include the outcome of work done in collaboration. This dissertation contains fewer than 65,000 words including bibliography, footnotes, tables and equations and has 75 figures.

Some of the work contained in this dissertation has been published presented as below.

Xin Chen H. L., Clarkson P.J., Sommer A.F. (2015). A study to identify engineering design resources in complex product development projects. Proceedings of the 20th International Conference on Engineering Design, Milan, Italy.

Xin Chen H.L., Moullec M.L., Clarkson P.J. (2016a). A method to improve design process resource management. Proceedings of the Design Conference, Dubrovnik, Croatia.

Xin Chen H.L., Moullec M.L., Ball N., Clarkson P.J. (2016b). Improving design resource management using Bayesian network embedded in task network method. Proceedings of ASME Design Engineering Technical Conference, Charlotte, USA.

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Abstract

The planning and scheduling of appropriate resources is essential in engineering design for delivering quality products on time, within cost and at acceptable risk. There is an inherent complexity in deciding what resources should perform which tasks taking into account their effectiveness towards completing the task, whilst adjusting to their availabilities. The right resources must be applied to the right tasks in the correct order. In this context, process modelling and simulation could aid in resource management decision making. However, most approaches define resources as elements needed to perform the activities without defining their characteristics, or use a single classification such as human designers. Other resources such as computational and testing resources, amongst others have been overlooked during process planning stages.

In order to achieve this, literature and empirical investigations were conducted. Firstly, literature investigations focused on what elements have been considered design resources by current modelling approaches. Secondly, empirical studies characterised key design resources, which included designers, computational, testing and prototyping resources. The findings advocated for an approach that allows allocation flexibility to balance different resource instances within the process. In addition, capabilities to diagnose the impact of attaining specific performance to search for a preferred resource allocation were also required.

Therefore, the thesis presents a new method to model different resource types with their attributes and studies the impact of using different instances of those resources by simulating the model and analysing the results. The method, which extends a task network model, Applied Signposting Model (ASM), with Bayesian Networks (BN), allows testing the influence of using different resources combinations on process performance. The model uses BN within each task to model different instances of resources that carries out the design activities (computational, designers and testing) along with its configurable attributes (time, risk, learning curve etc.), and tasks requirements.

The model was embedded in an approach and was evaluated by applying it to two aerospace case studies. The results identified insights to improve process performance such as the best performing resource combinations, resource utilisation, resource sensitive activities, the impact of different variables, and the probability of reaching set performance targets by the different resource instances.

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List of abbreviations

ABM	Agent-Based Modelling
ABPC	Agent Based Process Coordination
AND	Agent Network Decision
ASM	Applied Signposting Model
APDP	Adaptive PD Process
BN	Bayesian Network
CAD	Computer Aided Design
CAM	Cambridge Advanced Modeller
CPM	Critical Path Method
CPT	Conditional Probability Table
DBIS	Department for Business Innovation and Skills
DMM	Domain-Mapping Matrices
DRM	Design Research Methodology
DS	Descriptive Study (it can be I or II)
DSM	Design Structure Matrix
EDC	Cambridge Engineering Design Centre
FTA	Fault Tree Analysis
GERT	Graphical Evaluation and Review Technique
HPC	High Performance Computing
IDEF	Integrated DEFinition for Process Description Capture Method
IPT	Integrated Product Team
MDM/MDDSM	Multiple Domain Matrices
RC	Research Clarification
RCPSP	Resources Constrained Project Scheduling Problem
RMM	Resource Management Method
OR	Operations Research
PD	Product Development
PDM	Precedence Diagramming Method
PERT	Program (or Project) Evaluation and Review Technique
PMI	Project Management Institute
PS	Prescriptive Study
SD	System Dynamics
UoB	Units of Behaviour
VDT	Virtual Design Team

1 Introduction

Product development (PD) projects are continuously challenged by the rising complexity of new products, tight competition, and specific customer expectations that demand better processes with shortened delivery times and lower budget. Both academia and industry conclude that reducing time to market is a determinant point for product success (Jarrett *et al.* 2002). Moreover, PD planning decisions also have a key role in the overall cost of the project, since the decisions taken can also set approximately 90% of the final product's costs (Ehrlenspiel *et al.* 2007, p.13).

In this competitive environment, PD projects and their underlying design processes call for the integration and interaction of thousands of designers and multiple resources within a careful designed plan (Wynn 2007). As a matter of fact, a complex product like the Boeing 777 involved 17,000 people for more than four and a half years (Ulrich and Eppinger 2011). Design processes refer to the set of activities within PD, focused on bringing customer requirements to a product's physical form to be ready for production (Ulrich and Eppinger 2011; Reinertsen 1999; Pahl *et al.* 2007). However, the scale and complexity of design processes pose many challenges (Kreimeyer and Lindemann 2011). They are highly uncertain: multiple and unexpected changes yield in iterations and rework that cannot be anticipated at the beginning of a project (Eckert and Clarkson 2010). These uncertainties are the result of the inherent innovativeness of PD and currently enhanced by the aforementioned trends and the inefficient management of available resources.

As an example, in 2003 Boeing announced that the 787 model would enter commercial service in five years' time with a development cost of 10 to 15 billion dollars. However,

the use of composite materials and the outsource of segments in the development process resulted in a project that was substantially more complex than initially predicted. More than three years of delay and 17 billion dollars over the budget, the Boeing 787 entered commercial service in September 2011 (Seattle Times 2011). Senior management had failed to adequately assess the effects of outsourcing and the challenge of integrating all resources in the new context. Hence, a major part of the project's cost and schedule overrun was a direct result of decisions made during the planning, coordination, and estimation of project resources in the newly complex system. The problems were so extensive that Boeing had to buy out some of the partners and was required to compensate customers due to delivery delays. As in December 2016, according to Bloomberg (2016): *"Boeing has maintained that it expects the 787 to recoup costs and turn a slight profit under current accounting projections, but has not yet shown any profits"*. Similar challenges are faced by medium and small companies that are highly constrained by both the cost and time to deliver the project. Yan *et al.* (2007) discussed that the growing complexities within PD processes are amplified for SMEs because they are expected to instantly introduce new products. SMEs are key to the UK economy since they account for 99.3% of all private businesses at the start of 2015 (DBIS 2015).

During the design process, crucial managerial decisions are essential to evolve the product to its final stage (Ullman 2009). However, trade-offs between the three major PD performance dimensions (Cohen *et al.* 1996), i.e. time, cost and product quality, can pose decision dilemmas. In this context, decision makers must agree on how much effort and commitment are placed in the project and define the resources needed to achieve the goals (Ullman 2001; Krishnan and Ulrich 2001). Appropriate resources are not only required to produce a quality product, but also have a significant impact on both project cost and duration. The range of resources to manage could include traditional designers to complex computational simulation engines, testing resources, materials, etc. More often than not, these resources are limited, which makes their allocation to complete each project an important decision making point (PMI 2013). In this competing environment, it seems that a key factor to success is appropriate resource management: understanding, estimating, allocating, and scheduling resources.

Researchers have agreed on the importance of providing design practitioners appropriate methods and tools to support specific design process needs and improve PD (Clarkson and Eckert 2010; Eppinger *et al.* 1994; Browning and Ramasesh 2007; Browning and Eppinger 2002). Consequently, this thesis focuses on design process resource management, during process planning and execution, by developing a novel method that supports design resource planning, allocation and scheduling. This is done by predicting

and quantifying the impact of resource effectiveness on design process performance metrics such as time, cost and quality (see Chapter 4 for more detail explanation).

The remainder of this chapter introduces this thesis in seven sections: Section 1.1 positions the research into context; Section 1.2 explains the background and the motivation; Section 1.3 discusses the research objectives, hypothesis and research questions; Section 1.4 clarifies the research scope; Section 1.5 briefly introduces the methodology; Section 1.6 presents the structure of the thesis; and Section 1.7 summarises the chapter.

1.1 Research context

The current research has been conducted at the Cambridge Engineering Design Centre (EDC), where engineering design has been one of the main research topics since its inception. The group has conducted both theoretical and empirical research in close collaboration with organisations, hence at the forefront of current industry needs. As a result, multiple methods to support engineering design management have been developed focusing on PD and design process, including initial research on design resource management. This research builds on EDC research streams and aims to extend them by providing a synergistic knowledge contribution taking into account industry needs.

The project was conducted in collaboration with Rolls-Royce plc, with the objective of supporting their needs and improving their current practises. Rolls-Royce plc was deemed an appropriate fit due to the complex design processes the organisation presents and use of multiple design resources, both human and instrumental. The author had initial discussions with Rolls-Royce plc regarding topics of interest, which were clustered into specific research streams. They were ranked by level of relevance in academic and industry interest, and yield in management of design resources to be the chosen research topic. Additionally, the collaboration permitted the author to extract important insights from discussions with design practitioners and conduct empirical work within the organisation.

1.2 Background and motivation

The following sub-sections introduce the field of design processes, its characteristics and design resources before discussing the challenge of resource management.

1.2.1 PD and design processes

PD is one of the first stages of a product's lifecycle that starts when a market opportunity is identified until its production (Browning and Ramasesh 2007). Hammer (2001, p.52)

states that: *"A process is an organised group of related tasks that work together to create a result of value"*. Thus, PD processes depict the group of tasks that transforms needs into a technical and commercial solution (Smith and Morrow 1999). A successful PD project is not only assessed by the quality of the product but also the performance of the process, often measured in time to market and budget (O'Donovan *et al.* 2003). PD processes have significant differences compared to business processes. To allow creativity and innovation, PD processes must be able to constantly change based on the state of the project. Uncertainty, ambiguity, and risk are inherent in PD processes (Schrader *et al.* 1993; Pich *et al.* 2002). They are characterised with increased number of iterations, and manifold of interdependent activities executed as a multidisciplinary effort (Browning *et al.* 2006; Kline 1985).
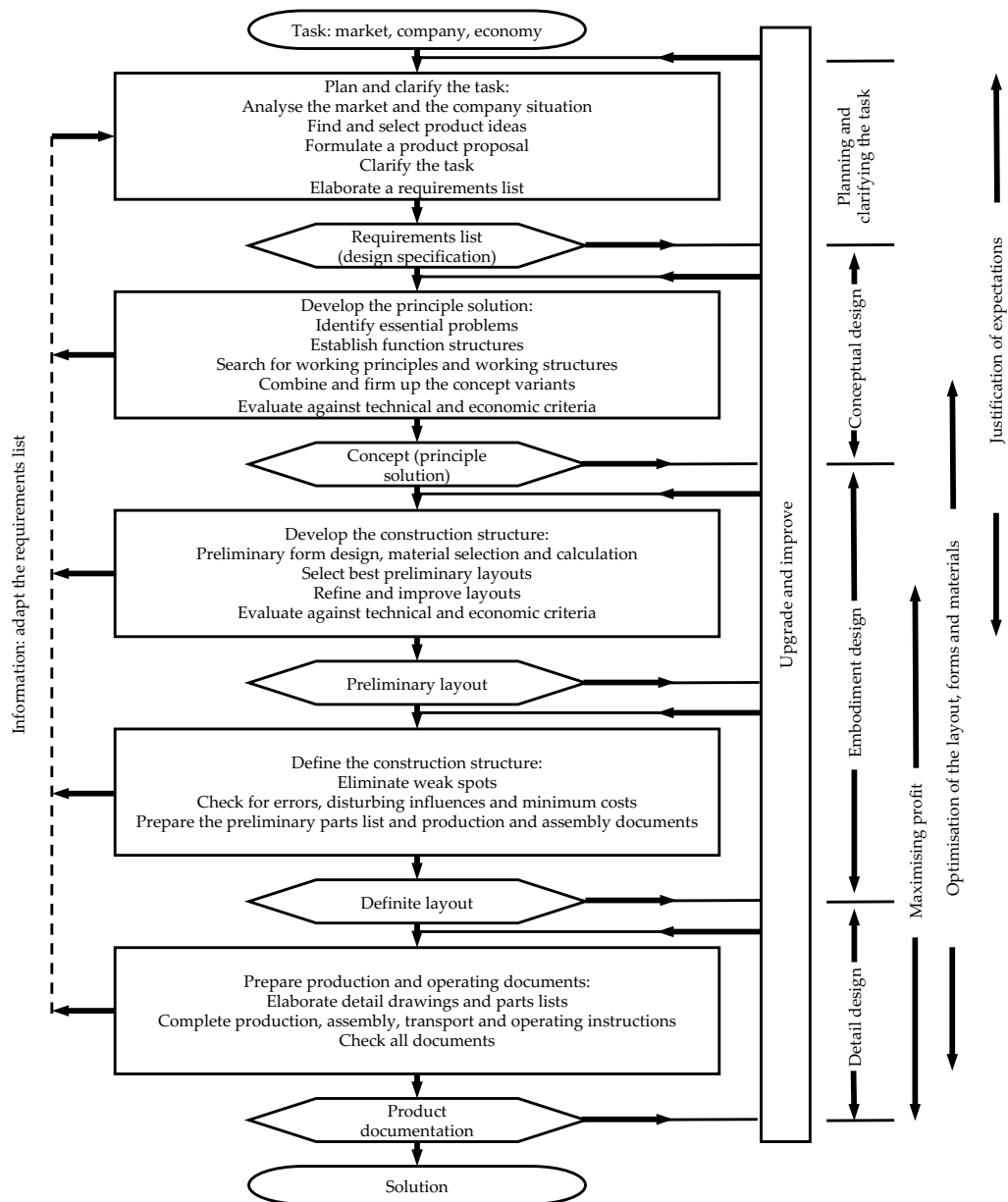
Figure 1. Model of the mechanical design process. Adapted from Pahl *et al.* (2007)

Design processes are part of PD (contextualised by Hales and Gooch 2004) and refer to the method by which new products are created (O'Donovan 2004). The work done during design activities can define as much as 80% of a product's functionality and cost (Eppinger *et al.* 1994). A generally accepted picture of design processes proposed by Pahl *et al.* (2007) subdivides design activities into four prescribed stages (Figure 1):

1) Planning and task clarification, in which market needs are transform into product requirements that could be later updated if new information arises;

2) Conceptual design, in which high level analyses are used to create and consider different variants of the desired product in order to choose one concept for further development;

3) Embodiment design, in which a definitive layout is formed after the selected concept is assessed on a technical and economical level through various preliminary layout candidates in terms of preliminary form design, material selection and calculations;

4) Detail design, in which product's dimensions, interfaces, properties etc. are ultimately specified for preliminary production in the form of detailed drawings, part lists, production, and assembly documents. Additionally, logistics and manufacturing instructions are generated. A final set of the product documentation summarises everything, marking the end product of the whole design process.

Planning engineering design processes poses challenges due to the inherent uncertainty that they attained (Eckert and Clarkson 2010). Earl *et al.* (2010) identified four different kind of uncertainties in design: uncertainty in the data, uncertainty in the description, known uncertainties and unknown uncertainties. Firstly, uncertainty in the data refers to completeness, accuracy, consistence and quality of recorded measurements. Secondly, uncertainty in the description are those that stem from ambiguity in product requirements or scope. Thirdly, known uncertainties denote the ones that can be anticipated and potentially solved based on past cases. Finally, unknown uncertainties or '*unks-unks*' are those that cannot be foreseen, and unmanageable until they became known (McManus and Hastings 2005). The presence of uncertainty creates a risk of not complying with planned estimations, resulting in an undesirable event or outcome (McMahon and Busby 2010). This includes risks that could impact on resource use, task durations, cost, and/or desired quality.

Another key element are iterations, which are inherent to complex design projects (Le *et al.* 2012). Due to their importance, iterations have been extensively studied in the field. Nukala (1995) described iteration as the repetition of activities to reach a goal. Cooper (1993) studied and developed methods to deal with a type of iteration that he referred as rework, which he had discovered to be the source of significant unexpected costs.

Frequently, rework is caused by activities starting with preliminary assumptions, failing to meet the desired standards or change of inputs due to rework from other activities (Cho and Eppinger 2005). Smith and Eppinger (1997a) stated that iterations are the repetition of design tasks triggered by the discovery of new information. This information could come from upstream activities modifying their outputs, coupled activities outputting new results, or downstream activities feeding data back due to errors discovered during validation activities (Smith and Eppinger 1997a). Researchers such as Smith and Eppinger (1997b) and Clausing (1994) have classified iterations as:

- Intentional or *creative iterations* are planned and purposely integrated in the design process to improve a solution and increase quality;
- Unintentional or *dysfunctional iterations* are unplanned and they are outcomes of a change in upstream inputs via internal or external causes. Rework falls into this category.

Inappropriate management of rework could heavily impact on time to market and budget expenditure, since rework accounts for most of PD projects duration and cost (Cooper 1993). In addition, late changes in a PD project can exponentially increase cost with each phase being ten times more expensive than the previous (Fricke *et al.* 2000). Therefore, a way to improve process performance is to reduce unintentional iterations that might result in reduction of duration and cost. This involves receiving information at the appropriate time and place, having activities sequenced effectively, getting resources when needed, providing robust requirements as quickly as possible, and minimising execution mistakes (Cho and Eppinger 2005). A comprehensive classification of different types of iterations can be found in Wynn *et al.* (2007).

1.2.2   Process performance metrics

In order to understand how resources can influence design project performance to deliver the desired product, performance metrics must be outlined. Established and often used metrics to evaluate design process performance are time, cost and quality (O'Donovan 2004; Clark and Fujimoto 1991; Griffin 1997). Out of the three, quality is more subjective and broad, but frequently referred to product quality. These three metrics usually exhibit a trade-off situation (Cohen *et al.* 1996) given the many external factors such as time requirements, resources and deadlines, that can constrain engineering design processes (O'Donovan *et al.* 2010). For example, if the deadline is shortened, in many instances cost increases to add additional resources to complete the same amount of work in less time. If a budget increase is not possible, the scope or quality might be affected as a result of attempting to deliver the product in time with the same budget.

Consequently, organisations are challenged to innovate in order to develop better products in less time at lower costs and higher quality (Eppinger *et al.* 1994).

1.2.3 The role of resources

In the broadest sense resources produce benefits that may include increased wealth, meeting needs, proper functioning of a system, or enhanced well-being (McConnell 2012). The Oxford dictionary defines resources as *"a stock or supply of money, materials, staff, and other assets that can be drawn on by a person or organization in order to function effectively"*. A key characteristic to keep in mind is that resources can be scarce and they should be managed efficiently (Mankiw 2008).

In an organisation, Hunt (1999) defines resources as tangible and intangible entities available to the firm with the end of producing a market offering that has some value. He classifies resources as financial (cash reserves, access to markets), physical (plant, raw materials, equipment), legal (trademark and licenses), human (skills and knowledge of the individual employees), organisational (controls, routines, cultures and competences), informational (knowledge about market segments, competitors, technology), and relational (relationship with competitors, suppliers, customers). Similarly, Caves (1980) defines resources as tangible and intangible assets that are semi-permanently part of an organisation. Examples are brand names, knowledge of technology, skilled personnel, trade contacts, machinery, efficient procedures, capital, etc. Barney (1991, 1992, 1995) argues that resources are controlled by the firm with the aim of implementing strategies to improve its efficiency and effectiveness. In order words, increase performance and obtain a competitive advantage.

Projects are undertaken by organisations with the objective of producing products or services. They are unique endeavours working towards established goals in a specified time, budget and resources (PMI 2013; Verma and Boyer 2010). PD and manufacturing processes are only possible with the use of resources (Ehrlenspiel *et al.* 2007). For instance, the development of automobiles requires effort, raw material, production equipment and well qualified personnel. In PD, Ulrich and Eppinger (2011) have addressed that primary resources to manage are effort of staff (man-hours), and other resources such as model shop facilities, rapid prototyping equipment, pilot productions lines, testing facilities, and so on. At the project level, the challenge is to estimate and decide the amount of resources needed. PMI (2013) distinguishes between project inputs and project resources, in which resources can be accounted as the type and quantities of material, people, equipment, or supplies required to perform each activity. Thus, information or data which are produced by precedent activities or external sources can be viewed as

inputs within a model. For example, Clarkson and Hamilton (2000) uses the term *parameters* to define information regarding a product's physical structure and performance that are input and outputs of design activities. The author also differentiates project resources from organisation resources by excluding the ones that are not involved directly in the development or accomplishment of the project. Hence, resources such as overhead (e.g., cleaning staff, rent of offices, etc.) are not accounted as project resources.

As design processes are part of PD projects, applying the same rationale as for project resources, design resources are those involved in design activities. Other resources such as manufacturing equipment or materials are usually not design resources, but still part of PD resources. Designers, or their time and effort, are resources that drive the design exercise and they have been a significant focus of research by the design community. Examples are Cross (2000), Ahmed *et al.* (2000), Crilly (2015) and Boyle *et al.* (2012), that have analysed how designers think and design. However, other key design resources, for instance computational resources, testing and prototyping resources, have been studied in a lesser degree. Computational resources offer crucial support to designers (Andreasen 1994) since a large part of designer's work is elicited through Computer Aided Design (CAD) models. Such models are often used to run simulations and analyses to advance the design process (Maier 2017). Innovations in this front have been key to increase possible simulation analyses without having to go through expensive experiment settings and reduce time to market and cost expenditure (Maier 2017). The value of simulation engines as computational resources has been recognised since the 1960's when Boeing Aircraft started construction of the first simulation engine (Blank 1984). Subsequently, numerous machines have been proposed and built. Unavoidably, real testing experiments must be conducted further down the design process. Other equipment, materials, and elements involved in the design process could also count as design resources. However, there is a lack of formal classifications of different type of resources in design literature due to the broad definition of the term. Resources have mentioned explicitly or implicitly throughout the literature as elements assumed to be known by the reader but have not been formally categorised. A more comprehensive study on elements considered as design resources is presented in Chapter 2.

Resources have multiple characteristics or attributes that can shape design processes during projects (PMI 2013). The amount and effectiveness of resources limit the rate at which different development activities are performed (Ford and Sterman 1998). As an example of effectiveness, Christiaans (1992) discovered that a designer's problem space is thought to increase with experience. Gunther and Ehrlenspiel (1997) found that novice designers spent more time than experienced designers when clarifying the task. Boyle *et al.* (2012) also concluded on the positive impact of expertise on decision making. These

studies illustrate that the difference in effectiveness between novices and experts could impact on performance output. Moreover, depending on which designer is allocated to which activity, the design process will behave differently (Crowder *et al.* 2012). Thereby, designers with different competences performing the same task could have a different outcome in process performance (Crowder *et al.* 2012). In other words, the time and quality output of a novice designer performing an activity will be different to an expert's. Additionally, the design process could be affected if the expert is no longer available for other activities. Special mention should be given to the availability of limited human resources, and other resources by extension, since their core competencies or skill sets can create competition to acquire them (PMI 2013).

The aim of process management is to deliver a more effective and efficient process that delivers a product with the required quality, in time and on budget. Thus, to improve the way in which projects are planned and scheduled, it is necessary to better understand how different resource attributes are related to their effectiveness in undertaking activities and influencing project performance. Further exploration of design resources and their attributes can be found in Chapters 2 and 4.

To summarise, design resources have a crucial influence on complex design process since:

1) Resources are required to undertake the design process;
2) Resources are limited and their effectiveness impact process performance;
3) Resource management is complex due to the multiple types of resources (i.e., human designers, effort, simulation engines, etc.) and their attributes.

1.2.4 The challenge of managing design resources

Resource management is concerned with the estimation, allocation and scheduling of resources to the process.
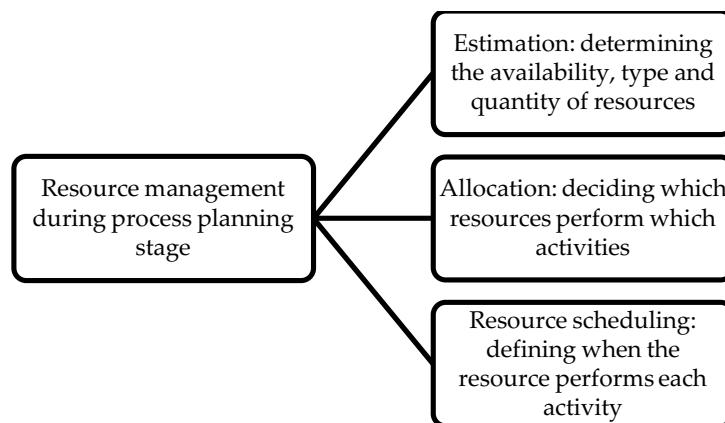
Figure 2. Resource management during planning: estimating, allocating and scheduling

Estimating resources involves determining the availability, type and quantities required –major factors in planning the project's cost, schedule, risks, and quality amongst other areas (PMI 2013). Resource allocation consists of deciding which resources will perform which activities, and scheduling is focused on defining when each activity should be performed while allocating scarce resources (Herroelen *et al.* 1998).

Resource management is continuously challenged by the inherent complexity and uncertainty of design processes (Eckert and Clarkson 2010) and the necessity of utilising the appropriate resource for each task (PMI 2013), while balancing their availability, effectiveness (Ford and Sterman 1998) and cost (PMI 2013). During allocation, quantifying the performance impact of instances of the same resource type (e.g., choosing between intermediate or expert designer) performing the same activity could help decision makers. Furthermore, as different type of resources are involved in design processes (i.e., effort, computational), their management requires different strategies (Chapter 4).

Cost and schedule overrun is common in a great number of large and complex PD projects (Lyneis *et al.* 2001). Morris and Hough (1987; p.7) reviewed 3500 projects and identified that overruns between 40 and 200 percent were usual. Another survey by Roberts (1992) of corporate R&D projects indicated that more than half of them went over the budget and time objectives. The Defense Systems Management College (Virginia) conducted a survey that specified that 45 and 63 percent was the average cost and schedule overrun respectively for a standard major engineering system and manufacturing development project (Kausal 1996). Reichelt and Lyneis (1999) examined a sample of ten projects to conclude that average budget overrun for them was 86 percent (66 percent not accounting for the cost of added work), and schedule overrun was 55 percent. The number of people involved and the duration of the project can roughly determine PD project cost (Ulrich and Eppinger 2011). Thus, during schedule overruns, not only the delivery time of the product is delayed, but also the effort or time needed from designers and other resources is extended. However, it is paramount for organisations to lower down time and cost to stay competitive.

Therefore, resource management could be supported by existing process management methods that are used in day-to-day basis, and might be benefited from an approach that quantifies the use of resources and their effectiveness on process performance.

1.3 Research objective, hypothesis and questions

The previous sections argued that design resources have significant impact on process performance. Effective resource management is cumbersome in terms of estimating, allocating and scheduling efficient resources in a cost effective manner. Therefore, the general objective of this research is to:

General objective: *Improve design process management by improving design resource management.*

As with any research work, a meaningful hypothesis can help to guide the project on the right direction. Keeping in mind the need to address both industry and academia, as discussed in Section 1.1, the following preliminary hypothesis was conceived:

Hypothesis: *An efficient approach (support method) will provide insights on resource management for decision making.*

The principal research question for this project can be derived from the objective and research hypothesis:

Principal research question RQ0: *How can resource management be utilised to improve planning and execution of complex design processes?*

This research addresses RQ0 by first investigating the current understanding of design process resources, their management and respective support methods, and subsequently developing and evaluating a comprehensive method for resource management based on the initially established knowledge. Therefore, two more granular questions were derived from the principal research question to guide the literature review on design resources and existing support methods presented in Chapter 2.

RQ1: *What are the different types of design resources and the current methods to support their management?*

RQ2: *What key attributes can describe the impact of resources on process performance?*

RQ1 explores design resources and how they are currently managed to understand the meaning of design resources in literature and industry, their relevant properties, and capabilities, and also the potential deficiencies of current approaches. Both RQ1 and RQ2 can be researched from an academic perspective since most of design academic research where developed with industry applicability in mind. Additionally, investigating design resources in industry will help to better comprehend their relevant attributes that impact process performance. It is expected the answers of RQ1 and RQ2 will unveil further questions after a more comprehensive understanding of the field is achieved.

1.4 Research scope

In order to set the scope of this research, the author will focus on resources in engineering design processes, excluding other areas of PD. The objective of the design process is to create a *recipe* for the development of an artefact (Reinertsen 1999; Pahl *et al.* 2007), which comprises physical products of different breakdown levels, i.e. small parts, components, sub-systems or the entire product itself. Section 1.2.1 emphasises on the difference between design processes and PD, which design processes are part of. PD also has links to the overall business and market environment and involves more organisational functions besides research and development, and engineering. Nonetheless, they will not be considered in greater detail, as they are not the primary focus in this research. At this point, the author has loosely defined design resources as those that are involved in the design activities or can constrain the design process (Section 1.2.3). The definition will be updated as more key characteristics of design processes and design resources emerge.

This thesis aims to improve design process performance by helping to manage the use of resources more efficiently and effectively. As mentioned beforehand, current methods to manage resources could provide key insights and it has been set as the initial point of reference. Resources can affect every major design process performance metric, thus the improvement can be considered in reduction of costs, time or increase in quality. However, this project focuses on examining the impact of resources on duration and costs. Although the relationship between resources and resulting product quality is highly relevant and an interesting research area, it exceeds the research scope. The complexity of the correlation between resources and product quality requires an entire project by itself to be researched comprehensively. Furthermore, the nature of Rolls-Royce plc guarantees that developed products have a standard quality that cannot be compromised, thus a sensible assumption is that activities will be iterated until the desired product quality is achieved.

It is important to remark that fundamental sequencing of activities is not studied exhaustively in this thesis since it has already been researched extensively (e.g.,, Ahmadi *et al.* 2001; Browning and Eppinger 2002; Yassine *et al.* 2003). Thus, the emphasis is on relatively fixed process architectures that are limited by human and instrumental resources. This is often the case of *evolutionary* (also *adaptive* or *variant*) design processes, which constitute the majority of product designs (Bucciarelli 1994; Eppinger *et al.* 1994), and likely to be carried out multiple times in a similar manner.

The decision of the granularity for the research and support method is important (Maier 2017). Since design resources can affect both the activity and the entire process, this study

should aim to investigate resource impact on both activity and whole process performance level.

Finally, this research aims to provide benefit to its direct stakeholders, consisting of design teams, their management and engineering design researchers.

1.5 Design Research Methodology

Due to the specific nature of design research that involves studies within organisations, only a few methodologies have been developed. One of the most successful is the Design Research Methodology (DRM), which was developed in Cambridge by Blessing & Chakrabarti in conjunction with Professor Ken Wallace in an effort to aid design process research. The full work was compiled into a textbook by Blessing and Chakrabarti (2009). DRM offers an iterative methodology that provides guidance throughout the different stages in design research. Other methodologies focusing on design include Duffy and O'Donnell (1999)'s approach and Eckert *et al.* (2003)'s Eightfold path. DRM provides more detailed guidance compared to the methodology by Duffy and O'Donnell (1999), which is intended to be more flexible. In addition, the current research aims to complete one case study, ruling out the Eightfold path methodology that aids research with multiple case studies.

Basic means	Stage	Main outcome
- Literature - Analysis	**Research clarification**	- Identify problem - Understanding key issues
- Empirical data - Literature - Experimentation - Analysis	**Descriptive study I**	- Understanding design resources and its attributes
- Assumption - Experience - Synthesis	**Prescriptive study**	- Theoretical support
- Empirical data - Analysis	**Descriptive study II**	- Initial evaluation

Figure 3. DRM. Adapted from Blessing and Chakrabarti (2009)

As it is shown in Figure 3, DRM is iterative through the different stages, revisiting previous states as more information becomes available.

In DRM, *Research Clarification* (RC) is concerned with defining research goals and scope of the following stages through field exploration and understanding industry issues. During *Descriptive Study I* (DS-I), literature review will help to comprehend the research problem to identify the key factors that can improve the design practice. At the same time, elements such the success criteria will be defined. The core of *Prescriptive Study* (PS) is to develop a support method that improves the existing situation. *Descriptive Study II* (DS-II) will evaluate the support method against the context of industry applicability and academic success criteria.

1.6 Thesis structure

This thesis is presented in nine chapters. The structure broadly follows the chronological development of the topics covered. The simplified thesis structure is also depicted in Figure 4, with reference to the main stages of the research methodology (discussed in more detail in Chapter 3).

1) Introduction: Introduces research motivation, background of the field, main research questions, overall methodology and thesis structure.

2) Literature review: Reviews literature of engineering design, design process modelling, resources in design, and resources in related fields to provide a theoretical background and overview of the state of the art.

3) Methodology: Outlines the chosen research methodology, illustrates the followed research map, and refines the initial research questions based on previous chapters.

4) Exploratory case study: Provides empirical insights from a preliminary case study in Rolls-Royce plc, which sheds light into what elements are considered design resources in industry and their attributes.

5) Requirements for resource management model and prototype model: Comprises the set of requirements derived from the gained understanding from previous chapters. Presents an initial investigation of a support method (prototype model) trying to address the functional requirements, which helps to draw preliminary results and shortcomings to be addressed.

6) Design resource management method: Develops a support method to improve resource management in design process by addressing all the functional requirements from Chapter 5.

7) Application of support method: Embeds the method in an applicable approach and applies it on two real case studies from Rolls-Royce plc as a basis to evaluate the approach. Derives recommendations for management based on insights from the case studies.

8) Discussion and evaluation: Reviews the main findings and discusses their implication and contribution to the field, both in terms of research and practice. Evaluates the research through the application of the approach on the two cases studies. Discusses the research limitations, and outlines the potential for future work.

9) Conclusion: Revisits the main research questions and assesses them against the research outcome. Summarises the key findings and contributions.
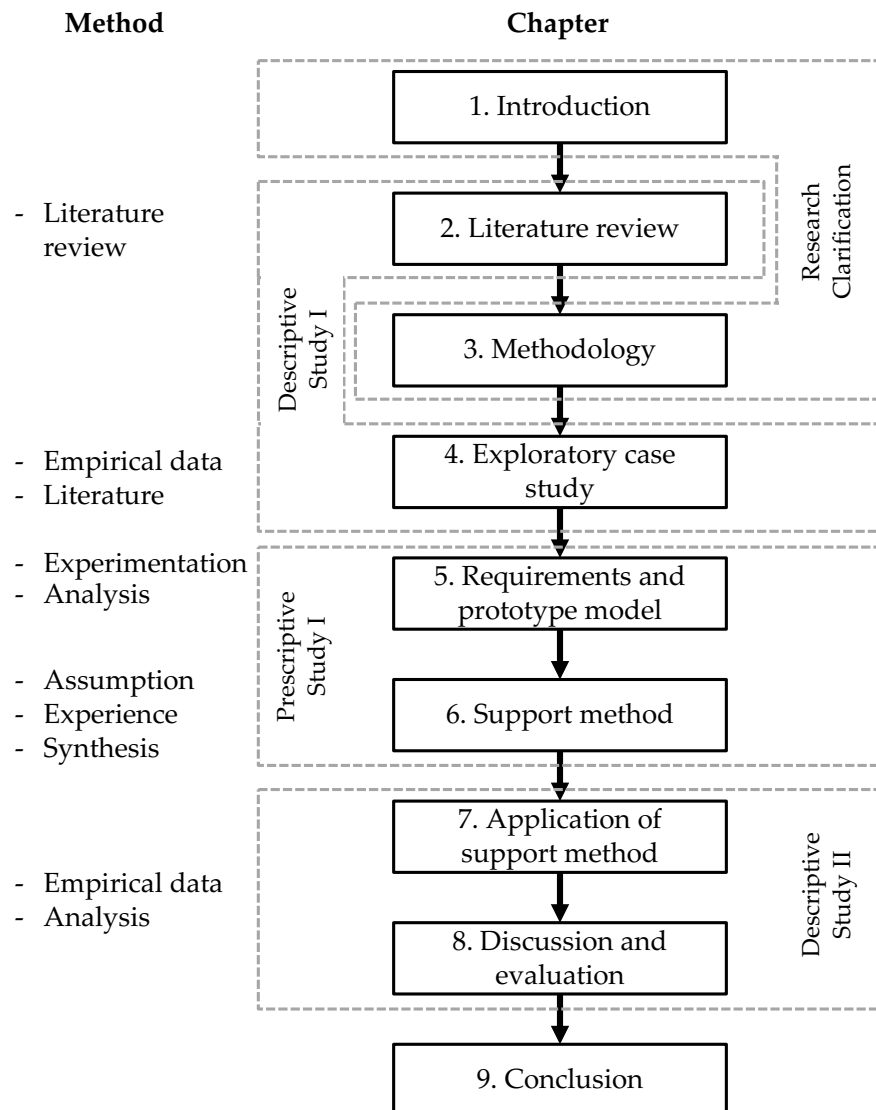
Figure 4. Thesis structure

1.7 Summary

This chapter introduces the thesis by providing the motivation and background of the topic to be researched. The chapter discusses the research context of engineering design processes and the specific challenge of managing resources within process planning.

This is concerned with estimating, allocating and scheduling limited design resources in an effective way. To summarise the motivation for this research:

- Design processes are complex, inherently uncertain and iterative;
- Organisation needs to improve delivery time and cut cost while maintaining quality;
- Multiple resources are used to complete design processes, such as designers, computational, effort, testing and prototyping resources;
- Resources can shape the characteristics of the activities they undertake;
- Effective resource management is essential to maximise the impact of limited resources.

The overall aim of the research is to achieve better resource management and hence improve design process performance.

Moreover, the principal research question was derived and decomposed into two more granular questions to initially guide this research. Furthermore, a brief description of the intended research methodology is introduced.

The research scope directed the focus on the impact of design resources on process performance, time and cost, in a resource constrained environment as part of complex products' evolutionary design processes.

Lastly, the thesis structure is provided with brief descriptions of each chapter. The next chapter expands on literature review for the intended research.

2 Literature review

The previous chapter has motivated this research to improve resource management in design by developing an approach to aid resource estimation, allocation and scheduling. The principal research question **RQ0:** *How can resource management be utilised to improve planning and execution of complex design processes?*, is intended to be broad to initiate literature review in this chapter. The focus is to investigate approaches to support resource management in improving process planning and execution.

As explained in Chapter 1, different methods could be feasible and effective in supporting resource management. Due to the vast amount of possible approaches, an overview in Section 2.1 introduces relevant fields and narrows down to the ones that can address the specific issues of design processes and associated resources. The approach taken to conduct the literature review is explained in Section 2.2. The following section, Section 2.3, scopes resource management within the spectrum of PD process management to delimit the area of influence and contribution of the intended research. Section 2.4 details the search methodology used.

To recap, RQ1 was defined in Chapter 1 to guide literature review, **RQ1:** *What are the different types of design resources and the current methods to support their management?* Literature review results, which focuses on addressing RQ1, is presented in two sections: Section 2.5 introduces design process models and frameworks; and Section 2.6 compiles and discusses the meaning of design resources according to the reviewed models. Thus, Section 2.6 also describes resource attributes that were modelled, and the way these methods use and manage design resources. The approaches were developed with organisational applicability in mind, thus covering the theoretical segment of past empirical effort of researchers, partly fulfilling RQ1 and RQ2. Further empirical investigations in

industry is presented in Chapter 4. Discussion and analysis of literature review results are presented in Section 2.7. Finally, the chapter is summarised in Section 2.8.

2.1   Support for design resource management

A traditional project management approach to record, document and estimate resource utilisation is a *resources calendar*, which comprises information of resources such as people, equipment, and material (PMI 2013). *Resource calendars* are editable documents including information about resource capabilities, human resources' experience and/or skill level, geographical location or origin, and period of availability. They are used to book the necessary resources for the period needed. Evolution of *resource calendars* includes many HR systems that capture human resource information for scheduling, amongst other objectives such as recruiting, payroll management, administration, etc. (Maier *et al.* 2013). Being mainly a procedure of booking resources from an available pool, criticisms to these approaches include the lack of proper management support or analysis. In many companies, resource allocation is still based on the simple approach of managers relaying on their experience: looking at the amount of work to be done in the current backlogs and allocating resources according to past experience, heuristics and rationality (Joglekar and Ford 2005; and see Ford (2002) for discussion and examples). However, the quantitative focus of this research (Chapter 1) aims to deliver a resource management method that allows analysis and improvement of design processes.

Other general or not design-specific approaches include, but are not limited to, conventional diagramming software (e.g., Microsoft PowerPoint), project management tools (e.g., Microsoft Project or similar), simulation-based planning tools (e.g., PERTMaster) (Wynn 2007), and methods (e.g., PRINCE2). Projects IN Controlled Environments (PRINCE2) is a project management method that follows a series of principles during a project lifecycle (Zhang *et al.* 2012). The method is aimed to improve project practice and englobes scheduling approaches (e.g., Gantt charts). Diagramming approaches, such as Gantt charts, or tools, such as Microsoft Project, can produce project plans, resource allocation plans, schedules and provide an overview of overall project progress. They can capture some resource attributes such as resource availability (Microsoft). However, a fundamental issue regarding those methods is their inability to represent the complexity and uncertainty of design processes, which requires models that allow iterative analysis (Wynn *et al.* 2007). In contrast, diagramming approaches mainly have a descriptive purpose and only provide limited support for analysis. Most of these existing methods have a preconceived assumption that enough knowledge is available to plan the design process in advance and execute it accordingly (Shapiro 2017). However, this assumption is

often inadequate for evolutionary PD, in which knowledge continuously evolves. Accordingly, Wynn (2007) concludes that design specific approaches are usually better suited to tackle managerial issues associated with planning, execution and decision-making in design processes, which includes resource management. Specifically tailored to PD and design processes, these can capture design uncertainties and offer iterative analysis.

Design process management is a complex and challenging endeavour that deals with systems comprised by multiple-domain elements that are interdependent: product, process and people (Lindemann *et al.* 2008). Modifying one component of the system can affect the other two elements. In order to aid decision making, many researchers have long stated the need for approaches in the realm of design to manage and integrate this complexity (Wallace and Blessing 1999; Ullman 2001; Bell *et al.* 2007; Wynn 2007; O'Donovan *et al.* 2004; Eppinger *et al.* 1994). In this environment, PD process management is concerned with planning, monitoring, and controlling of tasks using approaches, such as theories, methods and models (Wynn and Clarkson 2005). The objective is to explain and/or improve the design and development process. This improvement could be in terms of shorter development times, lower budget expenditure or any other suitable metrics.

Modelling frameworks are used to build models, which can be considered as *'virtual sandboxes'* and models as *'sandcastles'* (O'Donovan *et al.* 2010). Frameworks include the *'raw material'*, *'tools'*, and techniques to build models. Their properties, like the properties of different materials, limit the characteristics of models that might be built with them. The insights drawn from building models are the basis for process improvement (Fricke *et al.* 1998). In general, models are abstractions of the real world that are constructed to enhance our understating of it. Models can capture certain aspects of reality that are otherwise not understandable, and provide a foundation for virtual experiments when real experiments are not cost efficient, unpractical or impossible (Maier 2017). Models in engineering design can capture the underlying structure of design processes and/or physical artefacts for analysis and for synthesis (e.g., Simon 1996; Andreasen 1994) to support design and planning decisions. Modelling for synthesis prescribes how a target system should be, instead of simply describing it. Moreover, models provide the perfect platform to conduct *'what-if'* analyses thanks to the process simulation capabilities that could be built upon them. Different configurations and behaviour of processes can be set up to investigate cost effective improvements (O'Donovan 2004; Bell *et al.* 2007). It could help to quantify the effects of process changes, alternative architectures, resource changes, etc. Nevertheless, models are normally built with the purpose of enlightening specific parts of the process and answer defined questions at the expense of others.

George P. Box formulated one of the most famous quotes in the field: *"all models are wrong, but some are useful"*.

The resulting process does not just necessarily have to deliver the best product possible, but also be robust enough to produce the adequate product. Figure 5 shows how the trend is to move to an efficient process and adequate design.
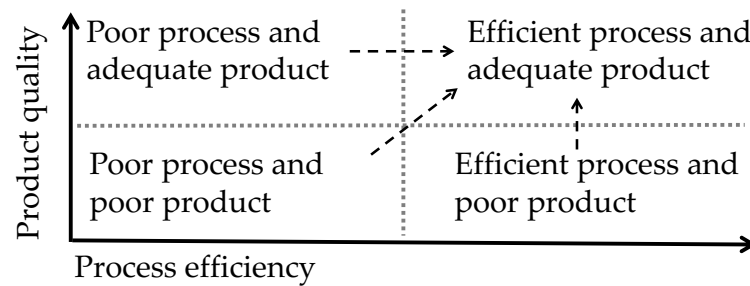
Figure 5. Process and product performance moving towards an improved state. However due to uncertainty in design, the desired state is hard to reach

To do so, process modelling aims to support the next areas (Wynn *et al.* 2006; Wynn 2007):

- *Knowledge capture:* Many complex designs' lifecycles span for long period of times and the rationale behind the design process must be documented to promote co-ordination and development of a shared understanding, and in case redesign is needed. Thus it is necessary to capture expert's knowledge to make it more accessible and explicit (Eckert and Clarkson 2010);

- *Management support:* Gantt charts have been traditionally used in different industries to represent processes for management purposes, but they have recognised limitations such as the lack of iteration modelling, task ordering resource allocation, risks etc. Thus, PD and design specific approaches are more suitable to provide managerial support;

- *Process analysis and reconfiguration:* Analysis of design processes can help identify and evaluate improvement opportunities. Process modelling can help evaluate the impact of resourcing levels upon project delivery, or identifying configuration changes which could improve process performance.

In summary, PD and design process modelling and simulation seem the most suitable field to continue literature investigations. They can be used to support resource management, in which simulations could help quantify the effects of alternative resource allocation strategies and utilisation amongst other analyses.

2.2 Approach to the literature review

Literature review was completed in four steps explained below.

Step 1 Scoping of literature review

The first step involved scoping the role of resource management in PD process management delimiting its area of influence. The purpose is twofold: 1) identifying the areas that resource management impact to bound the review search; 2) identifying the areas of potential contribution of this thesis.

The scoping of resource management is done through reviewing and compiling generally accepted classifications of PD and design process management objectives such as Browning and Ramasesh (2007) and O'Donovan *et al.* (2010). The author develops a purpose based classification of design process approaches based on planning, execution and after process stages highlighting which areas resource management can theoretically impact.

Step 2 Search methodology

As design process modelling was identified as the most suitable method for this thesis, literature of models for design were reviewed. The literature search was conducted according to Section 2.3 and the overall research scope set in Chapter 1. A two-step review combined an exploratory search using keywords with a more detail search in selected journals to cover all the relevant fields. Further details are presented in Section 2.4.

Step 3 Results

Initial investigations determined that within design process modelling, analytical approaches were identified as the ones that can provide more insights for decision making. Hence, the literature review results are presented in two sections. Firstly, Section 2.5 reviews key analytical frameworks that have been used or can be extended for resource management models. This provided a deeper understanding of design process modelling and simulation. It also served as a foundation for Section 2.6, in which models are classified according to what they consider design resources and how they manage them. Out of the approximately 600 publications reviewed following this approach- excluding general design process literature-, 31 key publications describing design process models for resource management were identified.

Step 4 Discussion

The literature and gaps in the field are discussed in Section 2.7. A table was constructed with the main reviewed approaches according to the purpose of the model, their meaning of design resources, the performance metrics used, and the attributes of resources.

The following sections describe the approach in more detail.

2.3   Scoping of literature review

This section presents the scope of resource management in PD process management, not to be confused with overall research scope presented in Chapter 1. The current project aims to study the management of resources in PD, focusing on design process of complex products. In order to set the research in context, process management applications areas in PD were categorised. This includes the wide spectrum of process modelling purposes and indicates the area of influence of resource management, also setting the intended area of contribution. The categorisation aims to help to complete a more systematic review on how different types of process models address resource issues.

PD project management is concerned with planning, controlling, monitoring and improving the process. More specifically, PD process modelling purposes were categorised by Browning and Ramasesh (2007):

Table 1. PD models purposes. Source: Browning & Ramasesh (2007)

Category	Purposes
PD project visualization	• Actions, interactions, and commitments • Customised "views"
PD project planning	• Making commitments • Choosing activities • Structuring the process • Estimating, optimising, and improving key variables (time, cost, etc.) • Allocating resources
PD project execution and control	• Monitoring commitments • Assessing progress • Re-directing • Re-planning
PD project development	• Continuous improvement • Organizational learning and knowledge management • Training • Compliance

Due to its established status, Browning and Ramasesh's work has been used to illustrate process modelling purposes. Furthermore, O'Donovan *et al.* (2010) added dynamic support, communication, training, and knowledge management to the list of process modelling applications. Hence, process model can support the planning, execution and after

process stages of a design process. As a result, Figure 6 indicates the areas of influence (and potential contribution) of resource management approaches in process management application:
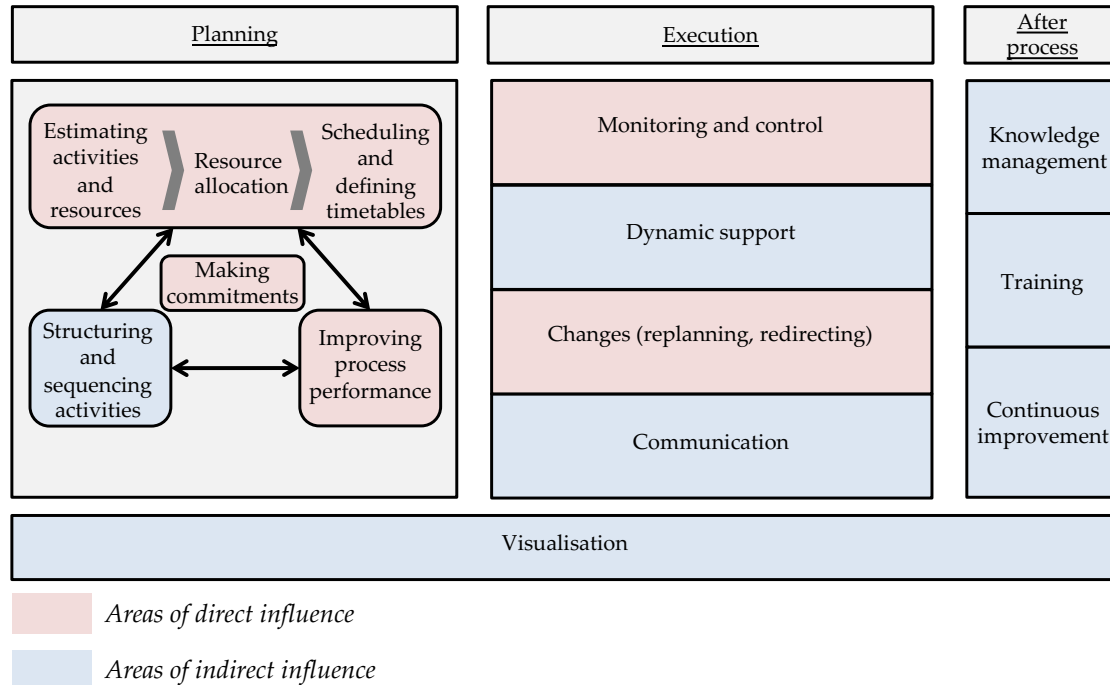
Figure 6. PD modelling applications and areas of influence of resource management. The terms were pulled from Browning & Ramasesh (2007) and O'Donovan *et al.* (2010)

The categorisation presented was developed through a literature review, aiming to compile application areas of process modelling. However, the emphasis of this categorisation is on deconstructing the role of resources in PD process. It does not intend to be a generalisation of the role of modelling in PD and design processes. The categorisation divides the application areas between planning, execution and after process. At the planning stage, the aim is to develop and extract insights to improve the design process. Within planning, specific concerns include resource and task estimation, task structuring and task sequencing (Lee *et al.* 2004; Eppinger *et al.* 1994). Resource estimation concerns the forecasting of the amount and type of resources needed. The estimation is done in combination with task estimation, since both endeavours tightly influence each other. To finalise the plan, resources have to be allocated and scheduled. Allocation is concerned with which tasks the resources will perform; and scheduling indicates which tasks and when to perform it (Herroelen *et al.* 1998). Chapter 1 has defined that this thesis objective is to support resource management, which includes improving process planning and execution by developing an approach for estimating, allocating and scheduling design resources. Hence, the red areas in Figure 6 are directly influenced by this research

with the aim of improving process performance. The process of task and resource estimation, allocation and scheduling, process sequencing, and process improvement is coupled and iterative, influencing each other in a refinement cycle. Hence, although this research does not specifically engage of studying task sequencing, it is indirectly impacted. Planning commitments must be made between stakeholders in this collaborative or competitive environment (Macal and North 2009). Decisions on how many resources and when they can be allocated are negotiated between stakeholders, thus resource management plans can be presented as arguments.

Additionally, areas that design resources could potentially affect are not limited to planning of processes. A plan can be used to monitor and control different stages of the project and evaluate its progress (Browning and Ramasesh 2007), thus having a direct influence. Moreover, if changes needed to be made, re-planning will require going back to planning and scheduling stages. Communication and dynamic support are indirectly aided since the plan provides a common understanding of the process for different stakeholders (O'Donovan *et al.* 2010) and can be updated accordingly. Resource management plans can also indirectly support after process challenges, in which plans can be kept for future projects as knowledge management. They can also point out areas to be focused on training or recruiting, as well as aiding continuous improvement. Analyses should be presented in an understandable way (Clarkson *et al.* 2010), hence visualisation is also indirectly influenced. Further investigation will be done in the next sections, in which different types of process models for design are reviewed.

2.4 Search methodology

As neither a clear definition nor a common terminology exists for design resources in literature, or simply mentioned as designers, effort, etc., an exploratory literature review was conducted by using key words: *Resources, engineering design, resource management, resource planning, design process, design process models, and design process simulation*. A number of publications were listed by relevance, and first reviewed by screening through their title and abstract following the criteria delimited in the research scope (Chapter 1). The main points were:

- Focus on engineering design processes involving the use of any resources (e.g., designers, effort, etc.).
- Papers needed to have an explicit focus on the engineering design domain. Papers that focused on another domain (e.g., modelling product and process in software engineering, design for X, etc.), and models that feature only manufacturing processes were considered out of scope at this stage;

- Focus on a single project, multi-project resource planning is out of the scope in this thesis;
- Only literature covering the design process stages from conceptual to detail design was reviewed.

A second search was conducted with the keyword *resource* in the title, abstract and key words to find publications that have not been already identified. The search was conducted for articles published between January 2000 and July 2016 in eleven relevant journals: *Research in Engineering Design, Journal of Mechanical Design, Journal of Engineering Design, Design Studies, IEEE Transactions on Engineering Management, Product Innovation Management, Computers in Industry, Systems Engineering, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Design Science.* The results included 678 articles that were further shortlisted based on their title and abstract. Additionally, the identified literature was complemented through cross-referencing of key publications.

2.5   Design process modelling

They are many models to support PD and design process management. Different reviews can be found in literature: Browning and Ramasesh (2007) reviewed task network models in PD; Krishnan and Ulrich (2001) compiled work from diverse fields such as marketing, operations management, and engineering design in the area of PD; Smith and Morrow (1999) reviewed process model frameworks and set criteria to evaluate them according to industry standards. In addition, example of relevant books for further reading includes Ulrich and Eppinger (2011), Pahl *et al.* (2007), Clarkson and Eckert (2010) and Hales and Gooch (2004).

The manner in which a model captures a process can be distinguished between descriptive or prescriptive (Wynn 2007). *Descriptive* process models are inductive models that try to capture explicit knowledge about what happens in a process. *Prescriptive* process models try to propose the design process plan and how it should be executed. They can outline rules, guidelines, and behaviour patterns that can lead to the desired process performance. Many process models have some degree of descriptive and prescriptive characteristics. Wynn and Clarkson (2005) differentiates between three types of approaches to model processes:

- *Abstract:* describes the design process at a high level of abstraction and does not provide with specific guidance for process improvement (e.g., Jones 1970; Ehrlenspiel 1995).
- *Procedural:* are less general, focus on a particular aspect of the design process, and can provide some practical guidance (e.g., French 1999; Pahl and Beitz 1996).

- *Analytical:* are used to model specific instances of design processes. They comprise modelling framework that describes the process; and techniques, tools or methods to investigate, prescribe and support improvements.

Abstract and procedural approaches are used to describe design processes and its characteristics, but are usually too abstract to offer support with enough detail in daily managerial decisions during planning and execution of a project. Lower level support is given by analytical approaches focusing on specific instances of the design process (Wynn and Clarkson 2005). Given the complexity of managing resources and the quantitative nature of the stated objectives, analytical process modelling frameworks appear suitable to support resource management. These methods can increase understanding of design process behaviour, while capturing design process characteristics and associated performance risks (Shapiro 2017). Hence, they provide a useful foundation for this research and are further reviewed in the following sub-sections.

To provide a structure to the review, the next sections follow Wynn (2007) process model classification, which divides analytical models into Task network models, Agent based models, System dynamics models and Queuing models. Relevant analytical models are presented emphasising on their suitability to support design process in general, and resource planning and scheduling in particular (Section 2.6). These models have been either applied to or have the potential to be extended for resource management purposes.

2.5.1   Task network models

Task network models divide a process into a set of activities that must be completed in order to reach the desired objectives (Browning and Ramasesh 2007). The activities are linked together to represent the information or deliverable flow from one task to another. A process is finished when the necessary activities are completed.

In PD, activities require information or deliverables to produce the desired results. The information flow can be captured by precedencies or dependencies. Dependencies indicate information flow between two elements. Precedence links are stronger than dependencies since it indicates order of task rather than just information flow. Stage, task and parameters are three basic elements often used to capture and drive a process. A stage embodies a set of tasks that must be completed with the necessary level of performance targets (often incurring in iterations) before moving to the next stage (Pahl *et al.* 2007). A task is an activity carried out in the design process. The completion of a task leads to the next one. Figure 7 illustrates how two task can be related to each other according to Eppinger *et al.* (1994). Two tasks are dependent on each other if one needs the output of the other task as input, and would typically be completed in sequence (*left*). On the other

hand, two tasks are entirely independent if they can be executed in parallel without interaction or information exchange (*middle*). Finally, tasks are interdependent if each task needs information from each other (*right*).
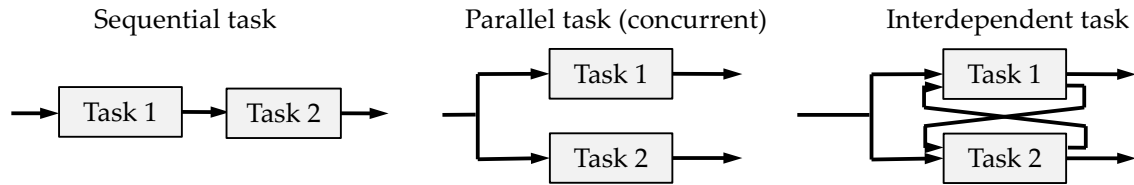
Figure 7. Different ways of task relationship. Adapted from Eppinger *et al.* (1994)

A design process is parameter driven when the selection of the next step is determined by parameter requirements of each task in a predefined task precedence network (Murata 1989). Parameter definition in design is ambiguous since it could denote an aspect of the product, deliverable, etc.
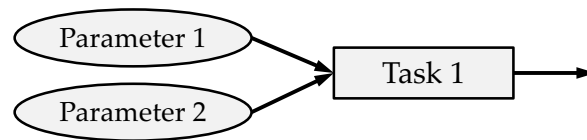
Figure 8. Parameter driven process: when parameters are available, the task starts

The diagrammatic representation of the process used by task network models has the advantages of easy visualisation, description and documentation of a process, and the manipulation of large volumes of data (Wynn 2007). Task network models also allow simulations, techniques and algorithms can be used to explore process behaviour. They include the following examples.

2.5.1.1   IDEF0

IDEF0 is a function modelling approach based on a formal graphical language (syntax and semantics) designed to capture decisions, actions and activities of an organisation (NIST 1993). IDEF0 organises functions in a hierarchical structure and connects them to manage the way they are triggered and controlled. Dependencies are represented by arrows and a full set of notation describes how to connect functions across and between hierarchical levels. The framework has the following elements:

- *Functions* in blocks that transforms inputs into outputs;
- *Control signals* that specify conditions or constraints representing the external effects that influences the functions;
- *Mechanisms* representing the resources that perform the function.
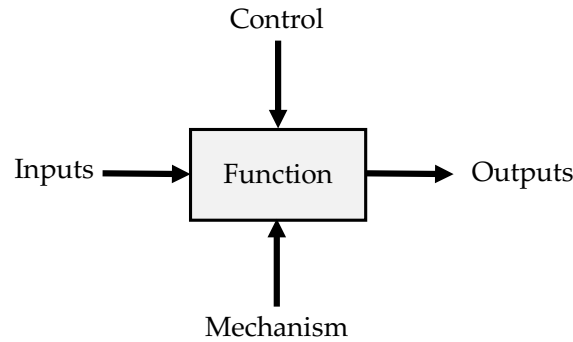
Figure 9. IDEF0 representing a function. Adapted from NIST (1993)

2.5.1.2 IDEF3

IDEF3 is a precedence model aimed to capture knowledge about process flow and '*object'* states transitions using two complementary diagrams (Mayer *et al.* 1995). The first diagram, called '*process flow'* diagram, describes a recurrent flow of actions in a particular problem-solving situation. Process flow diagrams are depicted using Units of Behaviour (UOBs), junctions (AND, OR, XOR), and precedence links. UOBs can be further subclassified into function, activity, event, scenario, or decision. The second diagram, Object State Transition Network (OSTN), intends to represent a process from an object's perspective, which transitions between different states as information evolves. OSTN uses object state nodes, state transition arcs, junctions, and referents to UOBs or other networks which are attached to the arcs:
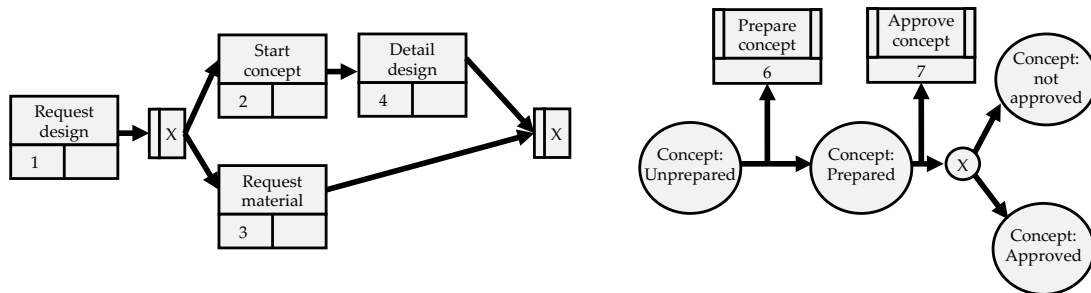
Figure 10. Process flow diagram (*left*) and object state transition (*right*) of a design process. Adapted from Mayer *et al.* (1995)

2.5.1.3 Precedence Diagramming Methods (PDMs)

The Critical Path Method (CPM) by Kelley and Walker (1959), and Project Evaluation and Review Technique (PERT) by US Navy (Miller 1963) are the most widely used Precedence Diagramming Method (PDM). PDMs are used to analyse a process to determine the activities of the longest possible path and the effects of tasks' delays in projects (PMI 2013). The process is represented with nodes or tasks connected together through precedence links. The duration of each activity is denoted in the node describing the earliest

start, latest start, estimated duration, the float (difference between latest and earliest start), earliest finish and latest finish. Hence, the critical path is identified as the set of activities with the longest duration route. Those tasks have a direct influence on the total process time since any delay will propagate to the end of the project. While CPM accounts for average task duration; PERT calculates a weighted average duration to consider extreme times. However, they have several recognised limitations, including the inability to model iterative behaviour and the capture of uncertainties.

Earliest start	Estimated duration	Earliest finish
Task identification number and description		
Latest start	Total float	Latest finish
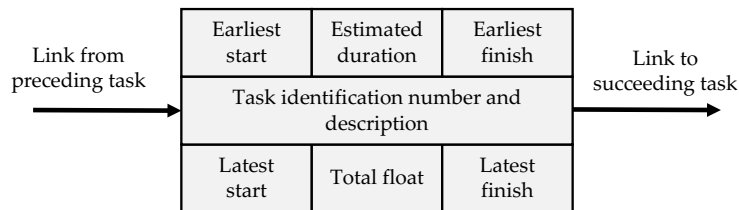
Figure 11. CPM description of task times. Adapted from PMI (2013)

A more suitable model for design is the Graphical Evaluation and Review Technique (GERT) developed by (Pritsker 1966). GERT is an extension of the PERT model that includes iteration cycles and multiple task outcomes. Therefore, it allows modelling failed tasks and the possibility of incorporating non-essential tasks to the process. Time is represented as probability density functions and the number of preceding tasks required to start the next one can be indicated for the first and subsequent iterations. The additional features provided GERT with enhanced logic and ability to provide more insights regarding process behaviour.

2.5.1.4   Petri net

Petri net, shown in Figure 12, is a graphical precedence model developed by Carl Adam Petri, which is represented by networks consisting of *places* (circles) linked to *transitions* in the form of vertical bars through which tokens may move (Peterson 1977).

Once a token is present in each input 'place', the transition is triggered

After the transition has fired, tokens are placed in the output places
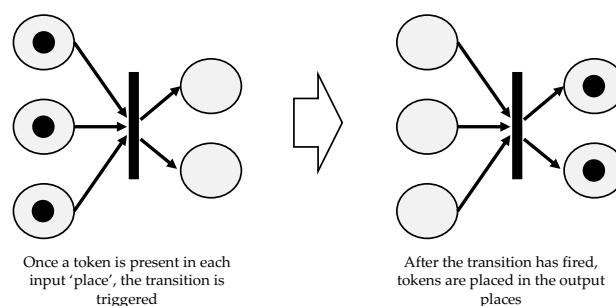
Figure 12. Petri nets transitions. Adapted from Peterson (1977)

A transition might be triggered when tokens are in the input side. Each token is then removed from the input to the output side when the task is fulfilled (Murata 1989). Petri

nets can represent the dynamic behaviour of discrete event systems or processes by constructing the relationship between tasks (transitions*)* and parameters (places) (David and Alla 1994; Peterson 1977). Tokens are used as an indicator of the availability of the necessary design parameters for a task to be performed.

Extensions to Petri nets include logic gates for firing conditions, multiple outputs selected stochastically, and Coloured Petri nets (assigning values to tokens) to identify specific data through the process. McMahon and Xianyi (1996) extended coloured Petri nets to automate a design process and execute computational design activities of an engine crankshaft. Horváth *et al.* (2000) developed the Advance Petri net, an extension to provide 'multi-functional representation' with simulation capabilities. The method was enhanced to model the process and the context in two layers that are interlinked. The procedural layer represents the flow of design activities along with time metrics and resource usage in transitions. The contextual layer captures the design decision flow.

An advantage of Petri nets is the possibility of modelling concurrency and iterative flows to represent serial, parallel and coupled tasks (Smith and Morrow 1999). On the other hand, disadvantages include the absence of other metrics such as time (original version) and all connections and parameters are assumed to be of the same weight without accounting for quality or confidence.

2.5.1.5 DSM and DMM

Design Structure Matrix (DSM) is a square matrix with identical row and column labels that has the ability to capture dependencies between activities and characteristics of the process. DSM describes tasks as information processing units, using and creating information (Smith and Morrow 1999). The information flows in one direction, where the outcome from one activity is the input information of another. Dependencies between two tasks are marked in the matrix, in which reading down a column reveals input sources and across a row indicates output sinks. Hence, dependencies below the diagonal denote sequential flow and above indicate iterations, which can represent serial, parallel and iterative design flows. A dependency can be denoted by marks (binary DSM) or numbers (numerical DSM). Since Steward (1981) introduced DSM, many researchers have enhanced it with techniques and with simulatable extensions to explore process structure. Yassine (2007) compiles a series of DSM applications in simulation and Eppinger and Browning (2012) includes 44 applications that are relevant to industry. Extensive material can also be found in DSM website (www.dsmweb.org).

The DSM has been used extensively to study sequential and concurrent processes in the presence of iteration and with uncertainty (Smith and Eppinger 1997a, 1997b, 1998; Ko *et al.* 2010), being the core of manifold of process simulation frameworks. These models

have been used to explore process architecture and by extending the DSM with different risk and impact of iterations, stochastic task duration and cost, overlapping and sequential iterations, learning curves, and task concurrency.

| | a) Information flow diagram | | b) DSM |
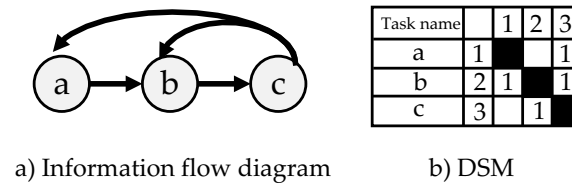
Figure 13. Example of task concurrency modelled with DSM. Adapted from Cho and Eppinger (2001)

In summary, DSM is a concise and compact way to represent the design process and enables different process improvement approaches to be explored (Eppinger *et al.* 1994). Nevertheless, disadvantages of DSM include that the process is relatively difficult to visualise compared to flowchart notation. The modelling framework does not allow hierarchical representation of activities, nor indicate the state of the product. It also assumes that design tasks can be predicted along with identifiable inputs and outputs. Additionally, as extensions increase in sophistication the model loses the attractiveness of practical simplicity (Wynn 2007).

Domain-Mapping Matrix (DMM) or Multi Domain Mapping (MDM) is an extension to the DSM developed with the purpose of modelling linkages between different types of element. Browning (2002) used the approach to integrate internal and external inputs and outputs in a process. Different applications of DMM can be found in Danilovic and Browning (2007).

Figure 14. DMM of tasks and persons performing them

2.5.1.6 Signposting

Signposting modelling framework was first introduced by Clarkson and Hamilton (2000) to support aerospace design. The framework captures dynamic processes by determining the next appropriate task based on designers' current confidence in their solution. In order to achieve this, Signposting is modelled through tasks along with their

required parameters, which are any element of the product or process that could evolve during the design process (Melo 2002). The levels of parameter confidence are classified as low, medium or high and the process starts with mostly low confidence levels. Signposting introduces the concept of confidence to assess the trust of a designer in a specific design parameter. Thus, the overall level of confidence represents the maturity of the design. Hamilton (1999) defines high confidence parameter to the ones that display values that are detailed, accurate, robust, and realistic.

Signposting does not have explicit dependencies and uses meta-knowledge to link and map parameters to tasks. After the process starts, selection of the next design task depends on the availability of the needed parameters in the correct level of confidence. Parameters in Signposting differ from their counterparts in a Petri net scheme by adding the dimension of confidence level, not just availability.

The framework uses tasks as knowledge transformers, which are triggered if the parameters' confidence is equal to or greater than the required input conditions of the task. Once the required input parameters are in place, the task is then selected to be performed if it leads to an increase in confidence in one or more parameters. When each task is performed, the level of confidence of the parameters can be upgraded, remain constant or degraded depending on the success of the activity execution. Failing the task would evoke the process to iterate and search for a new appropriate task depending on the input parameters' updated confidence.
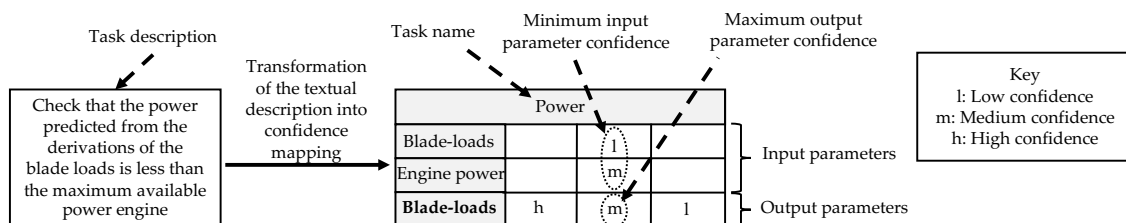
Figure 15. Signposting mapping of parameter confidence. Adapted from Clarkson and Hamilton (2000)

Signposting has been extensively researched at the EDC in Cambridge. As a result, multiple extensions were developed by Melo (2002), O'Donovan (2004) and Flanagan (2006), which included: enhancement to calculate cost of failure associated with each design route taking into account designer's expertise; appropriate visualisation output; triangular probability density function (PDF) for task duration; multiple probability outcomes; resources required by each task; mathematical algorithms based on Markov decision theory in order to choose the lowest cost- time paths; learning effects; Monte-Carlo simulations to output a distribution of possible outcomes; and *'Conditional Precedence Matrix'* visualisation to aid optimisation of the process.

2.5.1.7 Applied Signposting Model

Wynn *et al.* (2006) developed the Applied Signposting Model (ASM), a process framework that models both precedencies and dependencies between tasks based on their interaction with parameters. Design process progress is driven by changes in parameter availability (unavailable, available, and updated) and state. ASM includes *parameters*, *simple tasks*, *compound tasks* (alternative outcome routes), *iterations*, *sub-processes* (hierarchical representation of tasks) as basic elements (Kerley *et al.* 2011; Wynn *et al.* 2006).

ASM models can specify task duration and iteration outcome as probability density functions or as functions of process variables. Multiple and complex process logic can be modelled using equations and process variables. Furthermore, Monte Carlo simulations can be configured. All process parameters have an initial unavailable state and the simulation starts when the first input parameter is set to the updated state. After the first task is attempted, the simulation identifies the recommended successor tasks according to dependency and precedence links. A task is available to start based on its pre-conditions set within its properties, which specifies if input parameters need to be available or updated. Upon the start of a task, its upstream parameters will switch to *'available'*. When a task is completed, a single route is selected updating its outputs. However, a task can be reworked when its parameter availability shifts back to updated due to iteration. The process is completed when no more tasks are available to start. ASM has a series of advantages over other modelling frameworks (Wynn 2007):

- *Intuitive graphical notation:* its diagrammatic representation, graphical notation and visualisation facilitate the elicitation of process knowledge and boost its usability;
- *Complex definition:* elements within ASM allows capturing and describing the characteristics of the design process as well as the product thanks to the multiple dimensions of parameters;
- *Multiple hierarchical structures:* provides the ability to develop and manipulate highly complex design processes;
- *Flexible representation of dynamic behaviour:* process variables, task selection policies, mathematical equations and rework management policies allow ASM to model and simulate a wide range of process behaviour.

ASM is embedded in the Cambridge Advanced Modeller (CAM), a software platform developed in Cambridge for constructing, visualising, and manipulating models of complex systems (Wynn *et al.* 2010). CAM is being applied by hundreds of users (based on

over 6,500 downloads by October 2017) in industry and academia and continuously improved and enhanced. It also permits the addition of plug-ins to explore different kind of extensions due to its modular architecture.
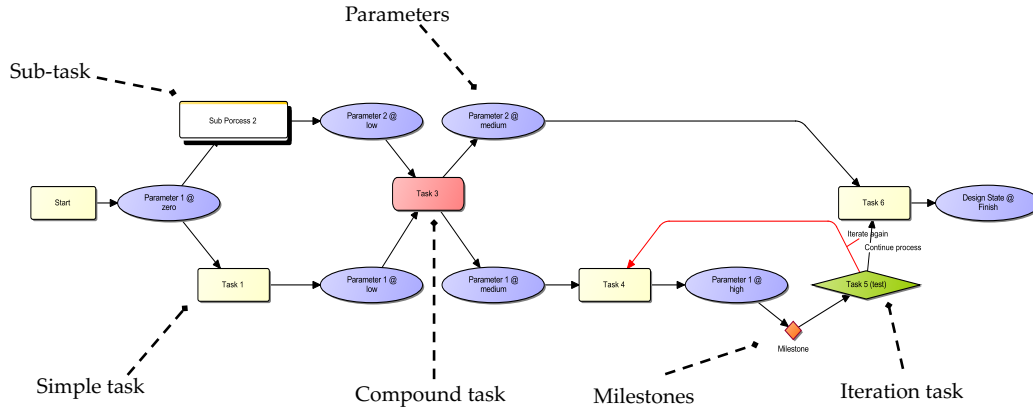
Figure 16. ASM process and elements

2.5.1.8 Adaptive PD Process

Adaptive PD Process (APDP) is a by dynamic modelling framework developed by Levardy and Browning (2009) to aid decision making during product development. APDP does not have dependencies or precedence links, instead it generates a *'process space'* (set of likely paths) based on the available *'options'* (activity modes). The selection of activity modes or options depends on the state of the project. APDP accounts for time, cost, technical performance measure (TPM) of current state as drivers of the design process. These variables form activity modes, which combine (according to simple rules) to develop an ideal path for the process. The metrics that decide which activity mode should be next in the process are technical entry conditions (EC), cost, duration, availability, fidelity (how detailed the result would be) and effectiveness (depends on project state). The model selects the next mode with the highest possible value, which means lowest possible risk of failure. However, the current state of the method does not capture resource constraints.

2.5.1.9 Next step support

Ullman *et al.* (1997) developed a technique that aids in deciding where to invest resources. The method models teams of stakeholders with different beliefs and preferences about design alternatives that can meet the objectives. The approach uses a mathematical model to evaluate if the alternatives comply with the desired standards in each *'criteria'* (preference) using variables such as *'knowledge in the area'* and *'confidence'* (they both comprise *'belief'*). The results indicate how likely the alternative will satisfy the preference of each stakeholder. Then, a sensitivity analysis calculates the maximum and minimum

levels of satisfaction that each design can achieved. The analysis allows to evaluate where resources should be added to increase knowledge and confidence on design decisions. In summary, the method has the ability to model stakeholder's biases and dynamics to decide where the effort of the project should be allocated.

2.5.1.10 Concurrent methods

Many researchers have resolved to use concurrency in design process to minimise project duration. However, concurrency can yield in issues such as quality loss, bad coordination of activities, or not reaching the optimum level of concurrency. Thus, authors have developed models to study the different aspects of concurrency. Krishnan (1996) proposes four kind of overlapping activities based on the speed of parameter evolution and impact sensitivity. Krishnan and Eppinger (1995) considered risks of concurrency such as iteration and loss of quality when determining optimal overlapping of tasks. To avoid loss of quality, this time in sequential processes, Krishnan *et al.* (1997) developed a technique to plan the right amount of design iterations.

The advantages and the flexibility of extending activity network frameworks seems to be adequate for the purposes of this thesis. In addition, task network approaches enable to model design processes at different levels of granularity and situations.

2.5.2 Agent based models

Agent-based models (ABMs) or multi-agent systems (MASs) consist of a set of entities (*agents*) characterised by its attributes that interact with each other following defined rules in a given environment (Barbati *et al.* 2012). ABMs model the phenomenon or problem to be simulated by defining its space, which is the object of the simulation (Weiss 1999). Population of agents can be hierarchically classified in categories depending on the characteristics of the system's components and the adaptive capability of each agent. (Billari 2006).

There is no exact definition for agents but they are characterised for being self-contained and shaped by its characteristics, behavioural rules and decision-making capabilities (Wooldridge and Jennings 1995). Agents are pro-active, with goal-directed behaviours. (Barbati *et al.* 2012). They also have social abilities, which means they can interact through a communication protocol to achieve their objectives (Macal and North 2009). Agents are also characterised for being autonomous and independent when it deals with other agents, at least in their predefined situations. They are flexible, learn and adapt their behaviour based on experience from the environment.

Bonabeau (2002) defines a set of situations in which agent models are well suited: the interactions between the agents are complex, nonlinear, or discrete; the agents' positions in the space (e.g., design space) are not fixed; the population is heterogeneous, each individual or set of individuals is different; the interactions between agents or environment are heterogeneous and complex; the agents present complex behaviour (e.g., learning and adaptation).

The benefits of agent models over other modelling techniques roots on the capability to capture emergent complex behaviour giving a natural description of a system and the modelling flexibility of the frameworks (Bonabeau 2002). In the context of design processes, some ABMs are focused on communication and negotiation of decisions between stakeholders. Another function of agent models is to document and model the interactions of the agents. Various interaction paradigms have been defined between agents in this area (Weiss 1999). Agents can be residing in a cooperative environment if they collaborate towards a goal or a competitive one if they have conflicting objectives (Macal and North 2009).

2.5.2.1   Collaborative

Participatory or collaborative ABMs combine the agent-modelling paradigm with notions from organisation theory to construct goal-driven simulations. Decision-makers whose actions are interlinked collaborate to reach a common goal. Collaborative models can use planning approaches to negotiate the use of resources and ensure the accomplishment of global objectives (Macal and North 2009). These models normally include agents, resources and jobs that are scheduled by *coordinators*. Two main categories (Macal and North 2009):

- *Distributed approaches:* Agents possess self- organising rules for resource sharing and goal pursuing;
- *Centralised approaches:* A mediator agent regulates agents' behaviours.

2.5.2.2   Competition model

Competition-based paradigm simulates negotiations among agents, when no mediator is involved and each agent has an individual self-interested goal (instead of a global goal) (Macal and North 2009).

2.5.3   System dynamics models

System Dynamics (SD) models consider processes as work-processing systems. It decomposes a process into stock and flows governed by feedback and feed forward loops.

In order to study the complex behaviour of the process, a number of factors will influence on the work or information flows. These factors are elements of the model in the form of equations that govern the loops that determine the dynamic behaviour.

In design, Lyneis *et al.* (2001) proposed a SD model to improve the performance of complex projects. Ford and Sterman (1998) simulated the performance of different stages in a development project using SD. The generic stages used are '*product definition*', '*design*', '*prototype testing*' and '*reliability/quality*'. Each stage is modelled separately as a phase that has four sub-systems (development processes, resources, scope, and targets), which interact to affect project performance. The model aims to help decision making by studying the influences of these dynamics on development projects.
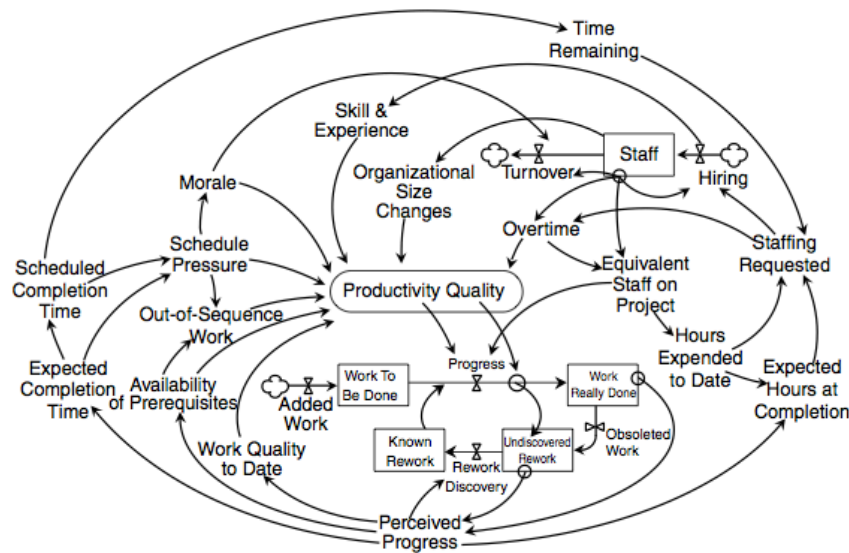
Figure 17. Capturing of structural reasons for the dynamic behaviour of productivity and quality. Source: Lyneis *et al.* (2001)

Lyneis *et al.* (2001) argued that SD could assist the strategic management of complex development projects. They can give insights on the level of resource usage and productivity by helping to design project schedules. In addition, it can evaluate risks, and aid in learning from past projects. Lyneis and Ford (2007) wrote a comprehensive review of SD models in project management, describing the use of four types of models: project features, rework cycle, project control, and ripple and knock-on effects. They advocate that the application of SD models has helped to identify common project behaviours and policy insights. SD models can support areas such as project planning and scheduling, change management, risk management, project control, amongst others. However, the high level of abstraction of SD models could be a disadvantage for its applicability.

2.5.4   Queuing models

Queuing models are concerned with optimising the utilisation of limited resources and are normally built on activity on node frameworks such as PERT or GERT. They are more suited for homogeneous activities due to the repetitive nature of workflows, which normally have well understood links and steady processes (e.g., manufacturing systems or supply chains), but also being applied to PD and design processes. Queuing models are closely related to Operations Research (OR), which is concerned with the study of resources in projects. Although OR is a research field by itself, some of their models can be applied to design processes.

2.5.4.1   Operations Research

OR is a research branch of mathematics that aims to optimise a range of logistical and business problems, which includes optimal scheduling of work. OR was defined by Carter and Price (2000) as *"the use of quantitative methods to assist analysts and decision-makers in designing, analysing and improving the performance or operation of systems"*.

OR research normally involves studies of operations within organisations instead of purely theoretical research (Flanagan 2006). Researchers will formulate the problem through observation of the operation's dynamics and build a model that attempts to abstract the essence of it (Hillier and Lieberman 2001). The models are then analysed and optimal solutions are found using algorithms to support decision making. OR has numerous sub-branches that comprises a set of tools and techniques, including linear programming, dynamic programming, queuing theory, inventory theory, game theory and simulation (Hillier and Lieberman 2001; Carter and Price 2000). The scheduling and sequencing theory area of OR has virtually an unlimited number of problem types (Herroelen *et al.* 1999). Thus, only selective and relevant areas will be reviewed in this section. This largely comprises Resources Constrained Project Scheduling Problems (RCPSP) and related problems that focuses on the optimal used of limited resources.

RCPSPs are concerned with scheduling project activities with a set of finite capacity resources. It can be expressed as a generalization of the job shop scheduling (Crawford 2008). Although they primary focus on deterministic processes, the field covers a wide variety of problem types including some scheduling approaches possibly valid for design processes. In RCPSPs, every project will have multiple inputs, various activities, some constraints and limited resources. Constraints are divided into: *resources,* limited in availability; *temporal,* time to perform the activity; and *precedence,* order of the activities in the project. Models are often built in acyclic networks with precedence constraints, and then algorithms are applied to identify the optimum schedule. Tasks will compete for resources and the aim of the algorithms is to output a schedule with one or multiple

objectives (normally minimise time span) without violating the precedence constraints or over utilising resources (Herroelen *et al.* 1999). The algorithm should minimise inefficiencies and maximise productivity with the objectives that the managers set.

Herroelen *et al.* (1999) propose a classification scheme for resource allocation problems with three fields as *Resource environment α*, the *Activity characteristics β* and the *Performance functions γ*. The scheme provides a concise taxonomy of the project scheduling field. In addition, the flexibility on defining parameters, specific objectives and constraints allows the scheme to identify and classify the majority of the scheduling problems (unconstrained and constrained by resources). Due to the high amount of RCPSPs, it would very challenging to review them all. Thus a series of important cases are listed below.

Brucker *et al.* (1999) compiled a comprehensive review of the most traditional cases of RCPS problems. It includes *single mode*, where the objective is to find a minimum make span schedule. Others included *Cost-time trade off* cases, *Max-min time lag*, *Non regular objective functions*, *Multimode cases*. Particularly, *stochastic activity solutions* case deals with unpredictable changes such as delays, resources availability changes etc. Hence, activities will not have deterministic processing times but only rough estimates. To account for such variability, the activity time could be represented as a probability distribution. Furthermore, there may be stochastic dependencies between the different individual processing times. Stochastic methods in complex projects have become increasingly important in complex projects scheduling (Brucker *et al.* 1999). Ballestín and Blanco (2011) defended the multi-objective nature of project scheduling since managers aim to finish projects as soon as possible with the minimum cost and the maximum quality. Thus RCPSPs have been evolving to add multi objective capabilities. Multi Objective Resources Constrained Project Scheduling Problems (MORCPSPs) can use exact and heuristic procedures to obtain efficient solutions. Kolisch and Hartmann (2006) reviewed and classified recent developments on heuristics for RCPSPs. Davis *et al.* (1992) introduced an interactive multi-objective programming framework allowing project scheduling problems to be more flexible for evaluation of trade-offs between project completion time and resource requirements. Another multi-objective scheduling by Słowiński *et al.* (1994) handled different type of resources in multiple modes with the objective of improving time and cost. It is based in three kind or heuristic algorithms, parallel priority rules, simulated annealing and branch-and-bound.

To summarise, RCPSPs started with a deterministic view on projects and one type of renewable resources. They expanded to add multiple types of resources and stochastic characteristics in activities to account for risk. Finally, it addresses more complex projects using multi-objective problems and heuristics approaches. Resource allocation problems

have been evolving to account with a limited extent PD projects. The introduction of more uncertainty in their models reflects that RCPSP is moving into a more *'design'* thinking (Golenko-Ginzburg *et al.* 2003). This can lead to more of these approaches to be applicable in the realm of design processes.

2.6   Resources involved in engineering design process modelling

This section presents analytical models that focus on resource management or include any type of design resources for other purposes (e.g., communication between stakeholders). Most of them are built using or extending modelling frameworks from Section 2.5. The sub-section is structured according to the elements that have been considered as resources by the models.

2.6.1   Models using resources as constraints or inputs

Some task network models consider resources as *'constraints'*, i.e. as elements needed to be in place to execute activities but limited in number or availability.

Belhe and Kusiak (1996) extended IDEF3 to schedule design activities with precedence and multiple resource constraints. The model allows OR relationship, adding to the existing AND relationships between precedence networks. Resources in the model are inputs needed to perform the activities. The model schedules resources in the form of constraints by defining the type, the amount needed by each activity, and the upper time duration for the process. The algorithm finds the best path to complete the process. Nevertheless, the research implicitly mentions designers as possible design resources.

CPM (Kelley and Walker 1959) and PERT (Miller 1963) have been used to model processes with activities competing for the same resources. Limited availability of resources can cause delay and bottlenecks, ultimately affecting on the overall project lead-time. Both models allow the identification of the critical path to subsequently analyse where and how much resources are needed to minimise delay risks. CPM has been widely used as the based framework in areas of OR (Section 2.5.4).

Andersson *et al.* (1998) have extended GERT with Monte-Carlo simulations, in which reworking a task impacts on process durations and likelihood of success. Each task has a time duration, cost per unit, and iteration likelihood values. In this model, learning curves could influence process behaviour by reducing iteration likelihood and task duration after each iteration following different functions (e.g., constant time, step down in time, learning by doing, etc.), providing a more realistic situation. The work was applied to an industrial case study. Although the main aim of the model is to conduct sensitivity

analysis between lead time and cost by exploring different process paths and perturbing iteration probability, the inclusion of learning acknowledges that resource performance is not always homogenous.

Browning and Eppinger (2002) used Monte Carlo simulations on a DSM model to explore alternative process architectures by calculating likelihood distributions of cost and process duration. The model incorporates different ways to capture uncertainty such as stochastic activity durations and cost, iteration likelihood, etc. Additionally, learning after iteration is present for both time and iteration likelihood. The model includes an extension to add resources as constraints for task execution. As a result, resource constraints could indirectly relate resources with task cost, duration and/or learning. The method was applied to an industrial case study.

Cho and Eppinger (2005) used DSM for resource scheduling in an advanced simulation model, which introduces a weighted parameter to decide heuristically which tasks are more important to execute first in case of resource competition. The model assumes that activities have unalterable resource requirements. Resources are included in a fixed and renewable pool, which consists on specialised individual or group of resources that exhibits the same performance or effectiveness. However, the model does not guarantee optimum allocation of resources. It was applied on a case study, but the author's argued that further empirical validation is needed.

Browning (2002) uses DSM to depict internal and external inputs, and internal and external outputs, to integrate the process into a larger picture. The model aims to improve task sequencing in which resources are treated as constraints needed for activity execution. The model studies the optimum process schedule since expected time savings from starting activities earlier might be offset by possible rework. Rework could also increase costs since resources perform the same task twice, instead of dedicating their efforts on other projects.

Clarkson *et al.* (2000) and Wynn *et al.* (2006) developed Signposting and ASM respectively, which are models that use resources as constraints during Monte-Carlo simulations of the design process path. Particularly, ASM allows to model resources as different entities in a specific pool, which enables the modeller to decide the resource type and quantity needed. Then, each activity indicates the required resources to perform it (type and quantity). Tasks can only begin when the necessary resources are available from the pool, only returning them when the task is completed. They were both developed in collaboration with industry and applied to industrial case studies.

Joglekar and Ford (2005) extended the SD model and control theory to explore resource allocation policies with the aim of improving project duration and test the impact of

concurrence on resource allocation effectiveness. The analysis focuses on testing different resource allocation policies, including '*foresight*' policies that take into account future resource needs, to compare against the backlog policy approach. The model mentions design resources as designers and it was applied on an existing model. A further extension by Lee *et al.* (2007) focused on explaining the effects, sometimes counterintuitive, of reduction project time through policies such as '*foresight*'. For example, minimum resource allocation delay does not always translate into a reduction in process duration.

Golenko-Ginzburg *et al.* (2003) developed a heuristic algorithm for RCPSP with alternative stochastic network projects. A network project, based on GERT, with probabilistic outcomes and stochastic activity duration (probability density distribution) is used to allocate resources. The model includes resources such as machines and manpower that are limited for the project. During a simulation, activities require resources to start. The method aims to minimise project duration using the proposed heuristic algorithm. It was applied on a numerical example. Golenko-Ginzburg *et al.* (2003) acknowledge that for some projects, especially the development of new products, the uncertainty level is too high to use deterministic and homogenous activities.

The above models consider resource as elements needed to be in place to execute activities but limited in number or availability. The relatively high number of models concerned with resource constraints highlights the importance of this attribute. Paradoxically, these methods seldom mention what the constraint refers to, which sometimes can lead to misunderstanding to which resources are being managed.

2.6.2   Models using resources as effort

Other task-based models have the capability of estimating the necessary amount of resources. Resources are thus treated as '*effort*' or any other implicit element that could help to accomplish a task or process. Some models that consider resources as effort:

Lee *et al.* (2004) extended DSM to calculate how much resources are needed to finish a design process in a desire number of iterations. Two different analyses, one homogenous and one non homogenous, provide insights into which tasks consumes more resources and time and monitors and control the rate of convergence of concurrent tasks respectively. It was applied on a camera design from another paper. As a result, a feedback gain matrix is provided to improve stability and convergence rate of concurrent tasks. The model explicitly refers to effort, although mentions resources such as designers.

Yassine *et al.* (2003) used DSM to study design '*churns*' (the not convergence of a process). The discovery of churns can avoid a vicious cycle of fire-fighting, allocating resources randomly, by allocating them to bottleneck tasks. The approach differentiates design

process teams in local and global sets and studies the interaction of information flow to determine through a mathematical model whether the design process will produce churns or converge. The strategies proposed to mitigate this risk include identifying bottlenecks, incorporate more resources to key tasks, and strategise rework situations.

Ullman *et al.* (1997) developed a technique that helps deciding where to invest more resources. The method has the ability to model stakeholder's biases and dynamics to decide where the effort (adding resources) should be allocated to increase knowledge and confidence on a decision.

Kusiak and Park (1990) developed a method to minimise project make-span through scheduling concurrent activities. The method decomposes a system into physical modules and activities in the form of a matrix and uses an algorithm to effectively cluster the activities. The aim is to effectively use the right amount of relevant design resources.

Similarly, the models often do not indicate what type of design resource is being managed or used, simply treating them as effort. It is also interesting to point out that effort, although measured in time, is presented as an element to evaluate the cost of the process.

2.6.3   Models using resources as designers

Some task based models have studied the use of designers in the design process. IDEF0 has been modified to model and analyse Integrated Product Teams (IPT) (Sim *et al.* 2009). The method centres on the idea that designers should be modelled as input entities since they perform the functions in the process. Extensions included temporal descriptions, performance metrics (e.g., cost and quality), and social aspects of designers. Signposting and ASM models, even though not explicitly stated, have the possibility to indicate that the resource constraint is a designer. Yassine *et al.* (2013) were concerned that the optimisation of process flow, product modularisation and efficient team arrangements that have traditionally done separately. However, this could miss the inefficiencies drawn upon the intersection of these domains. Hence, they extended MDDSM with heuristic methods to study and improve the relationships of the three key components of PD, the people, the product and the process. Additionally, different applications of MDM can be found in Danilovic and Browning (2007), which comprises exploring the interaction between different design process elements (tasks, product components and designers). Loch and Terwiesch (1998) developed a model to analyse the optimum level of task overlapping and communication with the goal of minimising lead-time. The hypothesis roots on that increasing communication, which incurs on rework delay, could help reduce overall rework in overlapped activities. The results showed that overlapping activities could have positive impact on project lead-time, being the impact larger in projects with

high and early uncertainty resolution. Adler *et al.* (1995) proposed a stochastic queuing model to calculate development time. The model provides a network of design team resources (in work stations) and jobs that must be performed. Each job is either being performed at the stations or waiting in the queue.

Hassannezhad *et al.* (2015) used Signposting as an ABM to study socio-technical properties. The model analyses resource schedules in a situation where some designers have multiple skills and can perform the same type of activities. Those designers interact between each other and the tasks, through socio-technical attributes (e.g., communication, motivation, etc.), to execute the process. An extension to ASM, called CPiW and developed by Wynn *et al.* (2014), predicts the resulting resource requirements and schedule risk after an externally imposed process change. The model is embedded in the CAM software and uses a workflow representation. During the simulation a task is undertaken to incorporate changes in its inputs, hence triggering an information output that could produce change propagation in downstream activities. The model uses agents as resources that perform the design activities. These agents complete each task individually, which means a queue is formed with downstream activities that needs to be reworked as a consequence of the change propagation. The parameters used are activity duration and propagation likelihood matrix. The extent at which the changes will impact subsequent activities is accounted by a *'duration sensitivity matrix'* for duration and *'output sensitivity matrix'* for the amount of necessary rework.

Some ABMs have been concerned with supporting communication, coordination and negotiation of decisions between stakeholders in the design process. These approaches normally involve *'human designers'*. They are able to model the interaction of design teams, including different designers' behaviour, and coordinate task execution for resources. Lian *et al.* (2009) employed a method to coordinate the use of resources amongst agents using Petri Nets as basis. The population of the model is composed of individual agents defining local behaviour and a coordinator that allocates the common resources. Madhusudan (2005) extended Agent-Based Process Coordination (ABPC) to an approach that helps decision making in planning and task sharing using agents that allocate tasks based on its needs, resource capabilities, and process state. Agents include coordinator agent and service agents (CAD, analysis, finite element analysis, material, and manufacturing-related). The approach was applied to a real world case study. Crowder *et al.* (2012) developed, in an industrial context, a collaborative agent based model for simulating teamwork. The model includes a number of variables at an individual level (competency, motivation, availability, response rate), team level (communication, shared mental models, trust), and task level (difficulty, workflow), which jointly shapes team performance in a project. The population of the model comprises three

types of agents: *Designer Agent* as the design engineer, *Resource Agent* as the team's computational information resource, and *Task Manager* as the management agent. During a simulation, tasks that are assigned to *Designer Agents* by the *Task Manager*. The algorithm computes the qualities of the designer and the characteristics of the task to output time to complete the task, working time, quality and learning time. The *Designer Agent* asks the *Resource Agent* for another designer to deliver information when the task level is higher than the designer's capabilities. Danesh and Jin (2001) developed Agent Network Decision (AND), a collaborative model that aids decision-making in concurrent engineering to reduce downstream iterations. The method captures the decisions about the process from each designer and supports negotiation between them, and it was presented with an example. Additionally, to support project execution, ABMs were used to shape collaborative environment platforms with the aim of allocating jobs and coordinating tools, resources and information during a distributed design process. Hao *et al.* (2006) developed such a platform using a process model with tasks that are allocated to the designers along with all the necessary parameter and files.

Competitive ABMs have also been present in PD, modelling designers as agents. Canbaz *et al.* (2014) developed a framework to simulate the overall performance of a design process, in which designers have different preferences on design targets and uncertainties are present. Monte Carlo simulations were used to explore and reduce design conflicts on an example from academia. Jin and Levitt (1996) extended the Virtual Design Team (VDT) in collaboration with industry, a multi- agent modelling framework to assess different configurations of design processes using discrete-event simulation. VDT models a variety of influences upon agent behaviours, including level of interdependency strength between activities and discrepancy between actors' goals. A satellite launch vehicle design was presented as case study to evaluate the impact of changes in process configuration on performance, for instance increasing agent skills or aligning goals. Theory wise, Coates (2006) developed a multi agent system methodology to coordinate distributed design teams in terms of scheduling of tasks and allocation of resources.

SD models have dealt with improving the use of designers within the design process. Lyneis *et al.* (2001)'s SD model, based on the rework cycle by Cooper (1980), analysed the influence and impact of different elements on productivity quality. Examples of discovered insights to enhance project performance included the level of experienced engineers and supervisors to increase, the development of more aggressive schedules, different staffing strategy, etc.

Designers have been extensively modelled for different purposes, including scheduling and coordination/competition analysis. Nevertheless, heterogeneity of designers has been mostly modelled for the later purpose.

2.6.4   Models using resources as tools and testing

ABMs sometimes involve *'tools'* used during the process. Madhusudan (2005) included service agents (CAD, FEA, etc.), and other models such as Clarkson *et al.* (2000), Wynn *et al.* (2006), and DSM models could be extended to consider tools (computational, design tools, etc.) as constraints. Some ABMs, as Hao *et al.* (2006)'s platform, helps to coordinate the use of tools.

In the area of testing, Loch *et al.* (2001) developed a model that estimates the right level of parallel or sequential testing in a product design process. Both have their advantages: sequential testing allows designers to learn from each test and reduced the number of tests, while parallel testing is generally faster. The model supports decision making of the ideal testing procedure (parallel, serial or mix) for the process with the objective of minimising cost and time of testing.

It is apparent that the estimation, allocation, and scheduling of tools and testing resources have been overlooked by researchers in the area, despite their key role in the process.

2.7   Discussion

The discussion of the reviewed literature is divided in the following sub-sections. Firstly, analytical models addressing resource management issues are discussed. Secondly, analysis of how these approaches model resources, the used performance metrics and resource attributes is presented. Thirdly, research gaps are discussed. They are mainly related to the way resource models have overlooked different types of resources and the effectiveness of each instance. Finally, a way to address the identified research gap is introduced.

2.7.1   Suitability of analytical models for resource management

Activity-network models have been widely used to address resource estimation, allocation and scheduling. In addition, these models have a focus on process improvement while capturing design evolution with enough detail and at different levels of granularity. Furthermore, they can capture the uncertainty of design in a variety of ways: *iteration*, *multiple outcome routes*, *stochastic time*, *probability of task failure* (leads to unexpected rework). The insights they provide can offer enough support for managerial decisions. Moreover, allocation and scheduling of resources to specific tasks requires a framework that can represent activities. Thus activity-network models are suitable candidates to support resource management for the purposes of this thesis.

ABMs are usually concerned with improving interactions between designers (or designer and tools) rather than structural analysis of the process. Their focus includes supporting communication, coordination, negotiation, and process interactions between agents and tasks. As a result of incorporating *socio-technical attributes*, they are able to model the behaviour of designers and their relationships. These models can also use a centralised coordinator to allocate tasks based on its needs, capabilities of the resource, and the state of the process. ABMs acknowledge the heterogeneity between different instances of designers, for example having different capabilities and goals.

Another type of analytical models, SD, include resources as whole entities, occasionally mentioning designers and effort. However, the analyses of SD models are focused on providing overall project insights on policies, and are too abstract for day-to-day managerial decisions in planning and scheduling.

Similarly, queuing models are less suitable to depict the design of complex products since they capture less uncertainties compared to other analytical approaches. Queuing models mainly deal with projects consisting of deterministic and homogenous activities that are normally well known a priori. However, iterations play an essential role in the modelling of design processes, which limits the suitability of techniques such as PERT/CPM that most RCPSPs are based on. They are concerned with optimising algorithms rather than developing modelling frameworks, more typical of the design field. Thus, there is a the lack of OR literature on the topic of design processes (O'Donovan 2004). Golenko-Ginzburg *et al.* (2003) argued that projects designing new products will undeniably introduce uncertainty in their process that has to be accounted with alternative outcomes. This can reflect that, at some level, RCPSP is moving into a more *'design'* thinking mode. Since RCPSPs have extensively researched project behaviour in resource scarce environments, it could be helpful to adapt some of their characteristics to the specific properties/behaviours of design process. Particularly the way RCPSP models process behaviour is captured by the three fields' classification scheme: *resource's attributes*, *activity's characteristics* and *performance objectives*. Consequently, it is important to model resource attributes and their interactions with tasks during the development of the support method in Chapters 5 and 6.

Finally, some models such as Wynn *et al.* (2006), Clarkson *et al.* (2000), Jin and Levitt (1996) or Crowder *et al.* (2012) were developed in collaboration with industry. Hence, their relevance, usability and applicability could have a higher face validity than the more theoretical ones.

2.7.2 Modelled resources, performance metrics, and attributes

Despite all the literature involving resources in design process modelling, often what is considered a resource is not clarified. Some approaches, such as task network models, acknowledge the existence of resources as a constraint for task execution or effort needed. Resources were not concisely defined, just merely elements needed to perform the activities (availability) or effort necessary to accomplish the tasks. For instance, Ullman *et al.* (1997) aids on deciding where to add resources without mentioning what kind of resource. It could have been designers, money, effort, etc. However, the approaches that mentioned and modelled resources often refer to designers. Thus, logically researchers have studied competences and performance of designers (Ahmed 2007; Crowder *et al.* 2012), while resources such as computational hardware, software, testing resources, amongst others have been overlooked during process planning stages despite their capital importance towards delivering the product (Chapter 1). ABMs have sometimes incorporated specific tools. However, they have mainly modelled designers. Similarly, SD models also focused on constraints and designers.

Numerous researchers have identified that achieving PD schedule deadlines is one of the most important performance indicators (Patterson 1993; Meyer 1993; Wheelwright and Clark 1992). Consequently, many of the reviewed models have *process duration* and *effort* as key performance metrics. *Cost* has been modelled in a lesser degree. However, Ulrich and Eppinger (2011) estimated that a PD project cost is proportional to the number of people involved and the duration of the project. A possible explanation is that some of these models measured cost as effort, i.e. designer's time spent on the activities. Yet, final cost based on each resource's effort can be different if resources hold different value to the company. It appears reasonable that a more effective resource will be more costly or valuable to the organisation.

A key feature of design processes is *iteration*, the main driver of improving design *quality* to the right standards (Safoutin and Smith 1996; Smith and Leong 1998; Whitney 1990), with the trade-off of increasing cost and schedule risk (Adler *et al.* 1995). It seems logical that iteration likelihood was modelled as an attribute in some approaches. Some other models (e.g., Signposting) rely on the concept of achieving enough *confidence* to select the next candidate task. Andersson *et al.* (1998) or Browning and Eppinger (2002), included *learning* after iteration as a resource attribute. Andersson *et al.* (1998) stated that *learning* increases the flexibility and accuracy of the model. He provides an illustrative example of a design process, in which large amounts of CAD work is necessary. After the creation of the first CAD models, subsequent rework will take less time and risk. If there is learning, time and risk could be reduced or stay constant. The attribute of *availability* is also key for a large number of models (Belhe and Kusiak 1996; Browning and

Eppinger 2002), since the absence of the required resource impedes the activity to begin, increasing waiting time and total process duration. Design processes, as multidisciplinary endeavours, usually require *skills* from different functional groups to contribute to the goal (Belhe and Kusiak 1995). An attribute incorporated by some of the methods (Crowder *et al.* 2012; Canbaz *et al.* 2014) were less focused on performance improvement but more on coordination or competition. Designers involved might possess different *expertise* that translates to distinctive effectiveness when performing the same activity (Ahmed *et al.* 2000). Consequently, it seems fitting that *process duration, effort* and *cost* are the main process performance metrics since the rest of attributes, *availability/quantity, confidence, iteration likelihood, skills/expertise, and socio-technical*, determined their effectiveness and influence on performance outcome. *Quality* is out of scope in this thesis (Chapter 1).

2.7.3 Research gap of resource management

Design activities are executed by a mix of designers from different disciplines and expertise (Belhe and Kusiak 1995). Different researchers have studied the influence of designers' experience and effectiveness on activities (Section 1.2.3). Similarly, computational resources have a range of capabilities and computational power to perform simulations (Section 1.2.3). However, traditional models have overlooked important resources such as computation and testing. Additionally, very few models can support different types of resources and fully incorporate their aforementioned attributes, which are the drivers of resource effectiveness. The study of the impact of resource effectiveness on process performance has not been researched thoroughly. There is an inherent complexity in deciding what instance of the resource should perform which tasks (perturbing resource allocation) taking into account their effectiveness towards task completion while adjusting to their availabilities and costs. In other words, the trade-off between effectiveness, availability and cost makes applying the right resources to the right tasks in the correct order a difficult decision.

Key managerial questions emerge with these complexities, for example: How to predict, plan and optimise future resource needs? Which resource should be allocated if it would be unavailable for subsequent tasks? How can processes be planned around key resources? Which activities are more sensitive towards a change of designer?

2.7.4   Improving resource management

Process structure based improvements (increasing concurrency, instating cross functional teams, etc.) and resource management are two of the primary approaches to enhance process performance (Joglekar and Ford 2005). Nevertheless, sometimes is difficult to reduce process duration with process structure improvements but still feasible with effective resource management. Even when resource quantities are fixed, effective resource allocation and scheduling could increase process performance (Joglekar and Ford 2005). Researchers have extensively used process modelling and simulation to study the effects of alternative process architecture (Smith and Eppinger 1997a, 1997b, 1998; Ko *et al.* 2010; Krishnan 1996; Krishnan *et al.* 1997). As explained, less work has been done on simulating alternative resource allocation strategies and utilisation, the main topic of this thesis. This can provide further insights on process behaviour and help decision making to answer the above questions.

In this context, process modelling and simulation could help in this endeavour (Andersson *et al.* 1998). Sensitivity analysis from process modelling simulation to understand the variability of key performance metrics can provide managerial insights (Andersson *et al.* 1998). Therefore, a process modelling approach to improve the way in which resources are planned, allocated and scheduled is proposed for this thesis. Resource modelling capabilities need to be enhanced, while keeping the ability to capture design uncertainties. Ultimately the method should suggest and aid design process improvements to achieve the desired performance. However, before such a method is developed, it is necessary to better understand the different types of resources and how their attributes influence process performance. Empirical investigations can provide a more comprehensive understanding on this matter (Chapter 4).

Table 2 and Table 3 lists the most relevant models found in literature indicating the type of analytical model, the used modelling framework and the purpose of the model according to the scoping in Section 2.3. In terms of the purpose of the model, only planning and execution areas are presented since this research aims to primarily support these two areas. The tables also specify what resources were modelled, the attributes linked to them and the performance metrics they impact. The attributes must be directly related to the resource, which means that they should not just be part of the model but has to relate to the resource behaviour in the process. For example, Browning and Eppinger (2002) includes iteration likelihood in the model but it does not relate to the used resource. While iteration likelihood is perturbed to study its effect on the process, the resource is set to be a fixed constraint. On the other hand, learning is mentioned as a possibility if the resource repeats an already familiar task.

Table 2. Categorisation of resource management approaches (part 1)

Category	Attribute	Loch et al. (2001)	Kusiak and Park (1990)	Loch and Terwiesch (1998)	Ullman et al. (1997)	Wynn (2007)	Clarkson et al. (2000)	Browning (2002)	Yassine et al. (2013)	Yassine et al. (2003)	Lee et al. (2004)	Cho and Eppinger (2005)	Browning and Eppinger (2002)	Andersson et al. (1998)	Kelley and Morgan (1959); Miller (1963)	Belhe and Kusiak (1996)	Sim et al. (2009)
Framework		Concurrent	Concurrent	Concurrent	Concurrent	ASM	Signposting	DSM	DSM	DSM	DSM	DSM	DSM	GERT	CPM/PERT	IDEF3	IDEF0
Purpose	Estimation		•		•	•				•		•					
	Allocation					•											
	Scheduling	•	•			•		•	•		•			•	•	•	
	Structuring and sequencing activities	•	•	•				•	•	•		•	•				
	Improving process performance		•	•		•	•	•			•			•	•		
	Monitoring and control																
	Dynamic support						•										
	Changes																
	Making commitments (coordination/competition)																
	Communication			•													
Resource	Constraint					•	•	•			•	•	•	•	•	•	
	Effort		•		•				•	•							
	Designer			•		•	•			•							•
	Tools and testing	•				•	•										
Performance	Time	•	•	•		•	•	•	•		•	•		•	•	•	•
	Cost or effort	•	•		•			•	•		•	•		•			
	Quality					•	•		•								•
Attributes modelled	Availability	•	•			•	•	•	•	•		•			•	•	
	Quantity	•	•		•	•	•	•	•	•		•	•		•	•	
	Confidence																
	Iteration likelihood										•			•			
	Learning curves											•	•	•			
	Skills or expertise																
	Socio-Technical (collaboration, communication, etc.)																•

Type of model: Task network

Table 3. Categorisation of resource management approaches (part 2)

	Adler et al. (1995)	Golenko-Ginzburg et al. (2003)	Lee et al. (2007)	Joglekar and Ford (2005)	Lyneis et al. (2001)	Danesh and Jin (2001)	Jin and Levitt (1996)	Canbaz et al. (2014)	Hao et al. (2006)	Coates (2006)	Crowder et al. (2012)	Madhusudan (2005)	Lian et al. (2009)	Wynn et al. (2014)	Hassannezhad et al. (2015)
Type of model	Queuing model	Queuing model	SD	SD	SD	ABM	ABM	ABM	ABM	ABM	ABM	ABM	ABM/queueing	ABM/network/queueing	Mix Task Signposting
Framework	Queuing	GERT	SD	SD	SD	AND	VDT	ABM	ABM	ABM	ABM	ABPC	ABM/Petri	CPIW	Signposting
Purpose — Estimation		•	•	•							•		•	•	
Purpose — Allocation	•				•					•				•	•
Purpose — Scheduling	•	•	•	•											•
Purpose — Structuring and sequencing activities															
Purpose — Improving process performance	•	•	•	•											•
Purpose — Monitoring and control											•		•		
Purpose — Dynamic support						•	•				•			•	•
Purpose — Changes						•								•	
Purpose — Making commitments (coordination/competition)						•	•	•	•	•	•	•	•		
Purpose — Communication						•	•	•	•	•	•	•	•		
Resource — Constraint		•	•	•				•			•			•	
Resource — Effort						•									
Resource — Designer	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Resource — Tools and testing	•								•		•	•			
Performance — Time	•	•	•	•	•									•	•
Performance — Cost or effort														•	
Performance — Quality										•					
Attributes modelled — Availability	•	•	•	•							•		•	•	•
Attributes modelled — Quantity	•	•	•	•							•		•		•
Attributes modelled — Confidence															•
Attributes modelled — Iteration likelihood	•														
Attributes modelled — Learning curves						•					•				•
Attributes modelled — Skills or expertise							•	•	•	•	•	•			•
Attributes modelled — Socio-Technical (collaboration, communication, etc.)		•				•	•	•	•	•	•		•		•

2.8 Summary

The chapter aimed to partly answer RQ1 and RQ2 by studying current approaches to improve resource management since the reviewed models have a practical aim. Firstly, resource management was scoped within process management applications to delimit the area of influence and contribution of this thesis. Secondly, design specific modelling approaches and the meaning of design resources were studied to answer **RQ1:** *What are the different types of design resources and the current methods to support their management?* Literature in relevant areas was reviewed to understand how current models have addressed the issue of resource management and what kind of design resources have been considered. The outcome led to believe that existing design planning and scheduling approaches do not capture the behaviour of resources with enough detail. In addition, the study of the effectiveness of using alternative resource instances has been overlooked. However, analytical models were found suitable for extension to fulfil the objectives of this research. In particular, task network frameworks seem to be the most appropriate for this case. Their simulation capabilities are potentially a powerful tool to explore resource management.

Literature study also partly answered **RQ2:** *What key attributes can describe the impact of resources on process performance?* Constraints, effort, designers, tools and testing resources were the resources addressed within the reviewed models. However, they were not concisely presented and further investigation is required. Similarly, a set of attributes were modelled by certain approaches: *availability/quantity, confidence, iteration likelihood, skills/expertise, and socio-technical* that determined effectiveness and influence on performance outcome. Further empirical investigations of the characteristics of resource behaviour within complex design process is necessary to fully address RQ1 and RQ2.

3 Methodology

The Oxford dictionary defines epistemology as *"the theory of knowledge, especially with regard to its methods, validity, and scope, and the distinction between justified belief and opinion"*. Thus, establishing a research paradigm will influence the subsequent choice of methodology, methods and sources (Grix 2002). In contrast with social science research, which usually follows a constructionist paradigm, or natural sciences, which follows a positivist paradigm, design research paradigm is frequently realism. Realists believe that the objective truth can never be fully acquired but they aspire to do so (Cohen and Crabtree 2006). Thus, the aim is to describe the reality as objectively as possible and through a comprehensive understanding of it, prescribe an improved situation. This research will combine both qualitative and quantitative methods to conduct the research, hence requiring a methodology that can integrate both.

A clear methodology helps to deliver rigorous research projects by providing a framework that comprises an approach and a set of supporting methods and guidelines (Blessing and Chakrabarti 2009). Due to the specific nature of design research that involves studies within organisations, only a few methodologies have been developed (e.g., Duffy and O'Donnell 1999; Eckert *et al.* 2003; Blessing and Chakrabarti 2009), often including both descriptive and prescriptive research. Design Research Methodology (DRM) by Blessing and Chakrabarti (2009) is the chosen framework for this research given its focus on design research, clear guidelines and methods, and potential iterative approach. Furthermore, DRM integrates two main aspects of design research: development of understanding and the development of support. Hence, aiming not only to understand but also to improve the design practice. Other methodologies in the field include Duffy and O'Donnell (1999)'s approach and Eckert *et al.* (2003)'s Eightfold path. The DRM provides

more detailed guidance compared to the methodology by Duffy and O'Donnell (1999), which is intended to be more flexible. In addition, this thesis aims to complete one research project, as opposed to guidance provided by the Eightfold path methodology, which is more suited for multiple or on going collaborative projects. DRM is divided in four main stages: Research Classification, Descriptive Study I, Prescriptive Study and Descriptive Study II. DRM is an iterative methodology, revisiting previous stages as more information becomes available. The different stages of DRM applied to this research is introduced in Section 3.1.

3.1   Design Research Methodology applied to this research

DRM proposes seven different project types depending on the level of existing knowledge, resources available and focus of each project.

Type	Condition for employment	Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Comprehensive into criteria	Success and measurable success criteria are little understood	Review based ➡ Comprehensive			
2. Comprehensive study of the existing situation	Criteria can be established, but a better understanding of the existing situation is necessary to identify the most relevant factors to address	Review based ➡ Comprehensive ➡	Initial		
3. Development of support	Understanding of the existing situation obtained from the literature review and reasoning is sufficient to start the development of support	Review based ➡	Review based ➡	Comprehensive ➡	Initial
4. Comprehensive evaluation	Support already exists, but an evaluation of its application is not available	Review based ➡	Review based ➡	Review based Initial ➡ Comprehensive	Comprehensive ⬅
5. Development of support based on a comprehensive study of the existing situation	The aim is to develop support, but the understanding of the existing situation is poor	Review based ➡	Comprehensive ➡	Comprehensive ➡	Initial
6. Development of support and comprehensive evaluation	The understanding of the existing situation obtained from the literature review is sufficient, and the project resources allow formal evaluation of the support	Review based ➡	Review based ➡	Comprehensive ➡	Comprehensive
7. Complete project	Little prior research has been conducted in the area of interest, yet indications are that the area has potential	Review based ➡	Comprehensive ➡	Comprehensive ➡	Comprehensive

Figure 18. Different types of DRM by Blessing and Chakrabarti (2009)

Each stage of DRM can be studied at a different depth depending on the project type. The first four project types have been recommended for Ph.D. research, while the rest potentially go beyond the scope of what is necessary for a Ph.D. However, the fifth type is chosen for this project. Although some literature to gain initial understanding on design resources and influencing factors were identified, due to the broad use of the term and to the author's knowledge, design resources have not been formally synthesised and interpreted (Chapter 2). Therefore, a comprehensive DS-I comprised by extended litera-

ture investigations, preliminary case study in Rolls-Royce plc and initial method experimentation was conducted. This was followed by a comprehensive development of a support method, and an initial DS-II was used to evaluate its applicability and usefulness. Figure 19 summarises the specific methods applied in this research for each DRM stage.
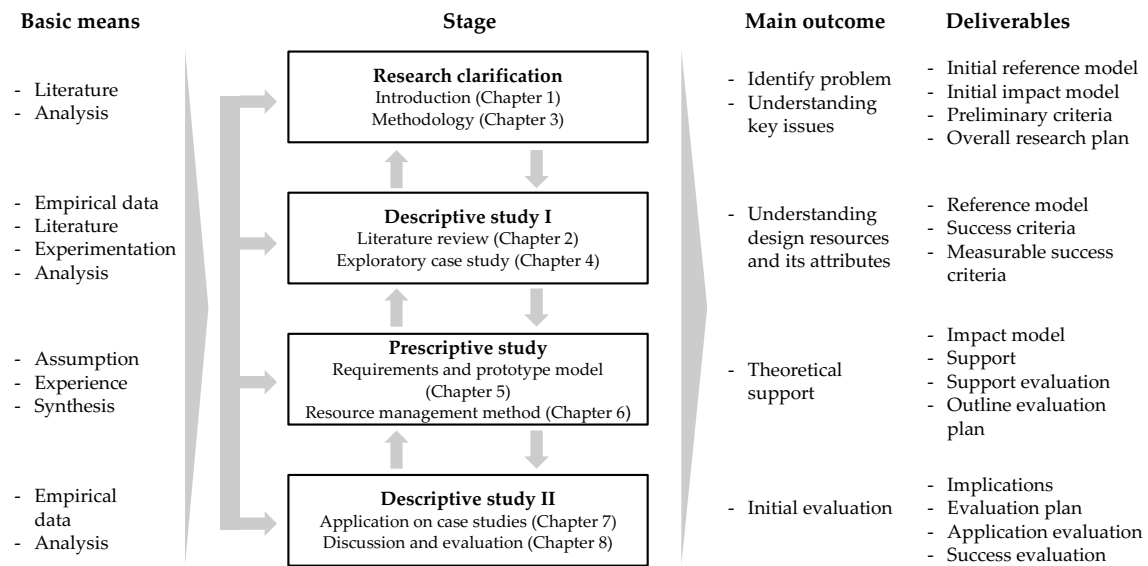
Figure 19. Stages of DRM and methods employed by Blessing and Chakrabarti (2009)

3.1.1   Research Clarification

Research Clarification (RC) helps to comprehend the main research problem, questions and hypothesis through literature review. In RC an initial background investigation was conducted to understand the foundation of the field through engineering design literature, with a focus on identifying major issues. A total of 49 research questions was identified and further synthesised into 17 possible research projects. Inaugural discussions with Ph.D. supervisor and industrial experts from Rolls-Royce plc narrowed down the research proposals according to their relevance to Rolls-Royce plc's current design management issues and author's preference. Finally, analysing impact of resources on process performance was selected as the research topic for this thesis.

An initial literature review was conducted to introduce the field, specify the importance of resources and identify resource management challenges. As a result, the main research question along with two initial granular questions were defined. Research questions are updated, as more information is discovered, at different points during the project. In addition, a research objective and hypothesis was also proposed along with an overall research plan (Table 4). The results of this stage are presented in Chapter 1, part of Chapter 2 and in this chapter, and guided DS-I.

Table 4. Overall research plan defined in Research Clarification stage

Overall research plan	
Research focus	Modelling, simulation and analysis of the impact of relevant design resources on design process performance
Research goal	Contribute to improve resource management in design processes by: • Increasing understanding of different type of design resources and their attributes that define effectiveness in process performance; • Quantifying the trade-off impact of using alternative resource instances on activity and process performance; • Increasing understanding of the impact of resource attributes on process performance; • Contributing to develop and improve process plans by estimating resource needs, allocating and scheduling resources.
Main research question	How can resource management be utilised to improve planning and execution of complex design processes?
Hypothesis	An efficient approach (support method) will provide insights on resource management for decision making.
Relevant areas to be consulted	Resource management in: Engineering design, Modelling and simulation in design, Systems modelling, Task network models, System Dynamics, Agent based models, Queuing models, Systems Engineering, Artificial Intelligence for Engineering Design, Operations Research
Type of research	DRM type 5
Expected areas of contribution	Engineering design, process management, design resources, resource management modelling and simulation
Deliverables	Design resource management approach to improve design process performance

3.1.2   Descriptive Study I

In *Descriptive Study I* (DS-I), a deeper understanding of the current situation, from an academic and practical viewpoint, will allow the development of a *reference model* of the current state of art. This is done through further literature review focus on addressing the research questions along with exploration and investigation of an exploratory case study. This stage identifies key factors to address to improve design practice, along with success criteria and measurable success criteria.

A literature review on current support methods in engineering design to manage design resources is presented in Chapter 2. The focus was on understanding how current approaches define resources and what key factors they addressed while modelling or managing them. Based on the insights gained at this stage, extracting and synthesising what elements are considered design resources and their attributes were essential before any development of a support method. Since many of the approaches in literature were developed to address industrial problems, the author assumes that they are an accurate representation of actual resources in projects.

To provide a comprehensive DS-I, an exploratory case study was conducted in Rolls-Royce plc to complement literature investigations. The objective was to identify and formalise empirically what type of design resources are present in industry and what attributes define them (Chapter 4). Multiple meetings were conducted with design experts from different departments at Rolls-Royce plc. Discussions were focused on understanding key types of design resource, their management and behaviour. The acquired knowledge should help to develop the support method. Hereafter, this also allowed to compare empirical results with theoretical findings from literature (Chapter 2).

As a result, a set of initial requirements for modelling and simulating design resources to improve their management emerged.

3.1.3   Prescriptive Study

The core of *Prescriptive Study* (PS) is to develop a support method, called *impact model*, which addresses the problems and improves the existing situation based on understanding obtained in DS-I. The development of a new method is the core of the research project and it aims to make a relevant contribution to the field. Chapter 5, part of both DS-I and PS, is a first iteration of the support method that improved the *reference model* and yielded in further requirements. Evolution of the support method from *reference model* to first iteration and final *impact model* was achieved through continuous *support evaluation* that involved discussions of the method with the thesis supervisor, Rolls-Royce plc stakeholders, and feedback from academic experts and peer-reviewed publications. The final support method was selected and described in Chapter 6, which presents in detail its fundamental elements, their interrelations, and a toolbox of possible analyses. The final approach comprises the final support method and the procedure to apply this for improving process management. Chapter 6 also includes the conceptual description and detail implementation of the model, introducing definition of its elements and quantifiable functions which can be specified in practice and implemented computationally.

3.1.4 Descriptive Study II

During Descriptive Study II (DS-II), the final stage of DRM, the proposed approach was evaluated in the application and academic success criteria context. The developed method is applied to two design processes at Rolls-Royce plc (Chapter 6), the Fan and the Turbine sub-system preliminary design processes. The interaction with industry will ensure the practical applicability of the developed method and validate the usefulness of the results to design teams (Chapter 7 and 8). The outcome of the evaluation will be essential to adapt and revisit the theoretical model in order to enhance it according to the discovered results, flaws and limitations. Furthermore, the method will be evaluated against the research questions to assess the impact of the model and whether the contribution of the research has fulfilled the initial goals and criteria (Chapter 9).

3.2 Evolution of research questions

The principal research question for this project as derived in Chapter 1.

Principal research question: *How can resource management be utilised to improve planning and execution of complex design processes?*

This research aims to address the above question by first exploring the current understanding of design resources both in academia and industry, along with their management and support methods. Subsequently, the objective is to develop and evaluate a comprehensive approach for resource management based on the initially established knowledge.

Firstly, two more granular questions were derived in Chapter 1 from the principal research question to guide DS-I:

RQ1: *What are the different types of design resources and the current methods to support their management?*

RQ2: *What key attributes can describe the impact of resources on process performance?*

RQ1 explores how methods in engineering design models and simulates design resources to support resource management, their relevant properties and capabilities but also potential shortcomings of current approaches. Emphasis is placed on understanding the meaning of design resources by these approaches, which were developed to aid industry. RQ2 explores the attributes that the different design resources have to impact on process performance, namely time, cost and quality. Hence, RQ1 and RQ2 are partly covered by literature review and extended with an exploratory case study to investigate actual resources in industry, their attributes and interrelationships with the tasks they undertake, and impact on process performance. The objective is threefold: correlate with

findings in literature, consolidate the knowledge on design resources, and use it as foundation for the comprehensive approach (support method).

Addressing RQ1 and RQ2 cemented the motivation for this research and provided the necessary foundation for the development of a comprehensive resource management approach. Exploration of the first two questions also led to the formulation of five other detailed research questions, decomposing the principal research question into a total of seven successive questions to conduct this thesis:

RQ3: *What are the requirements for a model that might enable prediction of the resource impact on process performance?*

RQ4: *What is a suitable concept(s) for a model for resource management that fulfils the requirements in RQ3?*

RQ5: *How well does the model concept meets the requirements in RQ3?*

RQ6: *How can the model be used in an approach for resource management to improve design process planning?*

RQ7: *How useful and usable is the developed resource management approach in industrial applications?*

The investigations guided by the first two questions yielded in a set of requirements for a resource management model in RQ3. The requirements were continuously revised and updated throughout the research, including an initial iteration of resource management model in Chapter 5. Standard stages of a systematic design process were applied for the development of a resource management approach (Figure 20). As RQ3 identified the functional requirements for a conceptual design of a resource management model, RQ4 explored the suitability of model concepts against the underlying boundaries set by the requirements (Chapter 5 and 6). A final support method was elaborated in detail by investigating RQ5 (Chapter 6) and integrated into an overall approach for resource management, addressing RQ6. Finally, the developed approach was applied in practice with two detailed industrial case studies and evaluated to answer RQ7 (Chapters 7 and 8).

The evolved research questions are addressed in the following chapters as shown in Figure 20:
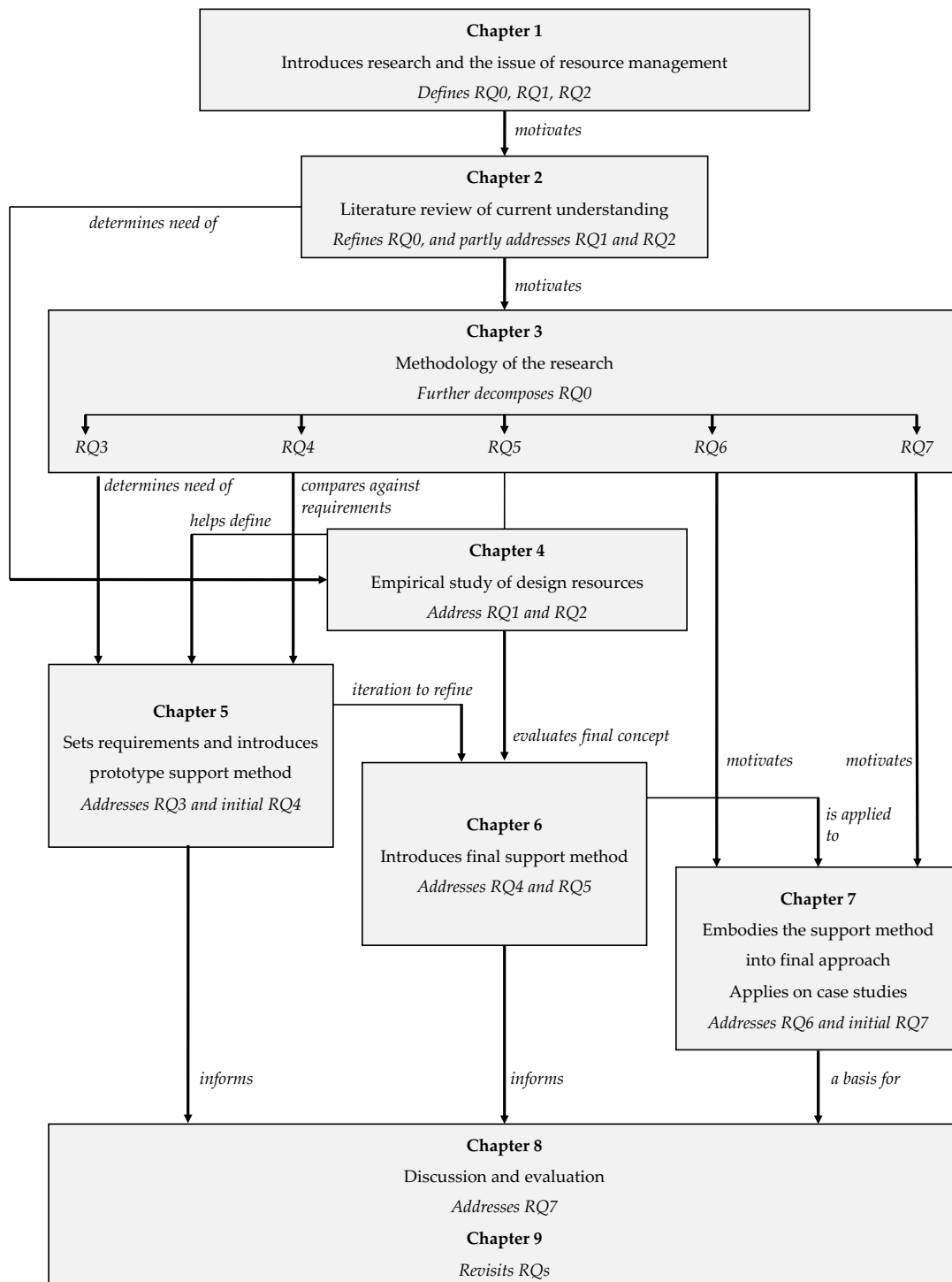
Figure 20. Evolution of research questions and thesis structure

3.3   Summary

The chapter presented the underlying methodology of this thesis, DRM, which should provide a comprehensive framework that can deliver rigour to the conducted research.

A research plan is introduced following the different stages of DRM, and decomposed into the chapters of this thesis. Principal research question and more granular research questions were presented to provide detail guidance. The development of an appropriate approach for resource management follows typical stages of a design process. After enough knowledge is achieved through literature and industrial investigations, a set of functional requirements emerged. An initial concept model is developed and iterated by addressing the requirements. The final model is then integrated in an overall approach for resource management that can improve design process performance. The approach is applied and evaluated using two industrial case studies.

4 Exploratory case study

An exploratory empirical study was conducted to complement literature investigations and deliver a comprehensive DS-I. This chapter aims to answer RQ1 and RQ2 by investigating the types of resources in industry and their key attributes that impact performance. This is done through studying the actual resources used in an organisation such as Rolls-Royce plc. The investigations explore Rolls-Royce plc resources to increase the understanding of design resources, the way they are managed and their attributes that impact process performance. The findings were referenced and compared with literature results.

Section 4.1 presents the background of the case study and Section 4.2 details the method followed. Section 4.3 introduces the different resources found in industry, while the subsections detail the way they are allocated and scheduled in the design process, and their attributes that impact process performance. Section 4.4 discusses the findings and proposes a set of requirements to distinguish design resources. Section 4.5 summarises the chapter.

4.1 Case study background: industrial context, needs, and objectives

Rolls Royce plc was founded in 1906 by Henry Royce and Charles Rolls as a manufacturer of luxury cars before diversifying into aircraft engine manufacturing. Rolls-Royce plc produced its first aircraft engine in 1914, and it is currently one of three leading providers of power systems in the civil aerospace, defence aerospace, marine and energy sectors. In 2013 the company employed around 55,000 personnel in 50 countries and has

annual revenues of £15.5 billion (Rolls-Royce plc 2014). This section provides an outline of Rolls-Royce plc preliminary design process of new products.

The investigated company works under a bidding system, in which a number of competing companies present their preliminary design as a proposal for the same contract. The aircraft manufacturer initiates the preliminary jet engine design via a request-for-information or a request-for-proposal to Rolls-Royce plc. A set of customer requirements coupled with the company's market research regarding airline needs, competitor actions and technology trends are considered for the design. The process is run and coordinated by a Central Division, defined as the vertebral column of new projects. The early stage design process starts with generation of first concepts by Preliminary Design division that feeds to Sub-system divisions, including functional requirements, which is called request-for-a-bid. More detailed work on specific parts of the product, aerodynamic and mechanical design activities are carried out by each sub-system team to fulfil key functional requirements. Then, each sub-system bids its design back to the Preliminary Design team to be integrated. The process is highly iterative and interchanges information between divisions and with customers through the Central Division until a solution satisfies all requirements.

The final proposal is then sent to the aircraft manufacturer. Once the contract is obtained, orders are placed before the product is fully designed, developed and produced. Contractual agreements set timelines to deliver the product, and breaching them will result in financial penalties. A simple depiction of the Preliminary Design division and interactions can be seen in Figure 21.
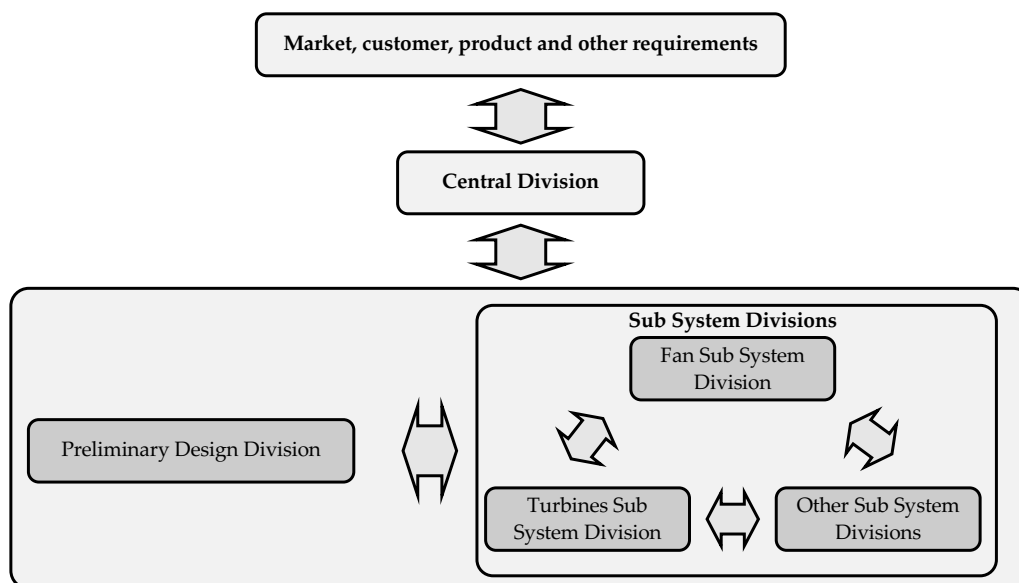
Figure 21. Simplified view of company's design divisions based on case study experience. Similarly described in Fernandes *et al.* (2014)

The company has continuously worked on improving its design processes. In this context, management have been generally concerned with the use of their limited resources to enhance their process performance in terms of:

- *'Quality'*: Due to the end use of the product, its quality cannot be compromised;
- *'Cost'*: The company constantly looks to cut cost expenditure to improve profitability;
- *'Time'*: Since their product has to be integrated into a bigger system, the sooner they can produce a bid, the more they can influence the customer's design and secure the contract. Additionally, the final product must be delivered on time to avoid any financial penalties.

Rolls-Royce plc's design process features all the characteristics of a complex PD project. As most aerospace industry products, the development process needs the integration of thousands of engineers and is coupled with uncertainty, risk and iterations. However, the company is mature enough to understand their design process since specific instances of it are conducted regularly for different designs. The other main reason to have Rolls-Royce plc as a case study is the large variety of resources the company uses, both human and instrumental. Thus, making it an ideal preliminary case study and also suitable for the application of a novel design support method in Chapter 7.

The objective of the exploratory case study is threefold: 1) understand what are considered design resources; 2) understand how resources are currently managed in the company; 3) understand the attributes and behaviour of resources that could be valuable to capture. Since design resources have not been formally classified (Chapter 2), discussion is focused on extracting requirements that allows identifying design resources that should be modelled.

4.2   Case study method

In order to enhance the understanding of the use of resources in industry, a set of interviews with experts in the organisation was conducted. Semi-structured interviews were an appropriate method for the exploratory case study, as they allowed experts to introduce fundamental process information and organisational functioning insights as well as giving the author the possibility to ask both high and detailed level questions whenever necessary.

Figure 22 describes the 16 interviews[1] that were conducted in this study. Both high and detailed levels of the product development process were investigated through five exploratory meetings followed by 11 semi-structured interviews based on developed interview guides. A visit to testing facilities concluded the study and provided additional insights.
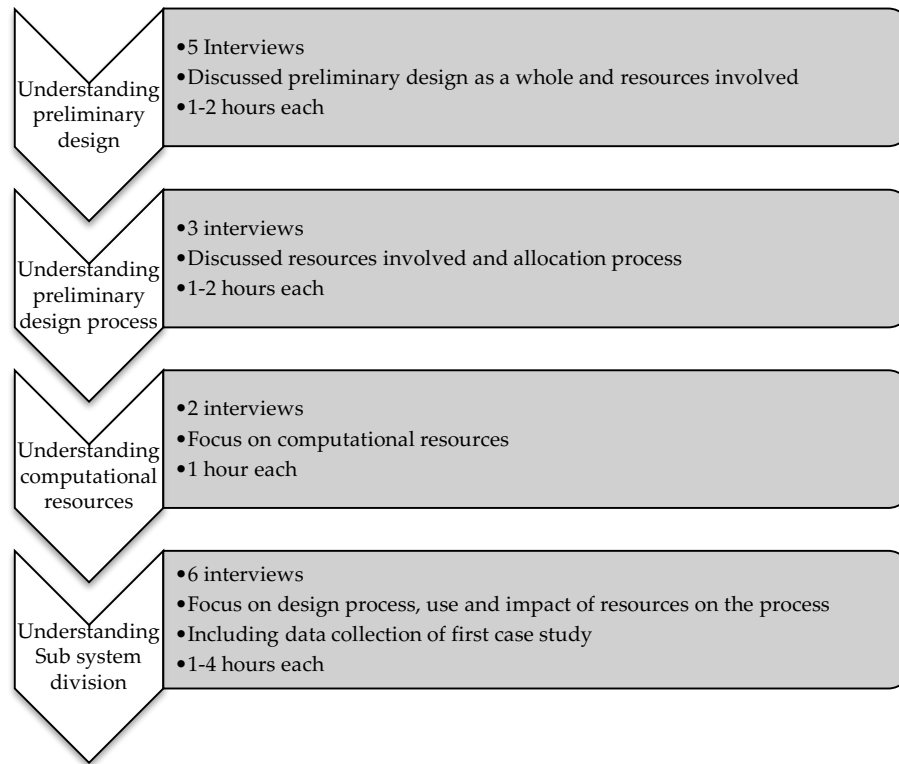
Figure 22. Exploratory case study interviews

To establish a comprehensive study of the resources involved in design, interviews first addressed the main stages of a typical design process: design clarification, conceptual design, embodiment and detailed design (Hales and Gooch 2004). Subsequently, resource classifications found in literature review were presented to interviewees and compared with the resource list mentioned during the interviews. Finally, discussion shifted specifically on resource allocation and utilisation in order to better contextualise and understand the impact of some specific resource attributes on process performance outputs. In total, approximately 38 hours of interviews were recorded and transcribed.

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[1] Interviews were conducted with Daniel Shapiro, another Ph.D. student at the EDC funded by Rolls-Royce plc, who focused on understanding a different aspect of design processes (Design Process Changes) and developed a different design support method.

4.3 The use of design resources as observed in industry

In PD literature, Cross (2000) has studied how designers think and design. In particular, he also mentions resources such as equipment, facilities, and materials used. Ulrich and Eppinger (2011) have mentioned that primary resources to manage are staff effort (man-hours) and physical resources such as model shop facilities, rapid prototyping equipment, pilot productions lines, testing facilities, and so on. Chapter 2 identified, from modelling approaches, design resources such as *designers*, *tools and testing*, *effort* and *constraints*. Resources have been mentioned explicitly or implicitly throughout the literature as elements assumed to be known by the reader but, to the knowledge of the author, have not been formally categorised (Chapter 2). Building on existing literature, the current empirical study was used to help contextualise and categorise design resources from Chapter 2 into a practical range of resources present in industry. Thus, this section is informed by the literature of the wider PD and contextualised by the case study.

As aforementioned, current modelling approaches have widely researched into human designers and elements that constraints the design process. However, interviews emphasised that a significant proportion of the actual practical work involves a whole range of other resources such as computational resources, testing and prototyping resources. During the empirical study, the four main types of design resources have been identified:

- *'Human designer resources'*: Comprise designers and managers directly involved in the process and activities. The company classified them in different ways such as by role, seniority or expertise.
- *'Computational resources'*: Interviewees explained that computational resources can comprise passive elements, needed for the activity and that could constraint the process, and active elements performing the activity independently. They were present in the company as hardware (High Performance Computing 'HPC', stations, grids, desktops), software (dedicated to FEA, CFD, etc.), licenses and network.
- *'Prototyping resources'*: Prototypes need preparation to be developed and materials to build them. Hence they refer to all materials, equipment, and maybe plants to prepare a prototype.
- *'Testing resources'*: Testing resources include those necessary for testing the product. It could involve plants, equipment and materials to run tests.

During interviews, the rationale behind the conceptualisation of design resources was trying to cover all resources involved in the different stages of a typical design process. The emerged list slightly differs from the one found in literature, whether the difference

is in characterisation or content is discussed in Section 4.4. Figure 23 shows a proposed categorisation of practical design resources found in the company and examples of relevant classifications. The list is not intended to be final and additional resources could be added as research progresses or the organisational context changes.
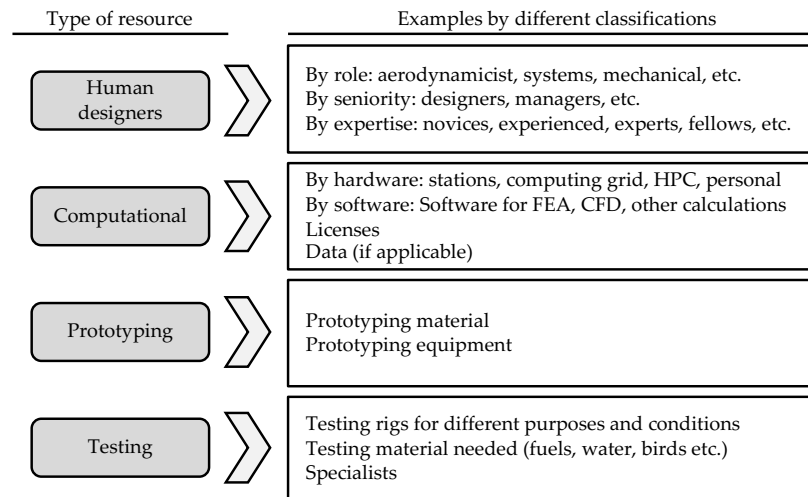
Figure 23. Design resources found in industry

Each of the above resources can indeed affect process performance in terms of total process duration, cost/effort and quality output in different ways. Assumptions include that some specialists are needed to run computational and testing resources, or building the prototype. However, it is presumed that they are organisational resources since they serve several projects, departments or divisions at the same time, not just the design process. Hence, they will increase with the workload to manage those resources (e.g., more HPC managers will be hired if the number of HPC rises). Another assumption is that data between the activities to evolve the design are treated as inputs rather than design resources, and only as a resource if they constrain the process activities. Design resources are described in detail in the following sections.

4.3.1   Design resource allocation and attributes

Having specified resources involved in design processes, this current section explains their allocation in preliminary design as described in the interviews and investigates the characteristics of resources through their attributes. The result is a list of resource attributes that might affect process performance in terms of total process duration, cost/effort and quality output during process execution.

The allocation of resources is done at different levels. At the preliminary design level, when a project starts at CD request, different departments negotiate with project owners the involvement of designers and other resources. Depending on bid urgency and level

of detail, more or less resources are allocated to a project. The complexity of adjusting the availability of all resources involved is a key issue for managers. Currently, resource management decisions are based on logs of necessary work to be done and previous experience of finished projects.

A set of common attributes of different design resource types include resource *'quantity available'*, *'time'* needed to finish (or allocated to) a specific task, *'availability'* or constraint, *'time window to book'* them, and *'cost'* of utilising them. Resource capabilities determine the degree at which is capable of competently performing and successfully completing the task. Additionally, they have to be available at a required point in time. Supplementary information includes the time window when the resource has to be booked or geographical availability. Moreover, resource availability could be constrained by waiting times. For example, High Performance Computing (HPC) machines have a queue of activities waiting, which results in additional time before the activity can be executed.

4.3.2 Human designers

Human designers include designers and managers directly involved in the process and they perform the activities. They can be classified in different ways, for example, by role, seniority or expertise. However, allocation of designers should account for both project needs and designers' preferences since motivation of designers towards a task will also influence their performance. They require a treatment that differs from other resources, where allocation only follows project needs and cost-availability. Caldwell and O'Really (1990) also acknowledges that job-fit, matching a designer's traits, personality, motivation and skills to the work, is essential to boost productivity and performance.

During preliminary design, the allocation of designers is done through work packages (WP) allocated to projects. Projects normally require multidisciplinary effort from designers in different departments that are involved in specific tasks. For each WP, managers negotiate how many designers they need based on specific attributes that differentiate each designer type and instance: *'skills'* distinguish an aerodynamicist from a structure engineer, and *'experience'* can separate an expert from a novice (Ahmed *et al.* 2000). Experience can affect the time to perform the activity, a designer stated: *"depending on which particular person, let's say you put on that task, if it is an expert it will take a week, if it is a novice it will take three weeks and if it is somewhere in between it will take two weeks"*. Another designer affirmed: *"there is only a number of people that she will trust with certain structural design tools"*, illustrating the importance of incorporating the appropriate resource instance to perform certain activities. Skills and experience can influence other parameters such their *'learning curves'*. Indeed, having an expert and a novice working on the same task will not yield in similar learning curves. The expert's learning curve

would likely increase marginally, whereas a novice could increase steeply in the beginning before stabilising. A manager acknowledged that "*ideally keep the same people on next time and they get quicker and quicker*". In turn, all these attributes can potentially impact time of task completion, quality output, as well as '*iteration likelihood*', which is related to iterations due design exploration and risk of failure (Wynn *et al.* 2007). Interviewees agreed that quality for critical products like aerospace components can be taken as performance, compliance and fulfilling requirements. Finally, '*time dedication*' and '*availability*' (as a constraint in the process) remain crucial factors, since 1) many designers are often working on different activities or projects at the same time and 2) overloading designers could be very counterproductive according to interviewees. An engineer specified that "*resources are limited and we do have constraints on resource*" and similarly another manager indicated "*that all the people that are involved in here do a million and one other things as well*". The general consensus is that the more valuable or *expert* a designer is, the busier they are. This translates into experts having less time to dedicate to the different projects, while novices having more time. Additionally, experts normally supervise a large number of activities done by other designers. In the end, each designer could have a specific '*cost*' or value to the organisation, thus choosing the right resource enables to efficiently manage them without incurring in unnecessary additional costs. The level of focus on one project also varies as other projects come along and/or project priority, set by CD, changes. This could be due to upcoming deadlines to deliver specific bids.

Aside from expertise or skills, socio-technical attributes were briefly mentioned but they are not the focus of this research. As seen in Chapter 2, there is a field that specifically focuses on socio-technical aspects and it would require a standalone project to be thoroughly explored. Conversely, this research focuses on improving resource management in terms of estimation, allocation and scheduling rather than designers' social and communication interactions.

4.3.3   Computational resources

Interviewees explained that computational resources can comprise hardware (HPC, stations, grids, desktops), software (dedicated to FEA, CFD, etc.), licenses, and network. These resources either perform a design activity independently by receiving a series of inputs and producing results for the next task, or simply constrain the process by being necessary for the activity. The importance of these resources was indicated by an expert in charge with computational resources: "*we know we have really good computing, with lots of spare computing power available to us, which we are not using effectively. We know HPC is going to play a key part because we have, from requirements point of view we have got more and more, and bigger and bigger analysis which require a large amount of memory all round, which*

only HPC can provide". As a result, poor management of these resources can lead to tough resource competition and creation of bottlenecks. For example, HPC can sometimes include long waiting times that vary according to the number and size of the jobs submitted by each department. The bigger the size and number of jobs already submitted, the more waiting time. Consequently, some departments plan the number, size and time to submit jobs to the HPC department. Problems can arise when in order to push in front of the queue, some submitted jobs do not request the recommended computational power. As a result, the job is not set up properly and may lead to unexpected rework.

Summarising interviews, computational resources possess attributes such as '*computational capabilities*' of software and hardware power, '*compatibility with other resources*' and '*reliability*'. '*Computational capabilities*' determine the suitability of the resource to complete specific tasks and the computational power they possess. '*Compatibility*' indicates if they can be deployed and used in conjunction with other computational resources to perform activities. And finally, '*reliability*' for computational resources is the analogue of '*iteration likelihood*' for designers. However, reliability does not only account for failure in finishing a task due to insufficient or immature inputs but also for software and hardware stability (e.g., a computer running 12 hours' simulation breaks down during the night, leaving the task to be reworked). Regarding reliability, an interviewee indicated: *"so it does happen, quite a lot. Sometimes people have not set up their job correctly, or have not provided the right input. Or sometimes they are not the right ones"* and *"well HPC does break down at times. Memory or hard disk get full at times and sometimes there are unforeseen maintenance shutdowns or slowdowns"*. Whether computational resources have learning curves depends on the activity: some activities may perform standardised operations, while others may build upon previous iterations. Thus, this also provides a sense of learning.

4.3.4 Prototyping resources

Prototyping resources refer to all materials, equipment, and even plants necessary to build a prototype. The importance of prototyping resources stems from the negative knock-on effect that their absence could produce on the process when reaching the testing period. Managers have acknowledged that numerous testing slots have been lost due to lack of planning into acquiring the necessary resources to develop the right prototype. Common mistakes during prototype preparation includes overlooking the necessary time to develop the prototype, the settings needed for specific testing, the development of prototypes to the desired standards, the procurement of enough quantity in case of failure, amongst others. Interviewees emphasised on the development and testing of key components to study the results and iterate its design: *"we would be testing components within rigs, so doing sort of like first tests"*.

Prototyping resources have to be ready for testing. In some situations, the planning, developing and building of prototypes or component needs to be plan alongside the design process. '*Prototype fidelity*' regards achieving the proper functional requirements and quality of the tested element in the quantity needed.

4.3.5   Testing resources

Testing resources comprise those necessary to conduct product testing. It includes particular plants, equipment and materials needed to run tests. In complex PD such as aerospace products, testing resources are usually some of the company's most expensive assets. Their quantity is normally restrained to a level that aims for high utilisation, which results in important bottlenecks when the utilisation is at capacity. Also, sometimes the design process has to be scheduled around the availability of key testing resources, occasionally subjected to '*testing conditions*'. For example, it was acknowledged by the company that some test beds were only available to use during certain times of the year due weather conditions and in specific geographical locations: *"particularly with test bed resource for example. Which is a scarce commodity and there are certain tests you can only do for two months of the year"*. Appropriate anticipation of these type of constraints is necessary and must be taken into account during planning. In addition, for the testing activity to be successful it must be '*set up*' following the appropriate test requirements. As an analogue to computational simulations, a test can fail due to its '*reliability*'. The organisation acknowledges the key role of these assets: *"the other things that we tend to work a lot on, in terms of our technology, things like rig strategy, test strategy…"*.

Figure 24 summarises resources attributes found in our empirical study and prospects to be included in a support method. As mentioned, the list does not intend to be final.

Figure 24. Resource attributes found in case study

4.4 Discussion

The discussion aligns the key topics into three sections: 1) Resources and attributes in engineering design, in which knowledge gained in both literature and this chapter is compiled; 2) Requirements to distinguish engineering design resources, in which, through the gained understanding a set of high level requirements are proposed to distinguish design resources in PD; and 3) Resource management decision making, in which emphasis is exerted on the possible positive influence of resource management on overall organisation.

4.4.1 Resources and attributes in engineering design

Empirical investigations confirmed that the design resources extracted from literature in Chapter 2 were present in industry. Designers were probably the most prominent and common in both classifications. Other resources in literature such as tools were contextualised into practical resources such as computational, testing and prototyping resources. Effort and constraint, both modelled as resources in literature, were defined as performance metric and resource attribute respectively. The importance of properly managing computational and testing resources were repeatedly emphasised during interviews. In contrast, very few models in literature address their management.

Figure 25 shows, compared to models in literature, interviewees mentioned design resources that perform the activities. The difference between the literature and industrial classifications roots on the notion that the ones found in industry were abstracted to define more practical resources, for example computational. In contrast, literature resources focused on their effect on the process, for example constraint or effort exerted.
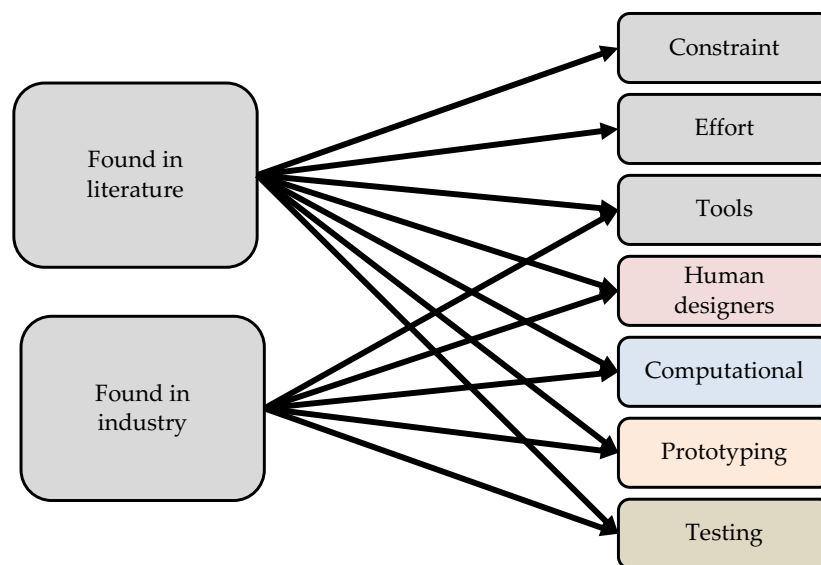
Figure 25. Resource types found in literature and in case study

The industrial classification allows for the formal introduction to the resources that design the product, while presenting the attributes that impact performance and those that should be modelled in the approach. Resource attributes shaped the behaviour of their represented design resources, with variation depending on the resource type. Therefore, different resource types are affected differently by their attributes and they need different management strategies. For example, the use of HPC is dependent on the number of jobs already submitted to the department, while the availability of designers can depend on bid urgency. This illustrates that different resource types have to be modelled differently given their attributes. Figure 26 links resources attributes found in literature and the empirical study. Both literature and empirical studies were similar in content, with the case study effectively extending the list. As the case study added to the attributes from literature, they should be considered for the intended approach.
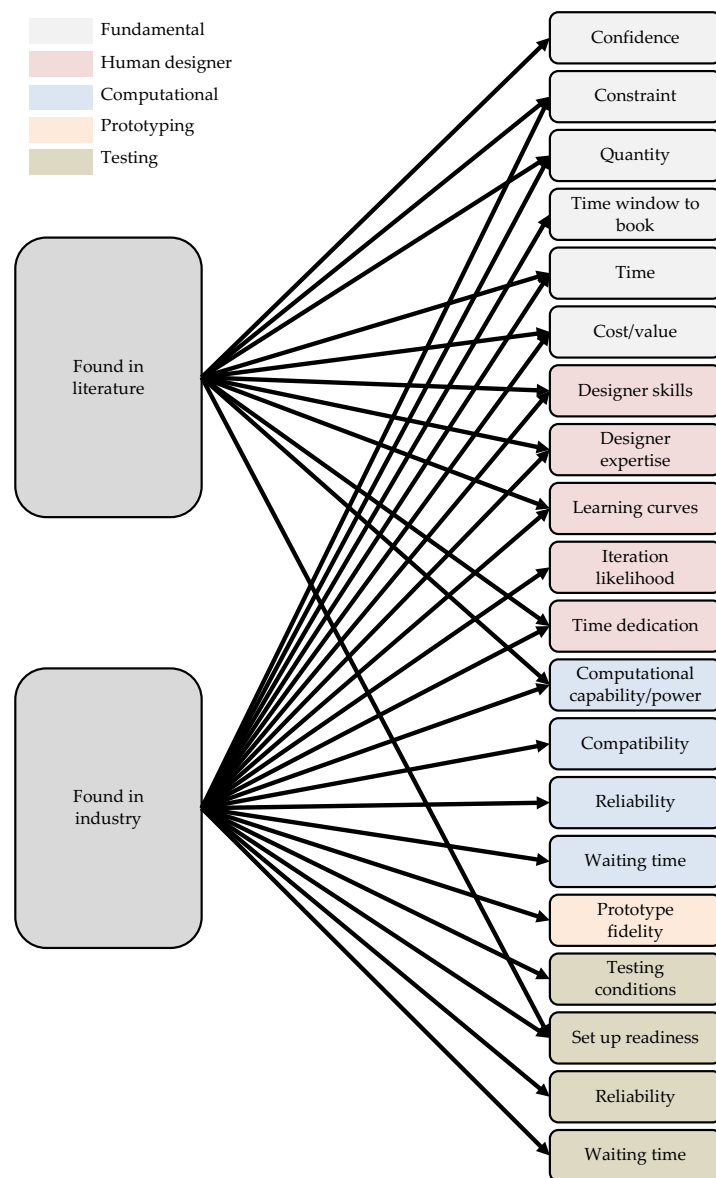
Figure 26. Resource attributes found in literature and in case study

The presented classification tried to cover all the possible design resources in complex design applicable to similar organisations, as detailed in the research scope. Therefore, the classification does not intend to be final or fixed but adaptable and extendable to other organisations. It is noteworthy that the resources and attributes included in Figure 26 as '*found in literature*' are the ones modelled by approaches reviewed in Chapter 2, mostly summarised in Table 2 and Table 3. The wide PD literature mentioned more design resources and attributes without characterising them.

4.4.2 Requirements to distinguish engineering design resources

Requirements or traits to distinguish engineering design resources based on literature and insights from preliminary case study interviews are developed and discussed in this section. This serves as foundation to identify design resources that should be modelled when the approach is applied to different companies, situations or industries. Correlating with literature, most of the discussed resources during interviews had direct involvement or participation in the design process, taking part either actively performing the design activities (e.g., designer, HPC) or passively as constraint elements (e.g., licences). Boyle *et al.* (2012) also distinguishes between active resource performing the tasks and passive required for the activity.

On one hand, literature has also identified that availability (or constraint) and impact on performance are critical to the process. Since availability of resources can drive and set boundaries to process performance, it has been modelled and regarded as crucial by many researchers (Chapter 2). It correlates with findings during the case study, where availability has been accounted for in several attributes (quantity available, constraint, window of time to book, time dedication, testing conditions and set up readiness). On the other hand, to derive significance from resources, they must somehow impact the performance of design processes. Impact on performance in terms of quality, total process duration and cost/effort have been accounted for in fundamental attributes (time needed to finish a task, cost of utilisation, etc.), designer attributes (expertise, skills, learning curves, likelihood of iteration, and time dedication to a task), computational attributes (computational capability and power, compatibility, and reliability), and testing attributes (reliability and set up readiness).

Thus, for an element to be considered a resource in engineering design, there is a primary requirement of whether the resource is necessary to the design process, '*required to deliver the design*', and sub-requirements regarding its '*availability*' and '*impact*':

- *They have availability*: Availability of resources is fundamental to allow the process to advance. The absence of a required resource can be reflected as bottlenecks and delays, or paralyse the project. Hence, design resources should be quantifiable. Other resources that affect global performance at a project level (e.g., missing information affecting a project as a whole) should be considered input or project resource.

- *Their effectiveness impact process performance metrics*: The effectiveness of different resource instances can produce different performance outcomes when executing the same activity. This due to the various attributes that differentiate resource instances (skills, expertise, etc.). For instance, an HPC could converge an analysis much faster than some stations or desktops, thus impacting on process duration. However, the higher cost of HPC could increase project cost. A designer during interviews stated: *"why does the task take different lengths of time; it is because you have a different person doing it for example"*.

In summary, resources that fulfil the above requirements are elements that influence process performance outcome. Thus, incorporating them in a resource modelling approach to study trade-offs and testing different '*what-if*' analyses could potentially yield in interesting insights.

4.4.3 Resource management decision making

Deciding what resources should perform which tasks by considering their effectiveness towards completing the task and adjusting to their availabilities is a complex endeavour which leads to key managerial questions (Chapter 2). An interviewee acknowledged that *"this is where it gets really difficult, there is always too many tasks for the amount of people you have got and the budget you have got and it is just trying to get the balance right and try and get the priorities right"*. A manager confirmed that you cannot always allocate the preferred expert to the project: *"it is a very specialised group of people and they are being pulled in all directions so it is very difficult to get their time"*. The organisation has stated that the use of managerial tools to plan and coordinate their development process appears as an essential need for their success: *"so it could put a bit more science into the prediction"*. Nevertheless, it seems that there is a lack of standardisation of the models used by the organisation. The design process models presented to the author's research team during preliminary interviews were mainly for capturing and depicting the process. Thus, the opportunity and need to enhance the current process models with simulation capabilities that permits analysis was confirmed. This way, different configurations of the process could be explored. As a designer stated: *"by simulating it I guess you can do what-if scenarios, if we were all experts how would affect it? Or if we just had two more novices how would it affect*

it? So do we invest in having more people or do we invest in actually making the ones we have got better and what could be the scenario". In the same way specific areas that more expertise is needed can be highlighted: *"there is a couple of people who can do that and I am now training up one of the people in my team to do that, so he is been sitting with one of the experienced guys to learn how to do that".*

As part of DRM, a reference model can be developed once the understanding of current situation has been achieved. Thus, investigations on both literature and industry developed into a reference model with only key factors relevant for this research, which is presented in Figure 27. Resource management was identified as the key factor that can be positively impacted to improve the current situation. The measurable success factors for this research are already discussed metrics such as process duration, effort and cost. The reference model reflects the current lack of appropriate capability for design process management. Which incurs in negative influence that propagates to the organisation's economic profit. The interdependencies of resource availability (constraint) indicate low availability of specific resource instances that can lead to increase process duration. Examples from literature or reference to the empirical study are indicated for all illustrated interdependencies, except for basic elementary business relationships.
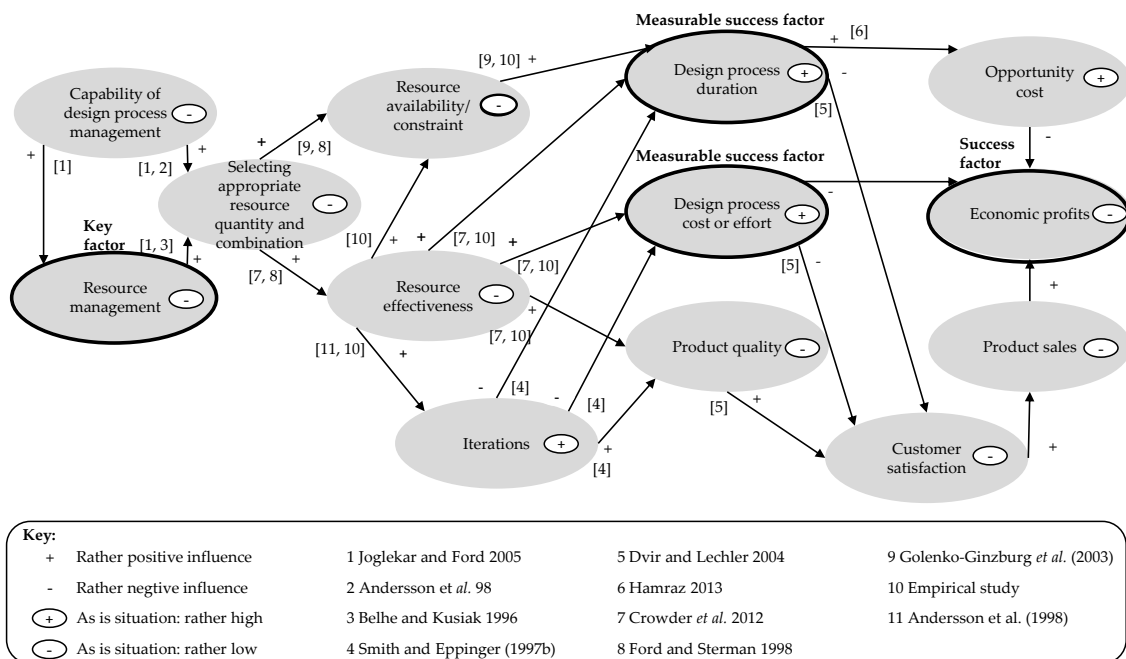
Figure 27. Reference model for this research according to DRM definition. Source: Blessing and Chakrabarti (2009)

4.5 Summary

The current chapter presented a preliminary case study, which is an empirical effort to study relevant design resources and its attributes, as well as how resource management

is carried out in a complex design organisation. The chapter fulfils **RQ1:** *What are the different types of design resources and the current methods to support their management?* and **RQ2:** *What key attributes can describe the impact of resources on process performance?*

The presented list of design resources stems from preliminary literature investigations completed with insights coming from an exploratory industrial case study. Similar resources were found in both literature and industry, with a slightly different characterisation. The main types of design resources found are: *designers, computational, prototyping and testing.* Each of them influences process performance distinctively. Discussion also provided with requirements to distinguish design resources in industry. The comparison of these insights with resource modelling in existing approaches shows a gap that this work aims to reduce by investigating the potential of detailed resource modelling in improving PD process planning.

5 Requirements for resource management model and prototype model

The thesis has the overall objective of *improving design process management by improving design resource management.* Chapter 2 indicated the suitability of process modelling and simulation in engineering design to reach this objective, while revealing a number of challenges and key issues to address. The preliminary case study in Chapter 4 complemented literature review in extracting key design resources, along with their attributes, relationships and impact on process performance that could be modelled.

As a result, the next step is to develop a comprehensive Resource Management Method (RMM) to model and analyse the use of different instances of resources addressing the identified gaps. The steps followed in the development of the approach mirrors an actual engineering design process (O'Donovan *et al.* 2003). It begins with deriving requirements, followed by developing concepts and selecting the feasible ones. Then, the selected concept is further elaborated, by iterating and detailing it. Finally, the method is implemented and applied for evaluation and refinement. The aim of this chapter is to derive functional requirements to build the support method through insights gained during literature investigations and interviews. A requirement based model ensures that key issues are addressed. This concludes DS-I from the stated methodology by addressing **RQ3:** *What are the requirements for a model that might enable prediction of the resource impact on process performance?*

The chapter also initiates the development of the support method, part of Prescriptive Study, which culminates in Chapter 6 by examining the fourth research question **RQ4:** *What is a suitable concept(s) for a model for resource management that fulfils the requirements in RQ3?* The method should ultimately achieve the stated goals in Section 3.1.1:

- Increasing understanding of different type of design resources and their attributes that define effectiveness in process performance;
- Quantify the trade-off impact of using alternative resource instances on activity and process performance;
- Increase understanding of the impact of resource attributes, that define effectiveness, in process performance;
- Contributing to develop and improve process plans by estimating resource needs, allocating and scheduling resources.

As a result, the reference model that emerged in Chapter 4 is hypothesised to evolve into the impact model in Figure 28 when the support method enhances the capability of design process management. In summary, Figure 28 illustrates that the selection and scheduling of appropriate resource instances will both: 1) reduce the negative impact that low resource availability could have and 2) increase effectiveness. This is a complex objective since both availability and effectiveness exhibit a trade-off relationship towards the success factors. The positive impact on resource management can potentially improve design process performance in terms of cost and duration, which will ultimately increase the organisation's economic profit.
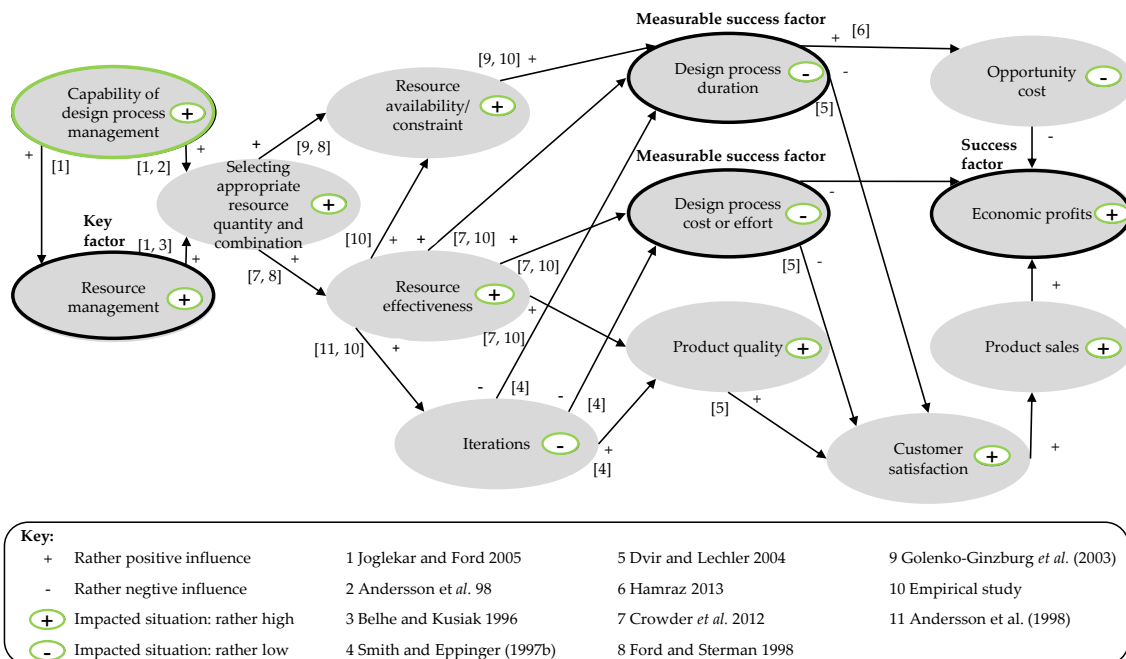
Figure 28. Impact model for this research according to DRM definition. Source: Blessing and Chakrabarti (2009)

Hereafter, the new model has to incorporate different design resources (designers, computational, prototyping and testing) and possible instances to study the trade-offs between availability and effectiveness.

Section 5.1 introduces the derived requirements to build the intended model. The requirements were divided into design process model requirements, resource modelling requirements, resource management analyses requirements and general requirements. Section 5.2 integrates the different requirements into a prototype model as a proof of concept. Hence, the fundamental model, its elements and relationships are introduced. A small case study is used to illustrate the model's application and some results are compared against the classical approach with resource modelling using non-optional attribute. Section 5.3 discusses the results and improvements to the model are suggested in areas that it did not completely satisfied the devised requirements. Finally, Section 5.4 summarises and concludes the chapter.

5.1 Requirements for a resource management model

The first four chapters have given a comprehensive study on the needs and objectives for this research. Hence, the gained understanding from literature and empirical investigations enables to synthesise the functional requirements in this section. The objective is to develop a resource management model, part of a general resource management approach, to support on:

1) Identifying key resources and resource sensitive activities;

2) Improving understanding between the relationship design resource attributes and the task characteristics on process performance;

3) Selecting the right combination of design resources for process execution given project characteristics and constraints.

The list of functional requirements for the intended model comprises requirements on design process modelling, resource modelling and resource management analysis. Requirements were continuously discussed with thesis supervisor, advisor, industry designers and academic experts. They have been updated accordingly during the time of this research. The application of the method also helped iterate the requirements, while confirming practical relevance based on the application of the approach on industrial case studies (Chapter 7). The developed model was compared against the requirements on a continuous basis and consequently enhanced.

The 12 synthesised requirements are introduced and briefly described below, indicating the sections from which the rationale was either initially discussed as a need, or later

researched to provide guidance on how to address it. Then three sub-sections, divided by requirement type, discusses model development options to address them.

Design process modelling requirements ensure that the model captures the complexity and uncertainty of design processes and can support day-to-day managerial decisions. Table 5 summarises the requirements, which were derived from previous chapters. In order to fulfil these, modelling frameworks should be evaluated in terms of their suitability in process modelling, capturing design process characteristics and uncertainties, simulation capabilities, and capturing process and activity characteristics. A flexible modelling framework that can be extended if necessary can act as foundation for the approach.

Table 5. Design process requirements

	Requirement	Description	Section
FR1	Modelling evolutionary design process	The model should be able to capture the activities and relationships in terms of precedencies and dependencies between different inputs and outputs.	§1.4; §2.5.1; §2.7.1.
FR2	Capture design characteristics and uncertainties	Design characteristics and uncertainties can be modelled in terms of: 1) *iteration,* 2) *multiple outcome routes* 3) *stochastic time,* 4) *probability of task failure* and 5) *hierarchical decomposition of processes.*	§1.2.1; §2.1; §2.5; §2.7.1.
FR3	Simulation capability	Allow simulation of the model that later enables analysis to devise insights for process improvement (time, cost, effort).	§2.1; §2.7.1.
FR4	Capturing process and activity characteristics	Capture process and activity characteristics such as: priority of the activity and process, if the activity allows learning, activity risk in terms of iteration.	§4.3; §4.4.

Resource modelling requirements are extracted to address the gaps and needs found in literature and empirical study. The requirements might be satisfied by modelling the key resources characterised in Chapter 4. Furthermore, resource attributes should be captured as elements that define the relationships and behaviour of the model, ultimately impacting on process performance. The model should include the functionality of setting resources as constraints, in which activities cannot start if the necessary resource is not present. These requirements have the ultimate purpose of enhancing modelling capabilities to capture and simulate the use of different resource instances. Table 6 briefly describes resource modelling requirements.

Table 6. Resource modelling requirements

Requirement		Description	Section
FR5	Modelling different type of resources[2]	Modelling the resources relevant for design processes (designers, computational, prototyping and testing resources).	§2.6; §2.7.2; §2.7.3; §4.3; §4.4.
FR6	Modelling resource constraints[3]	Take into account that resources are limited and necessary for the execution of activities.	§2.6.1; §2.7.2; §4.3; §4.4.
FR7	Modelling the effectiveness of different resource instances[2]	Capturing the multiple design resources attributes that impact on process performance.	§2.7.2; §2.7.3; §4.3; §4.4.
FR8	Defining relationships and process behaviour[2]	Capturing the relationship between tasks and resources in order to predict their impact on activity and process performance. As a result, process behaviour is modelled through activity characteristics and resource attributes internal dynamics that influence on task performance.	§2.5; §2.7.2; §4.3.
FR9	Allowing to simulate different resource instance options[2]	Providing the possibility to state different resource instances for activities that are not dependent on a specific one (e.g., some tasks can only be done by experts). Hence, simulating multiple resource configurations (even the whole design space).	§2.7.3; §2.7.4; §4.3; §4.4.

Resource management analyses requirements enforce that the output results can provide meaningful insights applicable by process stakeholders. In another words, they have to be both understandable and applicable to daily managerial decisions. Hence, this set of requirements are concerned with the applicability of results for analysis, mainly directed to the objective of discerning the impact of different resource instances. It also includes analyses that enable studying the impact of attributes, task characteristics

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[2] Resource modelling requirements that were partially addressed by taking advantage of CAM modelling flexibility in the prototype model (Section 5.2). They were fully addressed in Chapter 6 by creating a new approach and implementing it in CAM with new functionalities. Since the objective is to develop an overall approach, and not the tool itself, the implementation was done in conjunction with two other researchers in the author's group (Section 6.4).

[3] Resource modelling requirement that was already present in ASM and CAM tool, and not extended in this thesis.

on performance and vice-versa. The insights should improve resource planning and scheduling. Table 7 introduces resource management analyses requirements with a brief description. Reference to the sections in which the requirement was extracted or discussed is also included.

Table 7. Resource management analyses requirements

	Requirement	Description	Section
FR10	Analyses of the use of different resource instances	The approach should have the ability to measure the impact of using different resource instances per task and on the whole process. Analyses should help improve project performance (time, cost, effort), devise insights on the effects of using different resource options, identifying critical resources and resource sensitive activities.	§1.2.4; §2.1; §2.7.4; §4.4.
FR11	Analyses of the impact of resource attributes internal dynamics on performance and vice-versa	The model should be able to quantify how much each attribute influences on performance and vice-versa. This requires a model that allows setting both forward and backwards objectives to diagnose the impact of a variable (performance values, any resource attributes, etc.) on the rest of variables.	§1.2.4; §1.4; §2.7.1; §2.7.3; §4.3; §4.4.
FR12	Extract insights to improve resource management	The insights derived from the analyses should aid on decision making regarding resource planning and scheduling to improve process performance.	§1.4; §1.2.4; §2.1; §2.7.4.

The requirements combine relevant elements of different modelling approaches to improve resource management. Requirements FR4, FR7, and FR11 can be translated into modelling *activity's characteristics*, *resource's attributes*, and *performance objectives*, which are analogous to the way RCRSP approaches model process behaviour using the fields of *Resource environment α*, the *Activity characteristics β* and the *Performance functions γ* (Herroelen *et al.* 1999). In this manner, the flexibility in defining process behaviour can be captured adopting notions from RCRSP, a field that has a strong focus on resource allocation. Similarly, using resource attributes to define the different instances of resources denotes their heterogeneity, a characteristic that ABMs argue for (Wooldridge and Jennings 1995).

The new approach should aim to fulfil the aforementioned requirements to plan, allocated and scheduled resources. Ultimately the method should suggest and enable design process performance improvements.

Additionally, some general requirements related to developing support methods or approaches that can be used by stakeholders are also considered. Hamraz *et al.* (2013) and

Wynn (2007) included a few general requirements while they built their respective models. They largely refer to ease of application, effort needed, accuracy of results, and comprehensibility of results. Any developed approach, model or tool should take into account their usability and applicability.

Table 8. General requirements for a support method

	Requirement	Description
GR1	Ease of application	The method should be embedded in a format that eases its modelling, application and analysis of results.
GR2	Effort needed	The effort exerted in applying the method should not outweigh the insights that can be gained from it.
GR3	Accuracy of results	The results should be of enough quality that they can be used to extract insights for managerial decision for resource management in process planning and execution.
GR4	Comprehensibility of results	The resulting analyses should provide clear insights for resource management in process planning and execution.

With this objective in mind, the model should include elements that can facilitate the understanding, usability and applicability of the method by any stakeholder. In addition, the effort needed to model and analyse the results should not exceed the benefits exerted from the model. Moreover, the resulting simulations must provide accurate results for the intended purposes, as well as being sufficient and clear. Although the functional requirements guided the approach development, general requirements are also taken into great consideration. The next sub-sections discuss in detail how the functional requirements can be addressed.

5.1.1   Design process modelling level

The fulfilment of FR1 to FR4 is tightly coupled with selecting a modelling framework that offers the right elements to capture the complexity and uncertainty of design processes and provide simulation capabilities. To this end, the section evaluates different modelling frameworks to assess their feasibility as foundation of the support method.

FR1 Modelling evolutionary design process – Since resources have to be allocated to activities, it is paramount to unambiguously capture tasks in the process, along with their dependencies and precedencies. As discussed in Chapter 2, task network modelling frameworks seemed the most appropriate modelling approaches to be the basis for a method that improves resource planning and scheduling. Its diagrammatic representation of the process eases visualisation, description and documentation (Wynn 2007). To

appropriately capture evolutionary design processes there are two aspects to consider, the elements used to depict the process (tasks, parameters, objects states) and the information flow between the elements (dependencies and precedencies).

FR2 Capture design characteristics and uncertainties – There are several characteristics that can capture uncertainty in design that have been modelled by the approaches reviewed in Chapter 2: 1) *iteration*, 2) *multiple outcome routes*, 3) *stochastic time*, 4) *probability of task failure* (leads to unexpected rework), and 5) *hierarchical decomposition of processes*. The first four captures uncertainty characteristics, while hierarchies can aid in modelling complex design processes. In addition, flexibility in defining relationships between variables is crucial given the complexity of modelling resources and process behaviour.

FR3 Simulation capability – Many simulation techniques and algorithms can be built upon analytical models. Task network models can explore process behaviour using, for example, discrete event and time-stepping Monte-Carlo simulations. Moreover, simulations should at least output the following performance metrics: time, effort and cost.

In summary, due to its ability to represent evolutionary design process unambiguously, capture the characteristics and uncertainties of design, and explore process behaviour in enough detail through simulations, activity network based models have been identified as suitable to improve design process planning and scheduling (Chapter 2). Table 9 compares the reviewed activity network approaches according to their feasibility in representing design processes (FR1), its characteristics (FR2) and process performance metrics (FR3). It indicates whether the framework captures the characteristic, does not capture the characteristic, or in a limited way. The evaluation is conducted to the best of the author's knowledge and was discussed with the thesis supervisor and advisor.

Table 9. Comparison of task network models in their feasibility of capturing design processes

Frame-work	FR1		FR2					FR3
	Process elements	Infor-mation flow	Capturing design characteristics and uncertainties					Perfor-mance metrics
			Itera-tions	Multiple outcome paths	Sto-chastic time	Proba-bility failure	Hierar-chies	
IDEF0	Tasks, control signals, resources	Depend-ency	Lim-ited	No	No	No	Yes	Time
IDEF3	Tasks, object states, junctions	Prece-dence	Yes	Yes	No	No	Yes	Time
GERT	Tasks	Prece-dence	Yes	Yes	Yes	Yes	No	Time

Petri net	Tasks, parameters	Prece- dence	Yes	Yes	Yes	Yes	Yes	Time, quality (parame- ters)
DSM	Tasks	Depend- ency	Yes	No	Yes	Yes	Limited	Time, ef- fort, and adaptable
Signpost- ing	Tasks, parameters	Implicit depend- ency	Yes	Yes	Yes	Yes	Limited	Time, ef- fort, qual- ity refinement
ASM	Tasks, parameters	Both	Yes	Yes	Yes	Yes	Yes	Time, ef- fort, qual- ity refinement
APDP	Space, activity modes, states, technical parameters	Implicit depend- ency	Yes	Yes	No	Yes	No	Time, ef- fort, qual- ity refinement
Concur- rent	Tasks	Depend- ency	Yes	No	No	No	No	Time

The approaches that capture all design characteristics satisfactorily are ASM, Petri net and Signposting. However, both Signposting and ASM can model the evolution of design parameters, in which a task cannot start until the parameter is in the desired state of refinement. Although this research does not specifically deal with quality, a way to represent that the product has attained the required product specification is essential. ASM and Signposting can capture how specific parameters comply and reach the desired standard of requirements. Signposting is the best framework to provide dynamic activity selection, a powerful capability to simulate processes. Nevertheless, its strong dynamic capability makes it difficult to immediately distinguish and understand the whole process path. Additionally, the framework is limited in hierarchical decomposition of processes compared to, for example, IDEF0 or ASM. Hence, the possibility of depicting both dependencies and precedencies, and the easier diagrammatic visualisation gives ASM further advantages in the context of this research.

FR4 Capturing process and activity characteristics – ASM also provides a flexible framework in terms of building complex simulations through its function modelling capabilities. It can capture complex interrelations between variables with mathematical process functions. In particular, ASM has shown enough flexibility in increasing resource modelling enhancements, which is key for the intended model. It also shows strong capabilities in terms of Monte-Carlo process simulations. Moreover, it was specifically developed for modelling design processes and thus, contains many design focused features that eases its use.

To conclude ASM seems to be a modelling framework that has the required functionalities to represent uncertainty, depict process activities and parameters, offer convenient usability, and provide flexibility for further extensions. Besides, ASM has already been in use by design engineers at Rolls-Royce plc, a situation that gives the framework an extra advantage as an established framework within the organisation. However, ASM also has limitations, for example, both ASM and Signposting could also lead to different interpretations of parameter state and confidence. In addition, DSMs are easier to elicit and read.

DRM recommends to take advantage of any existing means to provide individual functionalities since the contribution of the research is not the tool itself, but the new concept and functions of the support method. DRM states: *"Using existing means not only makes it easier to detail and subsequently realised the support, but also easier to assess the likelihood that the functionalities and the support can realise the desired impact"* (Blessing and Chakrabarti 2009, page 164). This makes a stronger argument to use ASM provided with its functionalities and the ease of extending it through the academic software CAM. However, it is important to remark that using ASM as the basis framework is not a definite constraint of the approach. Theoretically, it can be built on any other activity network framework if sufficient extensions are made to complement the needed capabilities. Given the above comparison and stated reasons, at this point and given the purpose of the research, multiple factors deem ASM to be a suitable foundation for the support method.

5.1.2   Resource modelling level

Resource modelling requirements address the shortcomings found in literature in Chapter 2 which mainly relates to modelling resources, attributes and relationships from the knowledge gathered in Chapters 2 and 4.

FR5 Modelling different type of resources – The analytical approaches studied in Chapter 2 have modelled resources in different ways, including constraints, effort, designer, tools, and testing. The studied models were built for specific purposes, which they were fit for, and often only modelled one or two resource types. For example, ABMs often analyse designer's interactions. Similarly, planning and scheduling approaches usually modelled resources as constraints, without mentioning specific resource types. However, resource management capabilities can be enhanced by including all the key design resources. After identifying this gap, literature investigations allow to initially extract a list of relevant resources. Nevertheless, as they were not formally classified, an exploratory case study was conducted to deepen the understanding of how practical resources

were managed in design processes. Discussion in Chapter 4 consolidated the list of resources to model by characterising the ones in literature with the ones found in industry: *designers, computational, prototyping and testing resources.*

FR6 Modelling resource constraints – The availability or scarcity of resources is a key notion initially addressed in Chapter 1: resources are needed to execute design activities. Certainly, literature investigations confirmed that this is a key attribute to include for resource estimation, allocation and scheduling approaches (Chapter 2). Furthermore, the exploratory case study in Chapter 4 highlighted the importance of modelling the availability of the resource to perform the activity (constraints). ASM offers a built-in functionality to specify resource pools and constraints during simulation.

FR7 Modelling the effectiveness of different resource instances – A number of different attributes have been modelled by the investigated models in literature. Subsequently, the exploratory case study in Chapter 4 increased and categorised them within different resource types. Both literature and empirical investigations have acknowledged the impact of resource attributes on process performance (time, effort and cost, and quality). Specifically, interviews highlighted how each resource type has instances with different effectiveness towards performance, in which effectiveness can be modelled by resource attributes. Thus, the model should incorporate the attributes presented in Section 4.4.1.

FR8 Defining relationships and process behaviour – Chapter 4 describes how resources are allocated and scheduled, which can be translated into mathematical relationships between variables. This should be achieved by modelling the interaction between task characteristics and resource attributes to represent activity internal dynamics, behaviour and performance. This aggregates into process behaviour and performance.

FR9 Allowing to simulate different resource instance options – Simulating different resource instances of each resource type can yield in distinctive resource combinations with specific availability and effectiveness impact. Hence, performance trade-offs between using different resource instance option can be studied.

5.1.3   Analysis level

FR10 Analyses of the use of different resource instances – The method should be able to quantify the effect of different resource combinations on task performance and holistically to whole process performance. It should allow analysing a number of combinations instead of static resource choices. In addition, as stated in the research scope (Chapter 1), the model should permit analysis at both level of granularities: task level and whole process level. Ultimately, the research should help with deciding which resource combinations can adequately be chosen and scheduled to improve overall performance.

FR11 Analyses of the impact of resource attributes internal dynamics on performance and vice-versa – Process simulations should allow for the examination of resource combinations effects as well as the impact of constraining different variables (attributes, task characteristics and performance values) on the remaining variables. Firstly, as an analogy to the *objective* field of RCPSPs, in which a performance aim is set and the simulation searches for results that can comply, the support model could incorporate this objective based approach. This enables an exploration into which resource options could meet specific task and process performance values. Secondly, the impact or influence that each attribute and/or task characteristics exercises on the rest of attributes, task characteristics and performance should be *diagnosed*. Understanding which variables (attributes, task characteristics) are more relevant to the process could show areas in which more attention is needed to positively impact performance.

FR12 Extract insights to improve resource management – The results should be synthesisable to provide insights that can increase practical usefulness. The approach should thus identify multiple alternative process improvement options.

The functional requirements emerged through literature investigations and empirical study to conclude DS-I. In conjunction with general requirements these will guide the development of the support.

5.2   Prototype model

This section introduces a prototype support method that aims to include and assess the functionalities established by the requirements, and acts as starting point to explore the possibilities of the model. Additionally, it serves as foundation for the final support method in Chapter 6, which extends and refines the modelling and functionalities of the prototype. The method models the four types of resources described in Chapter 4 and is applied on a reduced and realistic case study inspired by the Fan Sub-system process from Rolls-Royce plc. To enable comparison, the case study is modelled in two ways: 1) the classical approach with resource modelling as constraints and using non-optional attributes; and 2) the prototype model with added resource types and attributes that includes multiple resource instance options for each activity and resource type.

5.2.1   Fundamental prototype model concept

The prototype model has ASM as foundation, using the built-in capabilities and extending the required functionalities. Figure 29 shows the three main steps of the model.
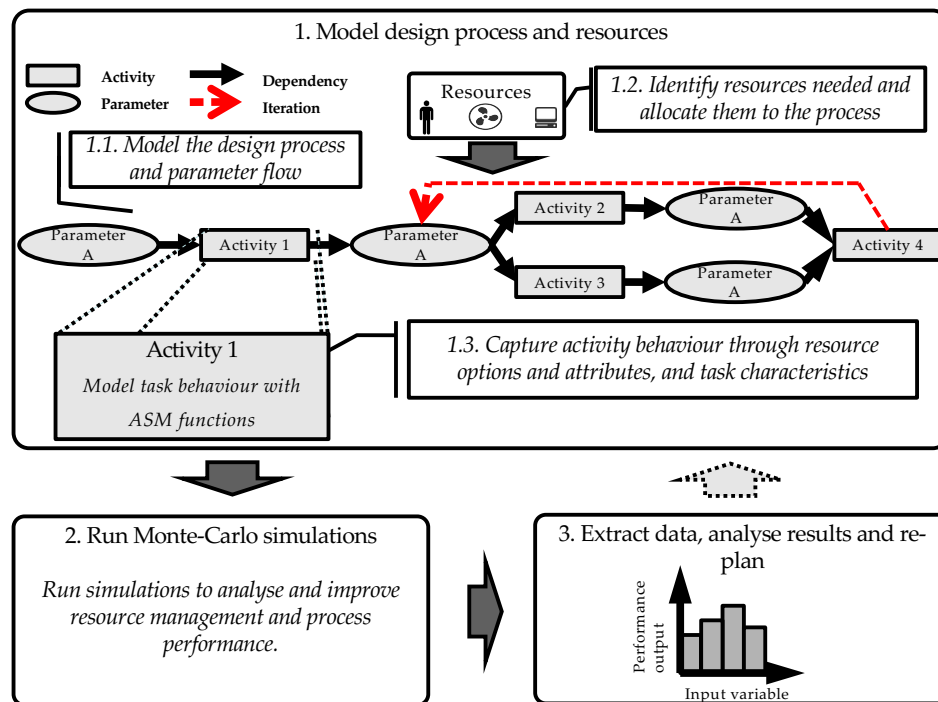
Figure 29. Overall prototype method steps

The steps follow the logical process to:

1. Model the process and resources, including how the resources are allocated to process tasks.

2. Run Monte-Carlo simulations with different resource instances to identify feasible combinations that yield in improved process performance.

3. Extract data, analyse results and re-plan to study different *'what-if'* scenarios (by changing process or resource configurations and applying learned insights) in order to ultimately improve the process.

Step 1 is presented in Section 5.2.2 defining process modelling, Section 5.2.3 describing the modelled resources and attributes and Section 5.2.4 introducing the impact on performance through fundamental relationships between variables. Steps 2 and 3 are addressed through the case study in Sections 5.2.5 and 5.2.6.

5.2.2 Fundamental modelling of the design process

There are three different ways to model activities in ASM, depending on their impact on the rest of the process:

- *'Simple tasks'*: To represent a task that transforms input parameters into output parameters.

- *'Compound tasks'*: To represent a task that can lead to alternative process routes. They transform input parameters into alternative output parameters, from which one will be chosen to carry the design process.
- *'Iteration constructs'*: To represent evaluation tasks that can result in either success (progress) or failure (iterate).

Subsequently, tasks are connected to model the design path. At this point, the outputs of each task are specified using design parameters. They also represent inputs for the downstream tasks and can indicate the different states of the process and current quality of the product.

Table 10 shows task properties (task characteristics, behaviour and performance) as well as the process performance variables measured throughout the simulation. Task characteristics will interact with resource attributes (presented in Section 5.2.3) to shape task behaviour and performance. In the proposed modelling framework, resources attributes linked to each resource instance option are used as process behaviour shapers. Then individual task performances will determine total process performance. Fundamental relationships between variables, that define impact on performance, are explained in Section 5.2.4.

Table 10. Task characteristics and process performances

Type	Variable	Notation	Description
Task characteristics to be input	**Project priority**	*PP*	The urgency to deliver the project (e.g., urgent bid or just exploration).
	Task innovation	*TI*	If task allows innovation, learning curve after iteration could be present.
	Iteration number	*IN*	Number of iterations performed.
	Jobs submitted	*J*	Number of jobs submitted, which can increase waiting time to use the resource.
Task behaviour	**Failure**	*F*	Probability of the activity to fail and requiring iteration.
	Waiting time	*W*	Waiting time to perform the task.
Task performance	**Task time**	*T*	Total time taken for the activity to finish.
	Task cost	*C*	Cost of the task.
	Task effort	*E*	Effort needed to perform task.
Process performance	**Total duration**	*TT*	Total process duration.
	Total cost	*TC*	Total process cost.
	Total effort	*TE*	Total process effort.

The knowledge gathered during DS-I enabled to extract the task characteristics and performance metrics used in this prototype model. While task characteristics are inputs, the

remaining task behaviour, and task and process performance are influenced by resource attributes.

5.2.3 Fundamental modelling of resources and attributes

Traditional ASM captures process characteristics within the activities (duration of tasks, iteration likelihood, learning curves, amongst the most used ones). The current model extends ASM to test the influence of using different resource instances on process performance. Thus, the activities that allow different resource instance options are shaped depending on which option is allocated to perform it. It involves modelling instances of resources that carries out the design activities along with its configurable attributes. Resources are modelled according to their needs towards the activities. Building on preliminary case study findings, four different types of design resources are modelled (designer, computational, prototyping and testing), as well as their attributes.

Table 11 summarises these resources and their attributes that affect design process performance: Based on Chapter 4, they are abstracted into functional variables to form inputs for the model.

Table 11. Resource attributes according to their type

Type	Resource attribute	Notation or representation	Description
Fundamental	Availability	*Built in ASM*	The activity cannot start if the required resource type is not available, a process execution constraint.
	Quantity	*Built in ASM*	Indicates quantity of the same resource type in the pool.
	Time window to book	*N/A*	This attribute was taken into account when building the model as resource allocation was done ahead of booking time.
	Time	t	Time initially expected to perform the task.
	Cost per unit	cu	Cost per unit time of designer, computational resource, prototype or testing rig.
Designer	Designer skills	*N/A*	This attribute was used to during resource allocation, by matching designer's skills to the required by the activity.

	Designer expertise	*m*	The different *designer choices available*, it represents the different instances of designers according to their expertise: *novice, intermediate* or *expert*.
	Learning curves	*li*	Designer's learning percentage improvement after activity iteration.
	Iterations likelihood	*il*	Likelihood of iteration inherent to the task and used designer.
	Time dedication	*a*	Designer's dedication or availability due to other projects/ commitments.
Computational	**Computational capability/power**	*m*	The different *computational choices available*, represented as the different instances of computational power or capability.
	Compatibility	*N/A*	This attribute determines if resource power could be added together.
	Reliability	*r*	Reliability of used resource.
	Waiting tine	*w*	Normal waiting to use the resource.
Prototyping and testing	**Prototype fidelity**	*tl*	Time limit for the prototype to be available or ready for the test.
	Testing conditions	*N/A*	The time of the year that the testing rig be booked, taken into account during allocation of resources.
	Set up readiness	*tl*	Along with prototype fidelity, it determines the deadline for process to perform the testing activity. Otherwise it incurs in waiting for the next testing slot.
	Reliability	*r*	Reliability of used resource.
	Waiting time	*w*	Normal waiting to book the next testing slot.

Table 11 lists all the characterised attributes in Chapter 4, translating them into either variables or considerations during resource allocation.

5.2.4   Fundamental modelling of impact on activity and process performance

The behaviour and performance of a task is shaped according to which resource instance is selected, task characteristics and allocation constraints. The selected option therefore drives the characteristics to be used for the task. The following fundamental relationships between resource attributes and task characteristics were empirically extracted from the exploratory case study. However, in order to be applicable to a wide range of

industries within engineering design, the allocation and use of resources were simplified to a generic level of abstraction.

The notation of resource attributes is presented in lower case to denote an instance attribute. Upper case is used once the attribute has been transferred to the activity and will be used for the simulation. Given a set of tasks $n= 1...N$, and a set of resources options as $m = 1... M$ per resource type. When the resource is a designer option m with time dedication a, it is translated to the task n as:

$$A_{n,m} = a_m \tag{1}$$

In the same way, the probability of failure F for activity n is allocated as the iteration likelihood of designer m given current task n, it changes depending on the task and resource option as shown in Equation (2). When the resource is computational or testing, F for a given activity n follows reliability r, presented in Equation (3):

$$F_{n,m} = il_{n,m} \tag{2}$$

$$F_{n,m} = r_{n,m} \tag{3}$$

Effort E, Equation (4), is set as time t that resource option m takes to do the task n multiplied by the percentage of decrease (or improvement) in time li when the task has been iterated (depends on the task and the resource) elevated by the iteration number IN. If the task does not allow innovation, learning factor is one. Time is given as a triangular distribution $Tri()$:

$$E_{n,m} = Tri\ (t_{n,m}) \times \left(li_{n,m}^{IN}\right) \tag{4}$$

Total time T for designers, Equation (5), is obtained by multiplying effort E by a factor that captures the time dedication A of designer m. In addition, it is multiplied by a factor that captures project priority PP. Time T for computational and testing resources, Equation (6), is equal to the time of resource option m given task n multiplied by project priority:

$$T_{n.m} = E_{n,m} \times A_{n,m} \times factor\ (given\ by\ PP) \tag{5}$$

$$T_{n,m} = Tri\ (t_{n,m}) \times factor\ (given\ by\ PP) \tag{6}$$

Waiting time W increases as more jobs are submitted from the department to used HPCs. In other words, factor J increases as the number of jobs submitted increment:

$$W_{n,m,j} = w_{n,m} \times factor\ (given\ by\ J) \tag{7}$$

In terms of prototyping and testing resource, if the prototype or materials are not ready when the testing slot arrives, extra waiting time W will be needed to reach the next slot:

$$if\ lost\ slot = \text{true};\ then\ W_{n,m} = w_{n,m};\ else\ W_{n,m} = 0 \tag{8}$$

Total cost C for designers, Equation (9), accounts for the cost of the designers per unit time cu multiple by effort E spent on the task. Cost for computational and testing resources, Equation (10), is given as the cost per unit time cu multiply by time t that the resource is working on the task:

$$C_{n,m} = cu_{n,m} \times E_{n,m} \tag{9}$$

$$C_{n,m} = cu_{n,m} \times T_{n,m} \tag{10}$$

Additionally, when various resources are working on the same task, the time for the task will be the longest taken by the any of the resources and the cost will be equal to the cost of each resource used added together.

Total process duration in Equation (11), cost in Equation (12), and effort in Equation (13) are the sum of the individual task values taking into account the chosen options for each task:

$$TT = \sum_{i=0}^{n} T_{n,m} \tag{11}$$

$$TC = \sum_{i=0}^{n} C_{n,m} \tag{12}$$

$$TE = \sum_{i=0}^{n} E_{n,m} \tag{13}$$

The relationships were modelled within ASM thanks to its process variables modelling capabilities that enables to define mathematical functions.

5.2.5   Application example

The example case study depicts part of a standard aerospace project where designers from different backgrounds and other resources need to be selected to participate in the design. The model is based on a bigger case study, the Fan Sub-system. It is constructed as a simplification of the larger process model and extended with key elements to test the functionalities of the model. It comprises 10 tasks involving four designers, one computational resource and one testing resource.

In essence, this process starts with three activities conducted by preliminary designers, each of these activities requiring specific tools to be used. Then, mechanical properties are generated and refined during two tasks involving a preliminary designer and a mechanical engineer. The product is further studied by an aerodynamic designer with four activities, in which one requires the use of High Performance Computing (HPC). Failure on aerodynamic performance may iterate the process. Finally, a testing slot has been

booked to take place in 27 days. The corresponding model as well as the options for each resource type are detailed in Figure 30.
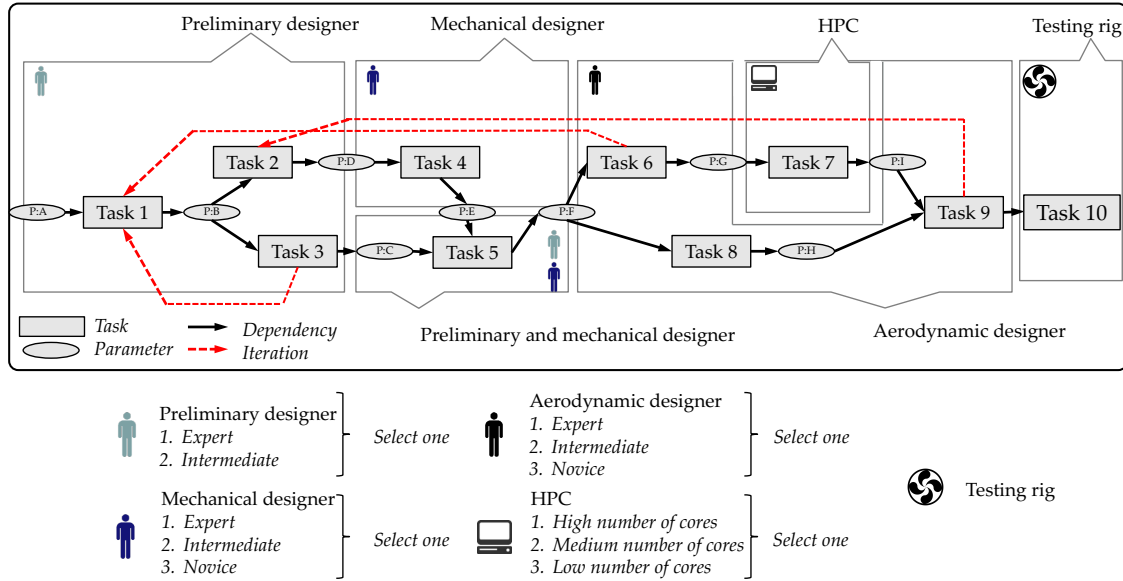
Figure 30. Design process and resources needed along with possible instance options

'*Time dedication*' for an expert designer is defined at 66%, 83% for intermediate, and 100% for novice designers. '*Time'* to task completion ranges from 2 hours to 1 week depending on both the task and the designer expertise: typically, expert designers complete tasks faster than intermediate designers, which are in turn faster than novice designers. Similarly, '*iteration likelihood'* value is 5% for an expert designer, 10% for intermediate designers and 15% for novice designers. However, learning after iteration, which corresponds to '*learning curves'*, is 25% for intermediate preliminary designer and not learning for expert preliminary designer; and 5% for expert, 10% for intermediate and 20% for novice mechanical and aerodynamic designers.

In this study, cost units are based on an arbitrary metric used to denote the value of one resource option in relation to the others within the organisation, rather than a specific monetary cost. '*Cost per unit'* can be found in Table 12. The number of jobs already submitted to HPC from the same department determines how long the current job has to wait. Depending if the number of jobs submitted is none, low, medium or high, '*waiting time'* varies from 'no waiting time' to a week. In this example, we start by assuming that no jobs are pending. When a testing slot is missed, the '*waiting time'* until the next slot opening will be 10 days approximately.

Table 12. Summary of values used for the case study

Resource	Variable	Expert/ High	Intermediate/ Medium	Novice/ Low
Designer	**Time** t	Between 2 hours to 7 days		
	Cost cu	6	3	1
	Learning li	5%	10% - 25%	20%
	Time dedication a	66%	83%	100%
	Iteration likelihood il	5%	10%	15%
HPC	**Time** t	Between 7 to 16 days		
	Cost cu	15	11	7
	Waiting time w	Between 0.5 days to 7 days depending on jobs pending		
Prototype and testing rig	**Time** t	Between 2 to 4 days		
	Cost unit cu	15		
	Waiting time w	10 days		
	Time limit tl	27 days		

Finally, the priority of the project can affect process performance: we assume that high priority is the default setting. As priority decreases, designer's time on the project may decrease to 75% or 50%. Similarly, it priority increases, designers can be completely devoted to the project. All possible resource combinations of the model are tested through Monte-Carlo simulation runs. The resulting variability in results stabilises after 500 runs. However, to further increase stability of results, the analyses discussed in the following sections used the mean of 1,000 simulation runs per resource combination. The chosen situation to study the variability of results was *medium* expertise for all designers and *medium* cores for HPC, which is the *baseline scenario*.

5.2.6   Results

Introducing resource options for each process task provides additional insights compared with the traditional approach, which consists in considering only one average type of resource. Possible analyses to find adequate resource management strategies include 1) identifying best resources combinations and critical resources; 2) identifying resource sensitive tasks; and 3) quantifying the impact of process characteristics on performance. In addition, process performances are compared between the proposed approach and the traditional one to illustrate the potential of using resource options. These insights are drawn based on process duration, effort and cost, the already discussed key performance metrics. However, other performance indicators could be added to the model depending on the modeller's expectations.

1) Identification of best resource combinations and critical resources

Figure 31 shows total process performance of all possible resource combinations as a percentage improvement over baseline scenario.
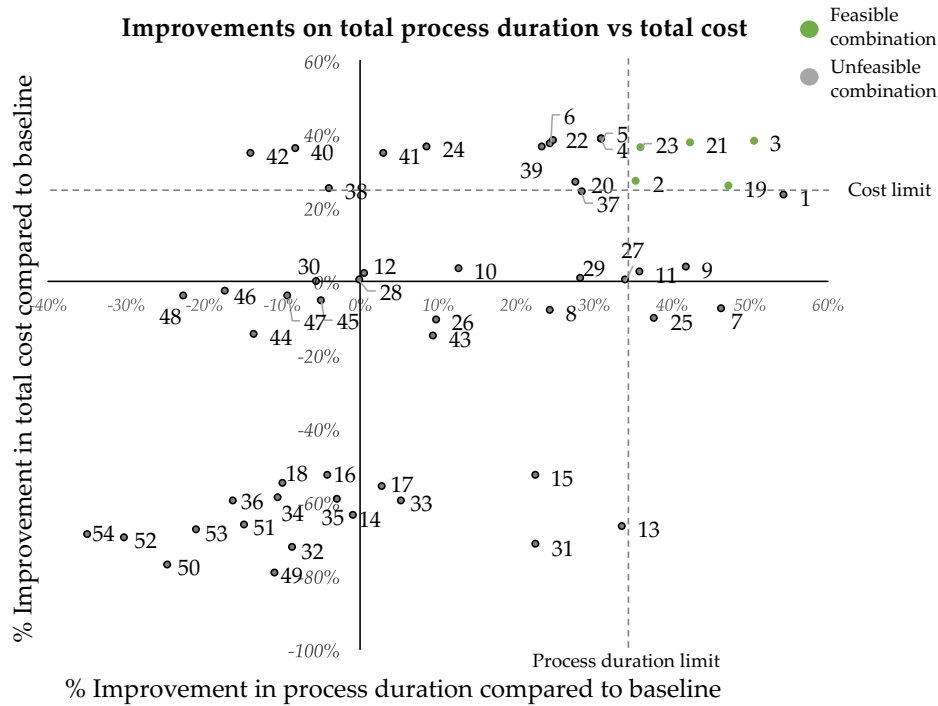
Figure 31. Improvement in duration vs improvement in total cost (full results in Appendix)

It can be seen that the top right quadrant includes the resource combinations that improved the baseline scenario in both cost and process duration. The design space depicts three distinctive areas of combinations in terms total cost. A possible explanation could be that results were biased towards the cost of HPC. In this particular case, the speed of higher cores greatly offset its cost (when no jobs are pending to create bottlenecks and waiting time). Hence higher cores seemed to have better time and cost improvements.

The identification of the best resource combinations depends on the manager and project priorities: one may choose to emphasise time to the detriment of cost, and vice-versa. In any case, most likely trade-offs between the different performance metrics will be required. In this example, the maximum budget for the process is set to 140. This is equivalent to utilising 19 days of expert time (6x19 = 114 units), 1 day of high number of cores for HPC (11 units) and one slot of testing rig (15 units). Therefore, any combination that does not exceed 140 unit cost is acceptable. The analysis proceeded by filtering out all the combinations with average process durations longer than 27 days (deadline for testing experiment) and 140 unit cost. As a result, only five resource combinations are able to achieve these objectives. Table 13 shows the five resource combinations with the corresponding resource option and summarises the frequency of resource instances.

Table 13. Time-cost trade off: feasible resource combinations given performance results

Combination	Aerodynamics	Mechanical	Preliminary	HPC
Baseline	Intermediate	Intermediate	Intermediate	Medium
23	Intermediate	Novice	Expert	High
21	Intermediate	Intermediate	Expert	High
19	Intermediate	Expert	Expert	High
3	Expert	Intermediate	Expert	High
2	Expert	Expert	Intermediate	High
Summary of instance frequency %	Expert: 40% Intermediate: 60%	Expert: 40% Intermediate: 40% Novice: 20%	Expert: 80% Intermediate: 20%	High: 100%

Although this example is focused on the trade-off of duration and cost, effort is also taken into consideration. Within the feasible combinations, it is in the organisation's interest to incur in the minimum effort possible to perform the same process. Given the amount of improvement over baseline, combination 3 seems to be the most efficient out the feasible combinations. However, given the nature of design, there is always a degree of uncertainty.

Figure 32 presents the level of improvement that each combination achieves compared to the baseline in terms of total effort, total cost, and process duration. Taking into account cost and time performance aims and instance frequency in Table 13, high cores HPC and expert preliminary designer seem to be more critical, while mechanical and aerodynamic designers are more flexible. The results are plausible since the output of preliminary design can condition the rest of the process. These insights can be used as a guide for planning and scheduling purposes for design process improvement.
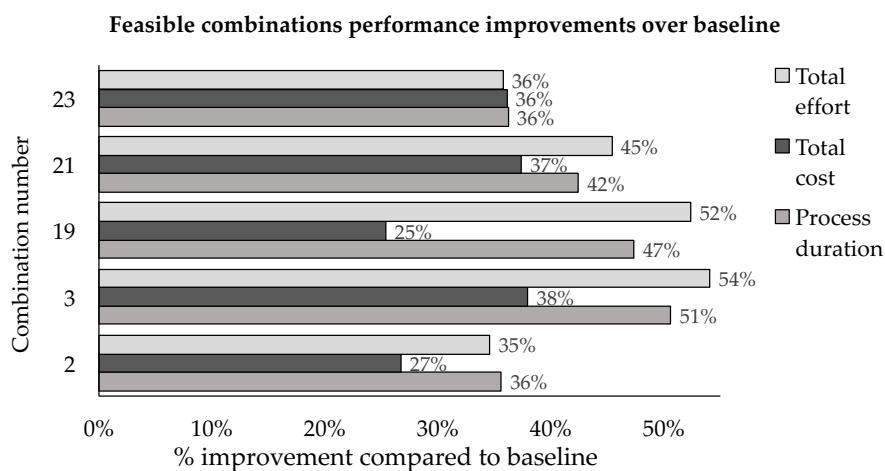
Figure 32. Percentage improvement of feasible resource combinations over baseline

2) Identification of resource sensitive tasks

Analysis should allow for the identification of resource sensitive tasks, i.e. those that display variability in performance depending on the resource used and therefore those that more susceptible to resource changes.

The current example prioritises time over any other performance metrics due to the urgency to reach the testing slot on time. It is assumed that there is a big potential negative impact otherwise. Figure 33 illustrates resource sensitive tasks in relation to time performance.
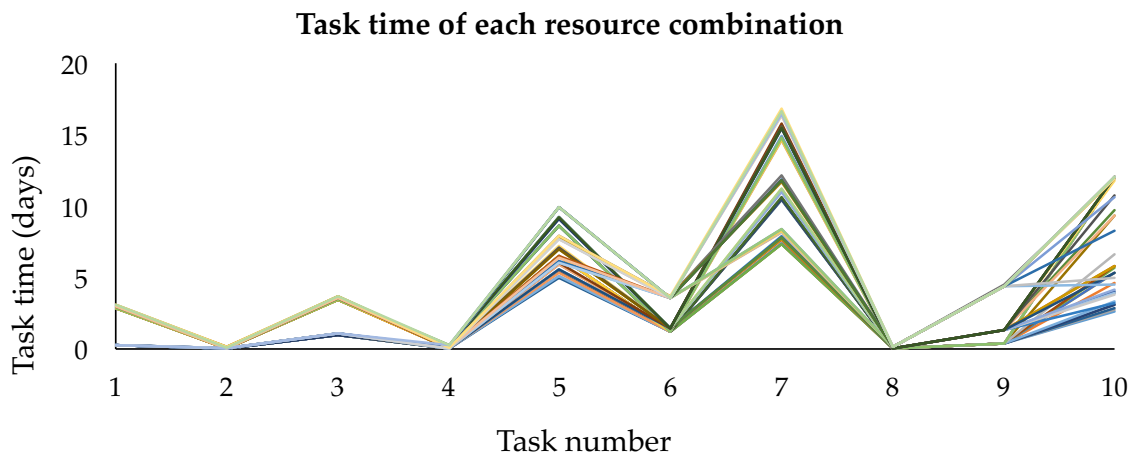
Figure 33. Task duration of each resource combination

Figure 33 shows all possible 54 resource combinations, each depicted as a single line. The x axis indicates the task, while y axis shows task duration. In this example, activities 5, 7, 9 and 10 clearly display a resource sensitive behaviour; followed by 1, 3 and 6; and less affected by resource changes are activities 2, 4, and 8.

3) Quantification of impact of project characteristics on performance

Two additional scenarios were tested by perturbing some attribute values to study their impact on process performance:

1. The influence of having more jobs submitted to HPC was tested in order to study the effect of overloading HPC on performance.

2. Project priority was decreased to simulate a scenario in which many projects run at the same time, hence overloading designers.

The two scenarios overloaded different types of resources to study which one is more critical to the process in hypothetical resource intensive situations. Figure 34 illustrates the results by plotting the feasible resource combinations against different overload sce-

narios for HPC (top) and designers (down). The results of baseline scenario are equivalent of those of Figure 32. The difference is that Figure 32 illustrated percentage improvement over a baseline combination (all intermediate designers and medium number of cores), while Figure 34 represents elapsed time.
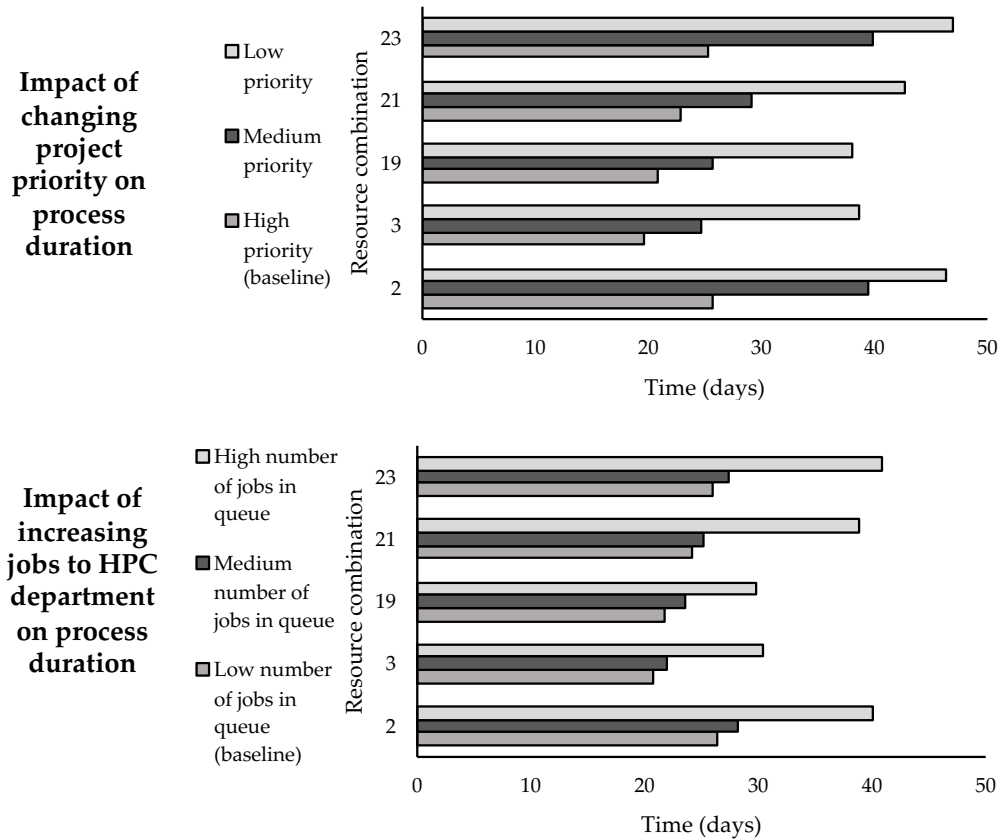
Figure 34. Process duration of key combinations when: Top) project priority changes; Down) number of jobs submitted to HPC changes

Compared to baseline scenario (low number of jobs and high priority project), it can be seen from the results that degrading project priority had a larger effect on performance (in case HPC already has high number of cores). Hence, if project priority is linked to designers working on multiple projects, then designer's time is a more constraining aspect than jobs submitted. In case of resource limitation, results suggest that acquiring more designers in this particular scenario could more beneficial than investing in HPC. An important point to note is that this conclusion is for this specific example, which only displays one activity that is dependent of HPC resources.

In addition, simulation results also recommend to book the testing rig four and six days later if project priority is medium and low respectively. This would allow having extra time to avoid losing the testing slot.

4) Comparison of approach without and with resource options

In order to assess potential benefits of the proposed approach, the above case was also built without detailed resource modelling. The values used for the baseline model (without resource options) are the intermediate levels for all resource types. Figure 35 depicts the differences between the traditional one and the resource options based approach. It shows the probability distribution of time performance in two histograms: the x axis indicates total time taken by different process simulation runs, and the y axis presents the percentage of runs that finished at that particular time on the x axis.
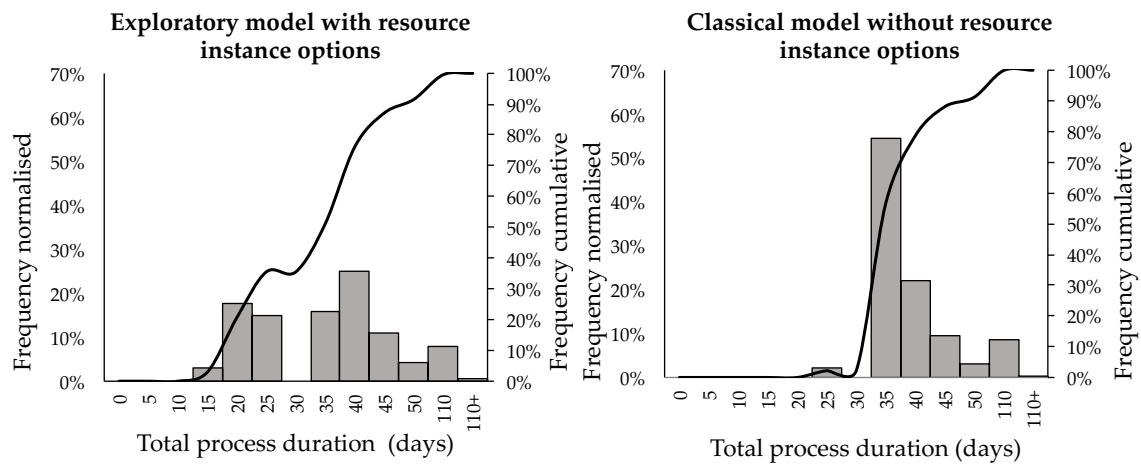
Figure 35. Total process time histogram comparison of traditional (without resource options) in the left and proposed approach (with 54 resource combination options) in the right

The model, using no detailed resource modelling, shows less variation compared to the histogram of the proposed approach. This is due to the standard approach was only able to simulate process performance values equivalent of using intermediate level for designers and HPC cores. With the proposed approach, it is possible to study 54 different resource combinations (scenarios based on choosing different designer expertise and HPC number of cores) and therefore explore larger variations of the design space in terms of resource options. In particular, it can be seen on the histograms that some runs are taking considerable more than 26 days to execute the design process. This corresponds to the processes where the testing slot was not reach on time, which resulted in adding around 10 days of waiting time (necessary to reach the next testing rig slot). Thus, it seems critical for the process to reach the testing slot on time.

5.3   Discussion and requirements for improvement

The functional requirements derived from the already gained understanding guide the development of a support method (Prescriptive Study).

A prototype model is introduced in this chapter based on ASM and extending its capabilities accordingly. FR1, FR2 and FR3 were fulfilled since ASM can model design processes using activities and parameters with an easy diagrammatic visualisation while capturing design characteristics and providing Monte-Carlo simulations. The framework was also used to model activity characteristics, thus addressing FR4.

In order to include different types of resources, ASM was extended to model instances of designers, computational resources, prototyping and testing resources and their attributes extracted from Chapter 4, addressing FR5 and FR7. In addition, FR6 took advantage of the fact that ASM models already had the functionality of modelling resources as constraints, not allowing an activity to start unless the required resources are drawn from the pool. To fulfil FR8, the relationship between activity characteristics and attributes were modelled to capture the impact on task and process performance. Designer expertise and computational capability/power were the representative of different instances. To accomplish FR9, the model extended the functionality to choose between designer instances (according to expertise: expert, intermediate and novice) and computational resource instances (in terms computational power: high, medium and low).

Monte-Carlo simulations were used to study the impact of using different resource combinations on an example case study. The model was first tested without any variation and a single resource option (intermediate expertise and medium cores) and compared to a traditional model (resources as constraints) using the same input data. The results confirmed the correct building of the model. Subsequently, it was applied on an example case study by simulating the process, with all design uncertainty characteristics, allowing different resource options.

To extract possible insights for resource management, the analyses compared the average performance in terms of duration, process, and cost of 1,000 simulation runs of different resource combinations. The mean values had an average fluctuation of around +-0.5% in approximately 95% of the simulation runs. Given the nature of Monte-Carlo simulations and amount of uncertainty modelled, the accuracy of the results can be considered satisfactory for the intended purposes. This accuracy can be improved by increasing simulations runs.

The analyses enabled for the identification of key resources and resource sensitive activities, the first of the stated goals in Section 5.1. The feasible resource combinations given time and cost performance aims (27 days and 140 cost limit) were listed in Table 13. Results also distinguished tasks 5, 7, 9 and 10 as more resource sensitive, marking the use of specific resources as more critical in order to achieve better performance. In contrast, activities 2, 4 and 8, in which the use of different resources has a lower effect on

process performance were also identified. They can be proposed as starting activities to train and allocate new or novice designers. Mechanical designer seemed to be the least critical resource, encouraging the introduction of novices. On the other hand, all the feasible combinations feature HPC with the highest number of cores possible, indicating the dependency of the process to HPC with high computational capability. Finally, the method tested hypothetical scenarios in which different types of resources were overloaded. In this context, overloading human designers had a greater impact on process performance than overloading computational resources. If various projects were sharing those resources, results suggest the potential benefits of adding more designers. Nevertheless, the last two goals in Section 5.1 were only partly fulfilled: improving understanding between the relationship design resource attributes and the task characteristics on process performance; and selecting the right combination of design resources for process execution given project characteristics and constraints. A point to note is that effort, even though a key metric to assess process performance, should be taken as an independent parameter. Hence is not a primary decision criterion such as process duration or cost, but still an important factor for process improvement.

In order to complete the goals, the approach has to address a few shortcomings. On the modelling side, enhancement of the modelling of complex relationships between the different resource attributes, as well as *diagnosis* capabilities to study their impact on each other. It could be especially beneficial since some attributes were conditionally dependant on other attributes. An example could be enhancing resource attributes to depict skills and expertise and their impact on other attributes and performance. The relationships that resource attributes and performance values exhibit might be too complex to capture with current ASM capabilities (although one of the most flexible of the investigated ones). The reason could be the highly complex, interdependent and probabilistic nature of these variables. Part of this complexity is due to some resource attributes having both qualitative and quantitative descriptions and the conditional relationships between them. ASM can model functions, which is mainly through mathematical variables with limited qualitative capabilities. Thus, a method that can capture more uncertainties with a large number of interdependent variables is necessary. Enhancement on relationship modelling would result in increasing the understanding of: 1) resource attributes internal dynamics; 2) resource influence on task performance, which it can draw more insights from; 3) resources complex and conditional relationships; and finally 4) the method should enable to constrain any resource attribute or process performance value to study the resulting optimal resource option. It should *diagnose* which resource options could meet specific task and process performance targets.

Given the shortcomings, the current prototype model does not fully capture FR8, related to adequately model the relationships between variables. In addition, the analyses also did not cover the intended granularity, set by the scope in Chapter 1, of studying performances at both activity and whole process level. Although insights were drawn at the process level, the shortcomings in modelling attributes internal influences and performances resulted in not fulfilling FR10 satisfactorily. To a larger degree, FR11, which concerns analysing the impact of resource attributes internal dynamics on performance and vice-versa (diagnosing the impact of selecting attributes and performance values on the rest of variables) was not satisfied. To conclude, the model needs to be extended to fully address the functional requirements.

5.4 Summary

The present chapter started by addressing RQ3, which consists of deriving requirements for a resource management model, by synthesising the knowledge gathered in previous chapters. The list of functional requirements comprises requirements on design process modelling, resource modelling and resource management analyses. Design process modelling requirements ensures that the model captures the complexity and uncertainty of design processes and can support day-to-day managerial decisions. Resource modelling requirements aims to set guidelines to model key resources, resource attributes, and define the relationships and behaviour of the model. Ultimately impacting on process performance. In addition, it requires the model capability to simulate different resource instances to be enhanced. Resource management analyses requirements ensures that the results provide meaningful insights applicable by the process stakeholders. They have to be both understandable and applicable to daily managerial decisions.

Subsequently, the chapter initiated the development of the new support method, thus examining RQ4 by developing suitable concepts that can fulfil the functional requirements. ASM was chosen as basis to build the approach since it offers flexibility in terms of implementing behavioural logic and presents a diagrammatic visualisation. It can capture design process uncertainties, iterations, product quality progress, and performance improvements (in particular cost and time). This prototype model was able to:

1) Model different resource types and attributes that affect process performance;
2) Allocate and simulate different resource instance options per task;
3) Identify resource combinations that reach a set desired time (reaching a testing slot) and budget;
4) Identify resource sensitive activities;

5) Facilitates setting up simulations to perform some *'what-if'* analyses (changing number of jobs for HPC, changing project priority).

However, key shortcomings were found in terms of modelling the relationships between resource attributes and performance metrics given the interdependent and probabilistic nature of the variables. Thus, some goals such as understanding resource attributes internal dynamics or constrain any attributes (or process performance) to study the resulting optimal resource option were not achieved. The next chapter extends the model into a final support approach that addresses all the functional requirements.

6 Design resource management support method

Chapter 1 stated the objective: *Improve design process management by improving design resource management*, while Chapter 2 determined that a method based on design process simulation and analysis seems appropriate to extract managerial insights for process improvement. Thus, the current chapter presents a novel support method to aid resource management in design processes and consequently, improve process planning and execution. The model should enable an investigation into process behaviour in light of different resource requirements, including not only the human designers, but also computational and testing. This includes testing multiple scenarios to study the impact on performance of different resource instances given trade-offs in availability and effectiveness.

This chapter extends the prototype model of design process management presented in Chapter 5, thereby the required capabilities to address the stated functional requirements. These englobes design process modelling, resource modelling and analyses requirements. The chapter finishes investigating **RQ4:** *What is a suitable concept(s) for a model for resource management that fulfils the functional requirements?* and addresses **RQ5:** *How well does the model concept meets the requirements?*

Although the approach can be built on different process modelling frameworks, Applied Signposting Model (ASM) is used as the foundation for the support method. The previous chapter identified ASM as a suitable process modelling framework that can be computationally implemented in the Cambridge Advanced Modeller (CAM) software

(Wynn *et al.* 2010, www-edc.eng.cam.ac.uk/cam/). The chapter provides explanation regarding the ASM modelling framework whenever required. However, it is not the primary focus of the research, which rather concentrates on the detail elaboration of the new approach. A more complete guide to ASM and its simulation algorithm can be found in Wynn *et al.* 2006 (conference paper) and Wynn 2007 (thesis); and the CAM tool with its documentation can be downloaded from https://www-edc.eng.cam.ac.uk/cam/.

The development of the support method is analogous to a design process, for example the one presented by Pahl *et al.* (2007): planning and task clarification, conceptual design, embodiment design and detailed design. Planning and task clarification was done in the previous chapters and finished with Chapter 5 eliciting the model's requirements. In this chapter, Section 6.1 identifies different resource management concepts (conceptual design). Section 6.1.1 also discusses the remaining requirements that were not fully satisfied with the prototype model in Chapter 5. The prototype model can be taken as the first iteration of the method. Subsequently, Section 6.2 lays out the possible development of the selected concepts, similar to design embodiment. Detail design is presented in Section 6.3 and Section 6.4. The former introduces the new method including its process elements, task characteristics, resources and attributes, and its fundamental relationships. The latter, finalises the detailed implementation of the support in a modelling tool. Section 6.5 presents the modelling procedure for the support method (the steps to build a model). Section 6.6 summarises the chapter.

6.1   Identification of design resource management concepts

The understanding gained from the prototype model helped to further improve the development of the new resource management approach (particularly, concerning the increasing flexibility in terms of choosing resource instance options). It also aided in identifying the three concepts presented in this section: *static resource allocation*, *flexible resource allocation*, *preferred resource allocation*. As stated in Chapter 5, requirements considered design process modelling, resource modelling, and management analyses. This is translated in the process data needed, resource data needed, and output results respectively. The first concept can be seen as a high level abstraction of current methods. The second concept has been developed to address the gaps identified in Chapter 2. Similarly, the third concept is an extension of the second, but fully incorporating all the functional requirements from Chapter 5.

Firstly, as identified in the literature review, many resource management models that improve resource estimation, allocation and scheduling traditionally consider resources as constraints. At the start of the process, all resources are in a pool until they are required to perform an activity. Then, the resource leaves the pool and executes the activity

before being released back to the pool. The traditional approach has no resource varia-
tion in terms of impact on performance. Most characteristics such as time, iteration like-
lihood, learning etc., are modelled within the activity. The author defines them as static
resource allocation. As shown in Figure 36, they require a set of process data, activity
characteristics, resource allocation data (where and amount needed), and hold static re-
source choices. Process data consists of information regarding process structure and path
such as activities, iteration constructs, parameters, precedencies/dependencies and path
logic. Activity characteristics comprise information to simulate the process such as ac-
tivity duration, iteration likelihood, cost, etc. Consequently, the results are equivalent to
simulating one resource combination and do not integrate the possibility to define the
distinctive resources that participate in a PD process. The concept assumes that every
resource has the same effect when performing a task, hence offering a static way of de-
fining the characteristics of the process.
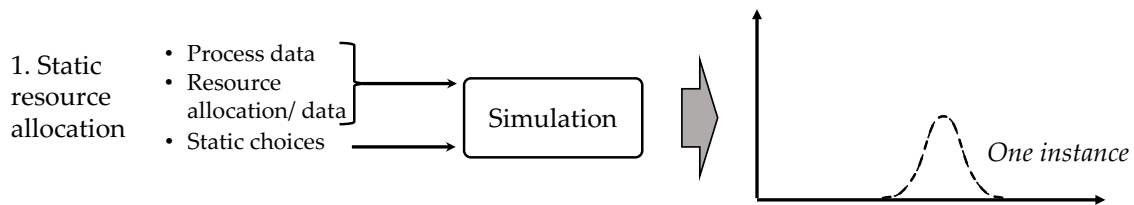
Figure 36. Static resource allocation concept with the data required and results

Secondly, as presented in the prototype model, *flexible resource allocation* accounts for the
heterogeneity of resources by providing the possibility to model several options of re-
source instances. Thus, addressing the gaps identified in Chapter 2. The concept, shown
in Figure 37, simulates a larger number of resource combinations to explore a wider de-
sign space in terms of process performance. The same resource type has different in-
stances that can perform the same activities, but attaining different availability and ef-
fectiveness towards process performance. However, the increased capability in model-
ling resource attributes and their interrelationships with activity characteristics has aug-
mented the complexity of the captured behaviour. Therefore, a fitting method is neces-
sary to incorporate the complex cause-effect relationships of resource attributes, activity
characteristics and process performance.
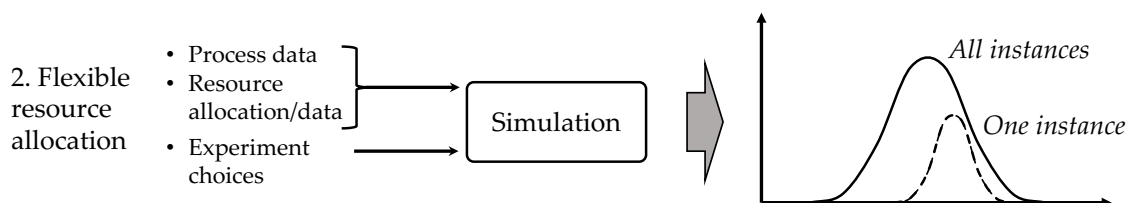
Figure 37. Flexible resource allocation concept with the data required and results

Thirdly, when multiple combinations are possible, *preferred resource allocation* aims to isolate the likely or desired combination given an objective process performance. Ideally, the new model should have the capabilities that enable the identification of preferred resource allocation. In addition to process and resource allocation data, this concept also requires a desired process performance value. The analysis follows a causal relationship, in which given an '*effect*', the interest lies in finding the instances that can provide such an outcome. In order words, the results are searched with backwards propagation approach to look for instances that can reach that desired performance. Figure 38 illustrates the preferred resource allocation concept.
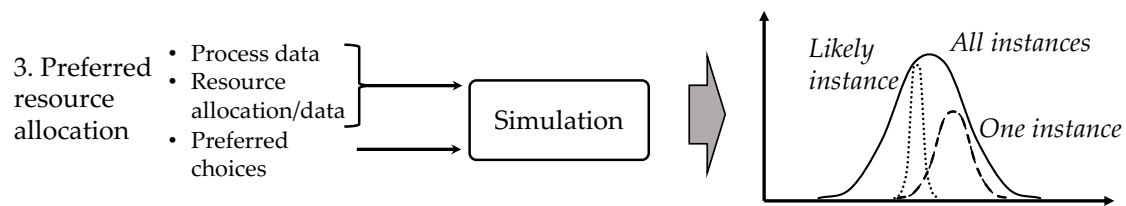
Figure 38. Preferred resource allocation concept with the data required and results

The three concepts have a logical evolution that increases the flexibility of testing multiple resource combinations. Translating the concepts into support methods, static resource allocation can be modelled with current frameworks such as ASM, Signposting, Petri net, GERT, etc. These frameworks also act as process simulators. The method involves feeding the model with various process data such as activities, parameters and dependencies; and activity characteristics such as task time and iterations likelihood. On occasions, resource constraints can also be added to the model.

The second type, flexible resource allocation, can be deemed into two different variations. The first variation was presented in the prototype model, in which resource attributes were modelled using ASM. A point to note is that depending on the purpose of the model, different attributes can be built in alternative frameworks. This is done by abstracting the resource attributes presented in Chapter 4 into variables that can define activity and process behaviour. Therefore, this enables the testing of different resource combinations. Nevertheless, the prototype model did not completely fulfil all the functional requirements for this thesis such as causal relationship analysis. The second variation, also has the capability of simulating different resource combinations. It draws on the conclusion that the framework or process simulator could have some limitations in capturing resource attributes, its complex relationships, and could be restrictive in performing causal analyses. Although, the process simulator still provides needed functionalities in terms of process modelling capabilities, an external method can be used to build the resource model. Such a model could mainly incorporate the interactions between resource choices, attributes, and relationships that defines task behaviour. Hence, this

second variation models the process with a *framework* or *simulator*, while resource attributes, activity characteristics and their interactions are captured with a *resource model*. Since each resource model can be embedded in a task, activity performance depends on which resource instance performs it. Then, activity performance values are input into the process simulator to be aggregated as process performance. Hereafter, process behaviour characteristics that can influence the resource model are fed back as *learning* data (the update of activity characteristics after iteration). As an example, a specific designer instance has a high iteration likelihood, which is an input from the resource model to the process model. If iteration is triggered and the resource instances present *learning curves* related to iteration likelihood, the process simulator will feed the number of finished iterations back to the resource model to calculate the new iteration likelihood value.

The third type, preferred resource allocation, has a specific activity or process performance indicated as objective. The value is input to the resource model to gain insights on which resource instance can achieve the desired performance. This third type is likely to require a separate resource model to provide the desired functionalities. The external model needs the capability of analysing casual and effect relationships between variables to '*diagnose*' their impact on the other variables. For example, which resource instance can achieve a specific performance value. The model advocates for the capability of selecting desired values of any variable ('*what-if*' scenario) to discover the instances that can correlate with those values. The three concepts are illustrated in Figure 39, in which key outputs of each concept are circled in red. The process simulator in the different concepts can be the same one, but fed with different information.
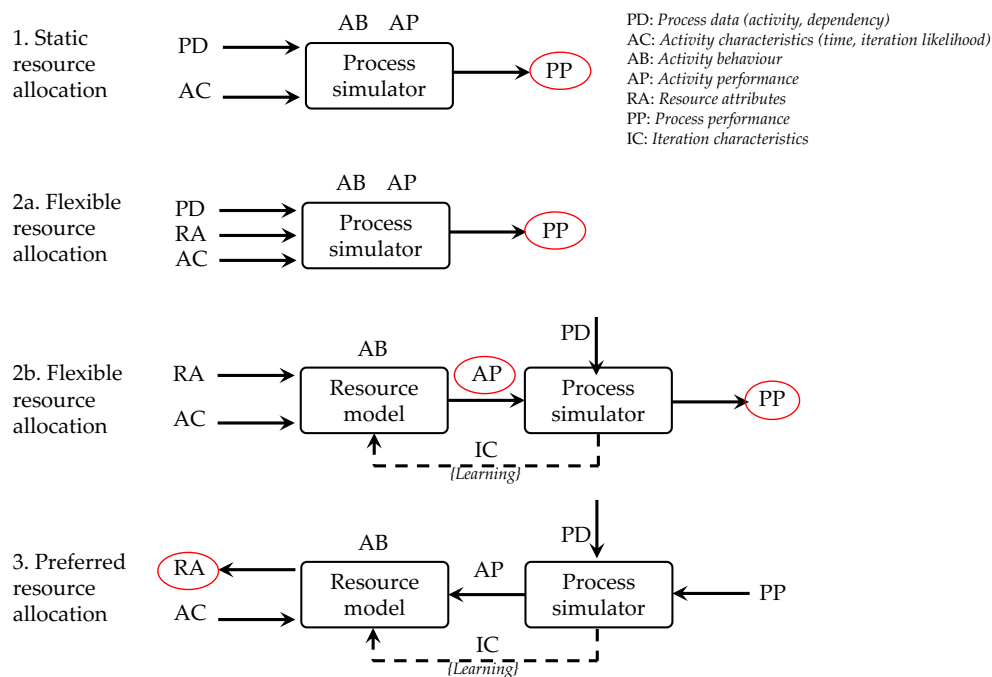
Figure 39. Resource management approach functional building

6.1.1 Addressing final requirements for resource management method

The present sub-section assesses the potential of the different concepts to fulfil the remaining requirements from Chapter 5. Static resource allocation does not fulfil all the requirements since it represents the current situation. Flexible resource allocation, which the prototype model is part of, has the potential to address all the requirements if the right method is applied. Preferred resource allocation needs that all the requirements are addressed to be applied. The prototype model presented in Chapter 5 was able to address most of the functional requirements except:

- FR8 - Defining relationships: The requirement advocates that the model should '*capture the relationship between tasks and resources appropriately*' to predict their impact on activity and process performance (modelled through activity characteristics and resource attributes internal dynamics). However, the prototype model did not fully capture the complex (qualitative and quantitative) and conditional relationships between probabilistic and deterministic variables.
- FR10 - Analyses of the use of different resource instances: The requirement is concerned with the ability to measure the impact of using different resource instances at activity and whole process level. The part of the requirement that was not fully addressed by the prototype model was to provide insights at activity level. The final model should provide '*analyses at both activity and process level*'.
- FR11 - Analyses of the impact of resource attributes internal dynamics on performance and vice-versa: The model should quantify how much each attribute influences on performance and vice-versa, hence requiring '*diagnosis capabilities*' that can perform both forward and backward analyses.

Figure 40 summarises the evolution of resource allocation capabilities and shows which ones each concept attains. *Static resource allocation* enables the modelling of constraints (e.g., traditional ASM). The first variation of *flexible resource allocation*, which the prototype model belongs, incorporates different resources but does not fully model their complex relationships. The prototype model had flexible resource allocation capabilities using ASM as modelling framework and process simulator. Increasing its capabilities using an external resource model, the *second variation of flexible resource allocation*, can potentially address FR8. This would be possible if the chosen resource modelling method can capture enough uncertainties and has the flexibility to integrate complex and conditional relationships. FR10 can also be addressed since the extension should be modelled at the activity level of granularity to provide enough visibility in diagnosing the impact of different resource attributes on each other. Although the prototype model can extract the value of a specific variable, it only outputs results at the whole process level. Given the large influence of resources on activities, the scope of the research requires to isolate

key activities and study the impact of resources at a task level. The author hopes to extract further insights that can increase the understanding of resource attributes internal dynamics and resource influence on task performance. Finally, this derives into addressing FR11, which requires to adapt the model into a *preferred resource allocation* method with diagnosis capabilities that indicate which resource instance can achieve an indicated performance objective.

In summary, the final concept has to incorporate both flexible resource allocation and preferred resource allocation. As identified in Chapter 2, flexible resource allocation enables the study of the whole design space in terms of resource combinations, consequently facilitating the investigation of trade-offs between effectiveness and availability. Preferred resource allocation, with diagnosis capabilities permits diagnosing not only which resources can achieve a set aim performance, but also the impact of different variables (resource attributes, activity characteristics, etc.) on the remaining ones. Thus, expanding the understanding of resource behaviour (a need identified in Chapter 4).

Evolution of resource management capabilities
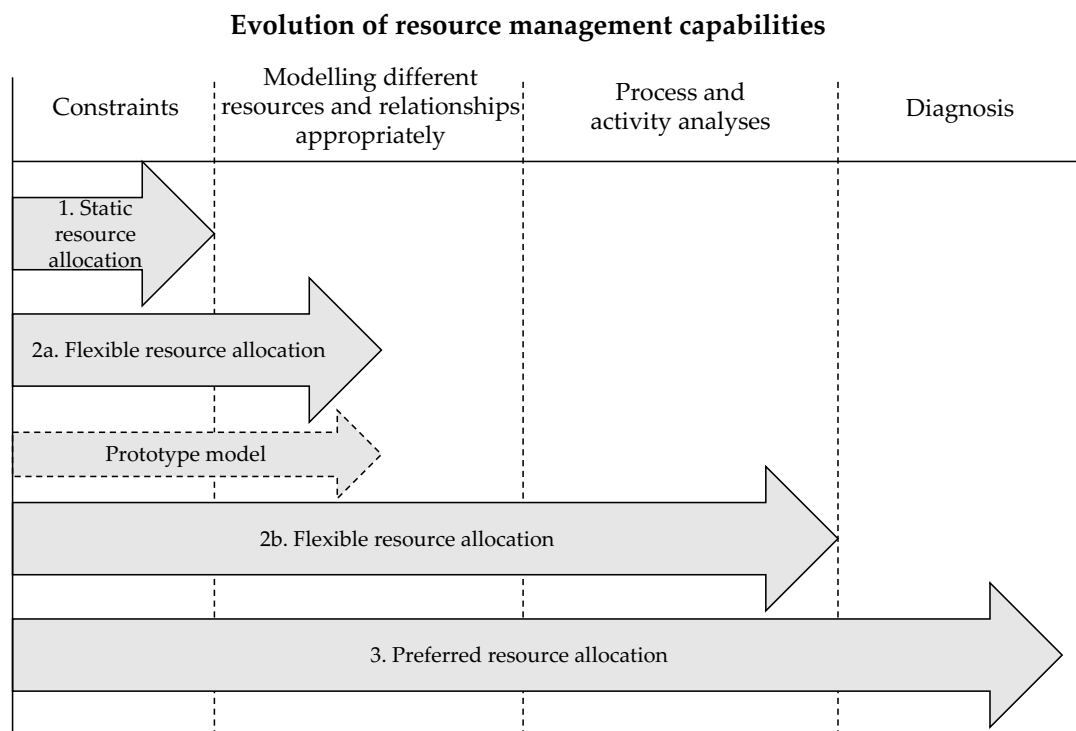
Figure 40. Resource management concepts and their capabilities

6.2 Development of resource management concepts

Chapter 5 modelled different resource options for each task by mainly coding resource attributes and relationships using ASM. The final model (support method) still retains

ASM as the process modelling framework due to its strong capabilities in terms of process simulation, and providing enough flexibility for further resource modelling enhancements. However, to address all requirements, the method needs an external resource model that 1) captures design uncertainties, 2) incorporate resource attributes' complex and conditional relationships, 3) outputs understandable results, 4) increases capabilities of analyses at a granular level, and 5) provides with the functionality to diagnose the impact of variables on each other.

In an effort to develop a method that addresses all the derived requirements in Chapter 5, the author has opted to incorporate Bayesian Networks (BNs) as a base for model construction of resources and their attributes inside activities. A number of reasons supports this choice: BNs can integrate data uncertainty into a modelling structure, has good data visualisation, captures complex relationships by combining quantitative and qualitative data, and enables back propagation analysis (Barton *et al.* 2008; Moullec *et al.* 2013). Incorporating BN as the resource model, the approach has the potential to attain both flexible resource allocation and preferred resource allocation capabilities.

Another technique that can combined large number of variables is DSM or MDM (Chapter 2). However, BNs have easier visualisation and more flexibility in terms of relationship modelling compared to them. In addition, it allows backwards propagation (diagnosis capabilities). In this sense, parallel coordinates technique has been used in combination with ASM by researchers such as Le *et al.* (2012) to provide some diagnosis capabilities for process analysis. They can be used to visualise specific results by constraining the data from one or various coordinates that represent the model's variables (e.g., performance metrics such as time). However, parallel coordinates depend on the order of the variables to gain insights, which have to be re-ordered accordingly. Furthermore, the complex dependant relationship of resource attributes and activity characteristics, in which child variables often have various parent variables, is more naturally depicted using BN. Parallel coordinates normally link one variable with the immediate next one. Hence, it is not the ideal candidate to analyse the multi-parent conditional relationships of resource attributes and activity characteristics, which is done at the activity level. Solé *et al.* (2017) has compiled a review of root-cause analysis approaches, including many techniques that can represent dependencies between variables and potentially extended with inference algorithms. Examples of these formalisms include Fault Trees, Markov chains, and neural networks. Fault Tree Analysis (FTA) is an analytical tool to identify weak links in a system by finding the causes of an event (basic event) from the occurrence of an unwanted event (top event). However, BN is a more suitable and flexible method for modelling complex systems in which probability and uncertainty analysis

are required (Hamza and Abdallah 2015). Moreover, BNs can dynamically update probabilities, which is a powerful method when new evidence is found (Hamza and Abdallah 2015). Generally, Markov chains do not indicate directed dependencies, hence the modelling technique does not capture the direct relationship between parent and child variables. Hidden Markov Chains adds a temporal component to BN (Ghahramani 2001), which the current research does not require. Artificial neural networks normally comprise a large number of nodes, or processing units, that are connected to each other by sending signals using weighted connections (Anderson 2009). They are used for problems that involve classification or forecasting and do not model the fundamental meaning behind the structure. In contrast, BNs can model the relationships between relevant variables and the intrinsic meaning of the model for diagnosis and decision making.

Bayesian Networks are introduced in the next section and further consideration on their suitability to extend the model is discussed.

6.2.1 Bayesian Network

A Bayesian network (BN) is a directed acyclic graph that captures the joint probability distribution of a set of variables. This probabilistic graphical model consists of a set of nodes, each one representing a variable, and a set of edges representing conditional dependency between variables. Each variable has a finite number of mutually exclusive states, which represent the possible options for the variable. The links represent the relationship in terms of conditional probability distribution between a parent node and a child node. In other words, the manner that the child node depends on its parent nodes.

Bayesian nets have the capability to perform *"inference"*. Given a BN, if the states of some variables are known in a given observed situation (setting a belief), inference can update the probability distribution of the remaining variables by applying the Bayes' theorem (Jensen 1996):

$$P(A|B) = P(A) \times \frac{P(B|A)}{P(B)} \tag{14}$$

The updated situation can be used to study its findings, which means the value for a particular variable (node) in a specific instance. Assuming a BN model with a prior distribution, if some nodes' states are observed, probabilistic inference calculates new beliefs to find posterior distributions. Inference can propagate in any direction, from causes to effects and vice-versa. This means that variables can be observed on both parent nodes and/or child nodes and the remaining probabilities will be inferred. A simple example to explain inference consists in a small model relating the possibility of raining and the presence of clouds (Netica). The variable of cloudiness has boolean states, either true or

false with 50% chance each. Rain depends on its parent node, clouds, the conditional relationship between the two can be captured by a Conditional Probability Table (CPT) shown in Figure 41. If clouds are present, there is a 40% chance that there is rain and 60% to be clear. In contrast, if there are no clouds it will not rain. Hence, if we observe that there is not rain and set the belief accordingly, inference updates the probability findings following the Bayes' theorem:

$$P\big(Clouds = true\big|Rain = false\,\big) =$$

$$P(Clouds = false) \times \frac{P\big(Rain = false\big|Clouds = true\big)}{P(Rain = false)} = \tag{15}$$

$$50\% \times \frac{60\%}{(60\% \times 50\%) + (100\% \times 50\%)} = 37.5\%$$
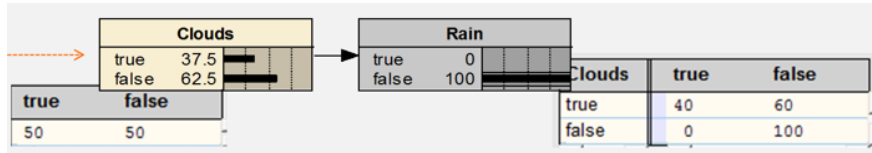
Figure 41. BN example for the possibility of raining. Source: Netica

The relationships between parent and child nodes can be incorporated in different ways: 1) deterministic CPTs, 2) probabilistic CPTs, 3) deterministic functions with parent nodes as variables, 4) probabilistic functions between parent nodes, and 5) logical constructs. The construction depends on the nodes (deterministic, probabilistic), the preference of the modeller, the nature of the relationship, etc. The advantage of BN, and the Netica tool, is that it allows great flexibility in defining relationships.

To further illustrate the capabilities of BN, Figure 42 introduces a clinical model, "Chest clinic", which is a famous example in BN literature (Moullec *et al.* 2013).
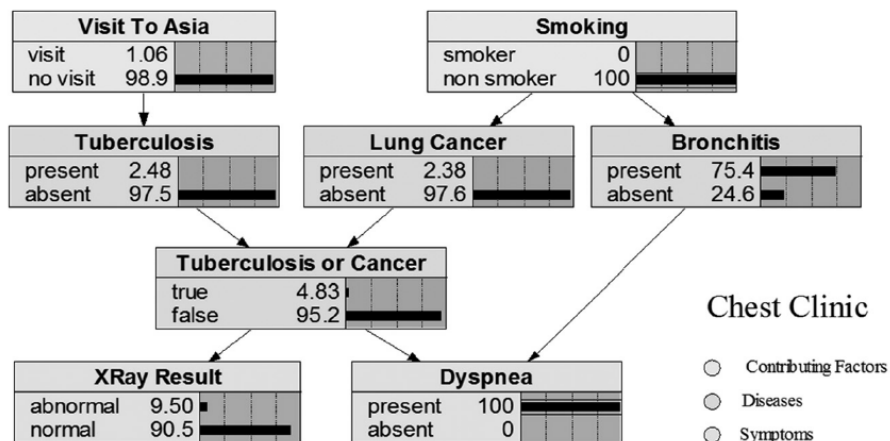
Figure 42. BN example from the Netica tool

The model presents a patient with a chest clinic condition. The variables are divided between contributing factors for the disease (causes), the disease, and symptoms (effects). If an observation is made that the patient has dyspnoea and he does not smoke, inference updates the probability distributions of the unobserved nodes. The new findings (or evidence) suggests that the disease explaining the dyspnoea is bronchitis, instead of tuberculosis or lung cancer.

The example illustrates various positive characteristics of BNs and the Netica tool. The graphical representation enables to visualise the structural dependency between variables in a global and intuitive way. The use of belief bars, depicting the probabilities of different states in proportional lengths, eases visualisation of inference results and facilitates the input of observations in a convenient manner. BN can represent a large finite number of both nodes and states within them. The network can aid decision making using the inference mechanism by inputting evidence on any node. The probabilities of the remaining nodes are subsequently updated in both parent and child nodes. This flexibility allows to propagate information 1) from causes to effects (to study *'what-if'* situations), and 2) from effects to causes (to perform diagnosis). More information on Bayesian nets is available in (Jensen and Nielsen 2007). In summary, some advantages of BNs are:

1) Graphical approach that shows causal/probabilistic dependencies;
2) Increased understanding of variable dynamics and influences;
3) Capturing of uncertainties and causal dependencies between nodes;
4) Variety of variables types such as continuous/discrete and probabilistic/deterministic;
5) Diversity of ways for defining probabilities such as probabilistic distributions (Gaussian, etc.);
6) Deterministic and logic equations;
7) Data input can be done through expert knowledge;
8) Ease of data input once network structure is known.

Mulled *et al.* (2013) indicates that different fields have successfully applied Bayesian nets: marketing, intelligent man machine interfaces, risk engineering, finance, medicine, etc. In the realm of design, researchers have used BN's capabilities or Bayesian approaches for decision making. Moullec *et al.* (2013) used BN to generate and analyse alternative product structures. The approach captures the system's architecture design problem and designer's knowledge. Combined with a developed algorithm, the approach enables to cluster and evaluate product architectures options that can reach a specific overall design confidence. Rajabally *et al.* (2013; 2002a; 2002b) has used BN to capture the reasoning regarding the trustworthiness of developed process and product models. Given that

models can not entirely capture the objective reality due to its inherent uncertainty and variability, the ad hoc methodology based on BN, helps to certify that at least the model is fit for its specific purpose. Ullman (2012; 2009) developed the Accord tool to help designers decide on the next step in PD decisions. It uses Bayesian updating to reach consensus between different stakeholders regarding the evaluation of design alternatives.

In terms of the current research, BN enables to model the complex relationships between resource attributes and activity characteristics, addressing FR8. The model can incorporate both design uncertainties and causal dependencies between resource attributes, task characteristics and performance. Thus, complementing the traditional ASM model, which shows insufficiency in modelling the logic of qualitative relationships such as resource skills and expertise, as well as only allowing one layer of logic definition (within the engine's Pre-Process tab). To address FR10, which involves outputting insights at both activity and process level of granularity, the approach aims to create independent BN models that can be analysed either individually or in conjunction with the whole process once integrated in ASM. As explained, BN also increases understanding of the impact of each variable by setting beliefs on specific nodes and use inference capabilities. Hereafter, the impact of variables can be quantified, fulfilling FR12.

It is noteworthy that developing inference algorithms is beyond the scope of this thesis since such an endeavour is a complex active research field by itself. In this context, this work will use classical inference algorithms part of the tool "Netica" (Netica). These algorithms can be found in (Jensen 1996; Spiegelhalter *et al.* 1993). This research takes advantage of the suitability of BN for the current research needs, and conveniently applies the method as part of the approach.

6.3   Resource management method

The novel method extends task network model with BN to address the remaining functional requirements. The aim is to test the influence of using different resource instances on process performance. The model's capabilities comprise flexible resource allocation and identification of preferred resource allocation to provide managerial insights for decision making at both activity and whole process level.

The support model captures characteristics of complex design and different resources participating in the process (designers, computational, prototyping and testing). To do so, within each task a separate BN is used to model resources that carry out the design activities along with its configurable attributes (time, cost, etc.), and tasks requirements. Then, process performance is calculated by adding the contributions from individual tasks when performed by a specific resource instance.

As explained, ASM was chosen as basis to build the approach. To recap, ASM is a task network based framework that offers flexibility in implementing behaviour logic, presents an easy diagrammatic visualisation and supports process analysis through Monte-Carlo simulations. It can capture design process uncertainties, iterations, product quality progress (parameter refinement), and performance improvements (cost, effort, time). The proposed approach consists in three main steps:

1) Modelling the process and resources using ASM and BNs, including how resources are linked to the process tasks.

2) Run Monte-Carlo simulations with different resource instances to identify feasible combinations that yield in improved process performance.

3) Extract data, analyse results and re-plan to study different *'what-if'* scenarios to improve the process.

Figure 43 depicts the steps of the method. Step 1 is described in this chapter while Steps 2 and 3 are addressed through the application on case studies in Chapter 7.
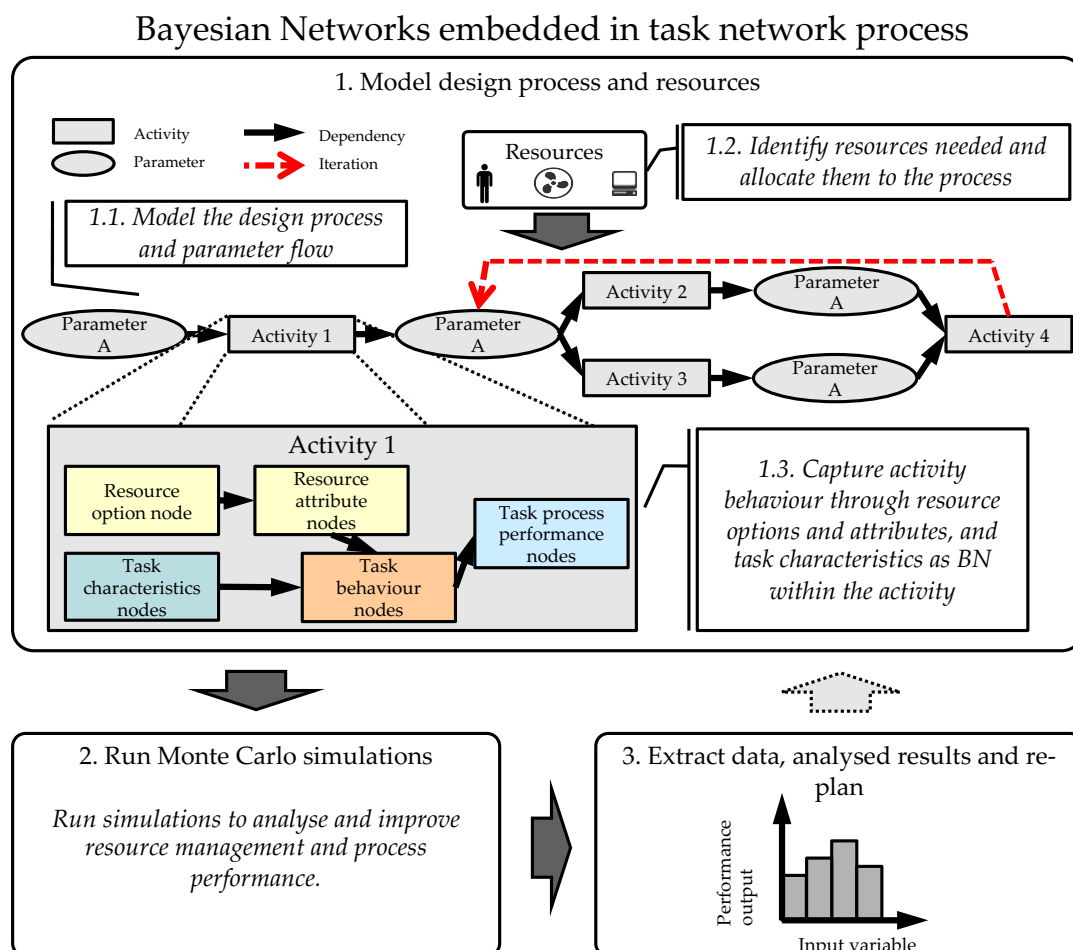
Figure 43. Overall steps for resource management method

The first step is the modelling endeavour, which involves constructing the process structure using ASM, along with task characteristic input variables. Then, depending on the skills or capabilities required, possible resources are identified and allocated to the activities. BNs for each activity are modelled with variables in the form of task characteristic input nodes, resource option nodes, resource attribute nodes, task behaviour nodes and task performance nodes (as explained in Section 6.3.4). During the second step, a specific scenario is decided. It can be focused to extract insights using flexible resource allocation or preferred resource allocation capabilities. Then, simulation of the process follows the design path and starts when both parameter and resources are available for each task. Within the task, BN captures the process behaviour and outputs variable values back to ASM as part of the simulation. The third step involves analysing the results, testing more scenarios and re-planning if necessary.

The next sub-sections define the modelling of the process in Section 6.3.1; the modelling of activity characteristics, and activity and process performance in Section 6.3.2; the modelling of resources and attributes in Section 6.3.3; and the modelling of the impact on performance through the relationships that define activity and process behaviour in Section 6.3.4.

6.3.1   Fundamental modelling of the design process

A design process comprises activities, i.e. sub-processes, which can be described as *"packages of work to be done to produce results"* (Browning *et al.* 2006, 117). Sim and Duffy (2003) differentiate between three types of activities: definition activities that scopes and synthesises the design problem to find feasible solutions, evaluation activities to consider the possible solutions, and management activities to coordinate the process to a successful outcome. Activities or tasks are connected to represent the required design path. For activities to start, it needs to receive parameter inputs and resources to evolve the design. Furthermore, activities can *'fail'* and produce iterations. Iterations can be either implicit or explicit. Implicit iterations occur when the specific task is rework internally and can be captured as part of the possible activity duration. When explicit iterations are triggered, they have an impact on other activities and can be depicted as iteration constructs. To recap, activities in ASM can be modelled as:

- *'Simple tasks'*: To represent a task that transforms input parameters into output parameters.
- *'Compound tasks'*: To represent a task that can lead to alternative process routes. They transform input parameters into alternative output parameters from which one will be chosen to progress the design process.

- *'Iteration constructs'*: To represent evaluation tasks that can either succeed (progress) or fail (iterate).

1) Simple task

Activity 1 → Parameter

Outputs parameters and can lead to one or more activities

2) Compound task

Activity 1 → Parameter → Activity 2 / Activity 3

Outputs parameters and leads to one of the alternative routes: activity 2 or 3

3) Iteration construct

Activity 2 → Parameter → Activity 3

The activity can iterate if the conditions are not met. ASM allows different ways (probability or functions) to model the iteration behaviour

Figure 44. Different task constructs in ASM

As the concept is based on ASM, *parameters* are generated and refined to advance the design and represent the inputs and outputs of each task. They can indicate the different states of the process and current quality of the product. Such parameters, or deliverables, can be of quantitative or qualitative nature and describe any characteristic of the product or process. Examples are geometry of a fan blade or a stress analysis' report (Wynn *et al.* 2006). The activities start when parameters are in the right state and the required resources are available.

6.3.2   Fundamental modelling of activity characteristics, activity performance and process performance

As identified in Chapter 4, activities and the process as a whole inherently have characteristics that affects the interaction with resources. For example, *'project priority'* can influence designers' '*time dedication'* to the process. An urgent priority can prompt designers to fully devote their time to a particular project, improving the chances to reach the target date. Both activity and whole process performances are included in the model since this research aims to provide insights at both levels of granularity.

Task characteristics are modelled as variables in ASM and as nodes in each BN. To specify a particular scenario, task characteristics are decided by the modeller as variables in ASM. The approach inputs activity characteristic variables into the corresponding BN nodes to set their beliefs during a simulation. They can be perturbed to test different *'what-if'* scenarios. Section 6.4.5 describes the linkage between the two models. Consequently, task performance metrics are influenced by task characteristics and which resource instance is selected to perform it.

Table 14 shows task characteristics and performance variables measured throughout the simulation. They function as linkage between the process model and the resource model.

<p style="text-align:center">Table 14. Task characteristics and performance nodes</p>

Type	Variable	Notation	Description
Task characteristics to be input	Project priority	*PP*	The urgency to deliver the project (e.g., urgent bid or exploration).
	License	*L*	Lack of licenses can increase waiting time.
	Task innovation	*TI*	If task is innovative, learning curve after iteration could be present.
	Task risk	*TR*	The inherent risk of rework for the task.
	Number of jobs submitted	*J*	More jobs can increase waiting time to use certain computational resources.
	Number of initial iterations	*IN*	Elapsed number of iterations already performed for the task when it starts.
	Elapsed time	*ET*	Elapsed process duration at the moment that a specific task starts.
Task and process performance	Task effort	*E*	Effort taken by a resource option to perform the activity. Given in person-days.
	Task time	*T*	Total time taken for the activity to finish.
	Task cost	*C*	Cost of the task.
	Total effort	*Total E*	Total effort of the process.
	Total process time	*Total T*	Total process time.
	Total process cost	*Total C*	Total process cost.

6.3.3   Fundamental modelling of resources and attributes

The new framework uses BN to model resources as process behaviour shapers. Building on findings to identify relevant resources to design processes in Chapter 4, this work proposes to model four types of design resources: *designers, computational, prototyping* and *testing* resources. Similarly, different resource attributes found during the exploratory case study (Section 4.4.1) are captured as variables using BN. The relationships between the different attributes influence other attributes, task performance, and ultimately process performance.

The resource types are described below and followed by a table with variables (nodes) that represents them. The tables are composed of resource option nodes that denote the

instance, and attribute nodes that abstract resource availability and effectiveness into variables. Depending on the selected resource option, the values for attributes change.

- *'Human designers'*: Comprise designers and managers directly involved in the process and activities.

Table 15. Designer attributes

Type	Variable	Notation	Description
Resource option	Designer	D	Denotes the instance of possible designer.
	Expertise	Ex	Expertise of the designer in a certain skill. Given as high, medium, low.
	Skills	S	Designer skills necessary for the project.
Resource attributes	Time dedication	a	Designer's dedication or availability due to other projects/ commitments.
	Iteration likelihood	il	Likelihood of iteration inherent to the task and designer instance. Given in %.
	Learning curves	li	Designer's learning percentage improvement after iteration of an instance in a given activity. Given in %.
	Time	t	Time initially expected to perform the task by each instance. Stated as a probability distribution in days.
	Cost per unit	cu	Cost of per unit time of each designer instance.
	Waiting time	w	Waiting time to use the resource. Given as a probability distribution in days.

- *'Computational resources'*: Can be introduced as hardware (HPCs, stations, grids, desktops), software (dedicated to FEA, CFD, etc.), licenses, and network.

Table 16. Computational resource attributes

Type	Variable	Notation	Description
Resource option	Computational capability	CC	Denotes the resource instance.
Resource attributes	Reliability	r	Failure likelihood of resource instance. Given in %.
	Time	t	Time initially expected to perform the task by each instance. Stated as a probability distribution in days.
	Cost per unit	cu	Cost of per unit time of each instance.
	Waiting time	w	Waiting time to use the resource as probability. Given as a probability distribution in days.

- *'Prototyping resources'*: Prototypes need preparation to be developed and materials to build them. Hence they refer to all materials, equipment, and maybe plants to prepare a prototype.

- *'Testing resources'*. Testing resources comprise those necessary for testing the product. It could include plants, equipment and materials to run tests.

Table 17. Testing and prototyping attributes

Type	Variable	Notation	Description
Resource option	Testing	*Tes*	Presents the testing resource instance.
Resource attributes	Reliability	*r*	Failure likelihood of resource instance. Given in %.
	Time	*t*	Time initially expected to perform the task. Stated as a probability distribution in days.
	Prototype fidelity and set up readiness	*tl*	Time limit in which the prototype has to be ready at the necessary fidelity and the testing rig properly set-up. If the process reaches the time limit without the necessary preparations extra waiting time will be needed.
	Cost per unit	*cu*	Cost of using the testing rig.
	Waiting time	*w*	Time needed to book the next testing slot

Fundamental attributes such as availability (constraint) and quantity of resources are still available as functionalities in ASM, and remains key to the process. The remaining abstracted attributes such as time window to book and compatibility are taken into consideration while allocating the resources. The next section captures the influence between the different activity characteristics and resource attributes.

6.3.4 Fundamental modelling of the impact on activity performance and process performance

The approach assumes that each task is done by an instance of the different resource types (designers, computational, and testing and prototyping). Resource option nodes denote the different possible resource instances that can perform the activity. They are linked to resource attribute nodes, which represent the variables (different depending on resource type) that shape the characteristics of each resource instance. The distinctive values of resource attribute nodes for each instance characterises them and captures their heterogeneity. It can be said that the method models design resources using their attribute nodes. As a result, the relationships between resource attribute nodes with task characteristic nodes shape activity behaviour and produce the values for task performance nodes. Finally, individual activity performance values are aggregated to output process performance.

Figure 45 summarises the different types of nodes and BN modelling construction (using Netica) that defines the behaviour of activities and ultimately the process. BNs for each type of resource can be constructed using the outlined procedure.
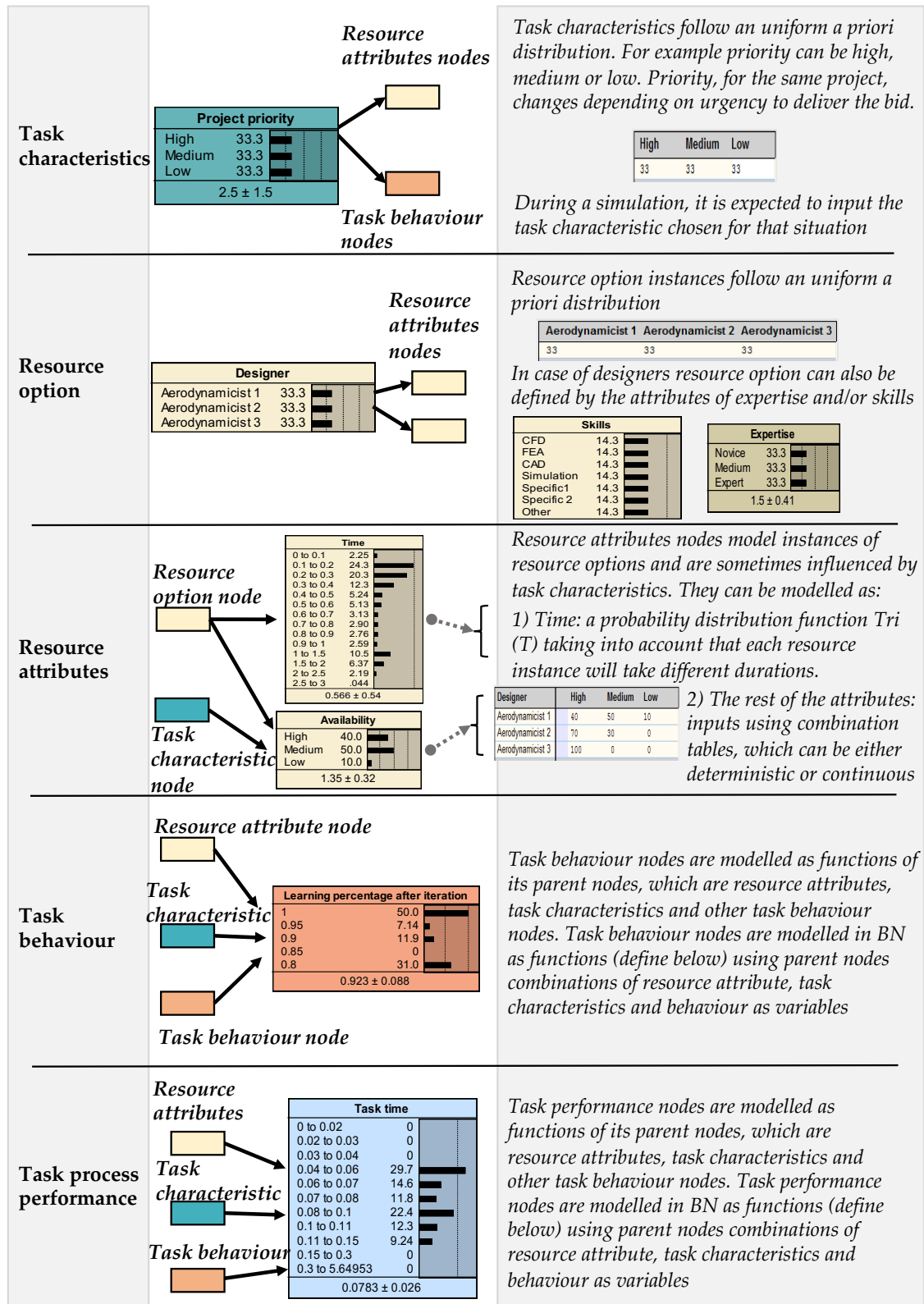
Figure 45. Type of nodes and resource modelling construction

Table 18 shows task behaviour variables shaped during the simulation.

Table 18. Task behaviour nodes

Type	Variable	Notation	Description
	Failure	*F*	Probability of the task to fail and requiring iteration.
Task behaviour	**Final number of iterations**	*IF*	Elapsed number of iterations after the task is finished.
	Lost slot?	*LS*	If the test slot has been missed.

In Netica, the relationships in BN can be modelled either by CPTs (probability, counts, boolean, etc.) or equations using parent nodes as variables. Taking advantage of BN capabilities, variables can infer their impact on each other (diagnosis). Different variable states can be selected (set belief) to update the new probabilities for the remaining variables. As explained, information can propagate from resource option nodes to performance nodes and vice-versa. This opens the possibility to test the impact of each variable in the model, either task characteristics, attributes or performance.

The next sub-sections introduce the BN model examples that are embedded in the activities, shaping their behaviour. Following the gained understanding in Chapter 4, the fundamental relationships between nodes are presented in the corresponding resource model.

It is noteworthy that this relationship and the BN models do not intend to be final or fixed. They are a guidance for model construction and adaptable depending on the organisation and situation to capture.

6.3.4.1   Designer BN model

Figure 46 illustrates a constructed BN for designers. Resource option and task characteristic nodes do not have parent nodes. However, initial iterations *IN* starts as zero and updates if iteration occurs. The rest of nodes are presented below, indicating their parent nodes and if the relationship is modelled using CPTs or functions.

CPTs: Functions:

$a = f(D, PP)$ $w = f(L)$ $t = f(D, IN)$ $li = f(TI, Ex)$

$cu = f(D)$ $F = f(il)$ $il = f(Ex, TR, IN, li)$ $IF = f(F, IN)$

$Ex = f(D, S)$ $E = f(t, li, IN)$ $T = f(E, a, w)$

                                            $C = f(E, cu)$
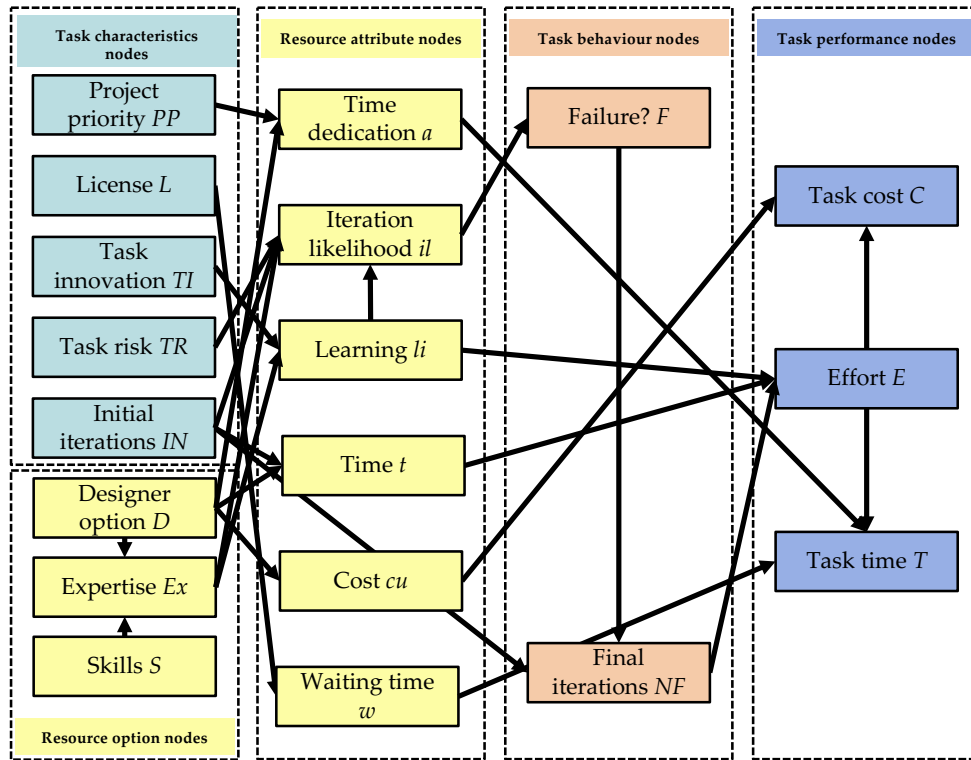
Figure 46. Designer BN model example

Task characteristics nodes

Task characteristic nodes have uniform distribution a priori, and belief can be inferred to create different simulations scenarios. Task characteristics shown in Table 14 can combine with resource attributes to shape activity behaviour and process performance. For example, project priority *PP* can be set to be low, medium or high, which will influence on the urgency to finish the task.

If the necessary licenses are not in place (boolean), waiting time can increase. This can be decided by the modeller at the beginning of the simulation to create a scenario in which licenses are either present or missing. The extra waiting time if licenses are missing can be specified as a time distribution.

Task innovation *TI* is a boolean node that indicates if learning curves are present for the task.

The number of initial iterations *IN* is an input variable that keeps updating if iteration is triggered during the overall process simulation.

Resource option nodes

Designers *D*, their skills *S* and expertise *Ex* represent the variables that can describe the resource instance (skills and expertise are also attributes). Resource option nodes are *'causality'* nodes, which states can be selected to update the rest of nodes to test different

situations. However, given the capabilities of BNs, other attributes, or performance objectives can also be *'set as beliefs'* to diagnose the probability of resource options attaining such performance (causal analysis). The expertise of each resource instance in the different skills can be elicited using a CPT.

Resource attributes nodes

Resource attribute values such as time dedication a, cost per unit cu, or waiting time w depends of the designer instance and can be modelled using input tables (CPTs). Time values are specified with a triangular distribution equation *Tri ()*, which can also change depending on the number of iterations.

Cost per unit cu nodes represent discrete cost values associated with each resource instance. The units could be either a specific monetary value or a representation of the resource instance value in comparison to other resources (proportion to a baseline or a metric).

Time t indicates the expected time that each option is capable of performing the activity. Time dedication a of designers could be high (e.g., 100%), medium (e.g., 75-60%) or low (e.g., 50%), depending on the designer D and project priority PP.

Learning improvement li is set as percentage improvement if the task iterates. Given a set of tasks $n= 1...N$, and a set of resources options as $m = 1... M$ per resource type, learning influence li of a task n is dependent on task innovation TI. If TI is positive, the learning factor by which time would be influenced in subsequent iterations is determined by the learning improvement of a given resource option m (depending on the expertise) in the context of task n. If task n does not allow innovation, then the learning percentage will be zero.

$$if\ TI_n = true\ ; then\ \ li_{n,m} = li_{n,m};\ otherwise\ updated\ li_{n,m} = 0 \qquad (16)$$

Iteration likelihood il is given as a percentage indicating the probability of task iterating or failing. Iteration likelihood il is equal to the inherent task risk TR multiplied by a factor that depends on the expertise of the designer m in the required skills of task n and by learning improvement li. The relationship is modelled with the following function using parent nodes as variables:

$$il_{n.m} = TR{\times}factor\ (Ex_{n,m}){\times}li_{n,m}^{IN} \qquad (17)$$

Waiting time w varies when a designer performing a task n needs a specific license L. It could be represented as a time distribution if the license is missing. The relationship can be modelled through a CPT or captured using the following equation:

$$Updated\ w_{n,m} = w_{n,m}\ {\times}factor\ (L) \qquad (18)$$

Task behaviour nodes

Task behaviour nodes are modelled through equations with their parent nodes as variables. In other words, interactions between resource attributes, task characteristic and task behaviour nodes. Modelling equations are below, and the rationale behind them can be found in Chapter 4 where resource attributes were identified, and their interactions to impact process performance explained.

Failure F is captured as a node that reduces iteration likelihood into deterministic states of either positive (iterate) or negative (does not iterate). The number of final iterations IF is dependent on failure F and number of initial iterations IN. If the parent node F is *'true'* then iteration number increases by one. IF will be fed back as input value to IN if the task is iterated during the process. The number of iterations finished are set by the equation:

$$if\ F_{n.m} = true\ ; then\ IF_{n,m} =\ IN_n + 1; otherwise\ \ IF_{n,m} =\ IN_n \tag{19}$$

Task process performance nodes

Task process performance values are captured through equations. Firstly, effort E is set as the time t that resource option m takes to do task n multiplied by the percentage of decrease li (or improvement) in time elevated by iteration number IN:

$$E_{n,m} =\ Tri\ (t_{n,m}) \times \left(li_{n,m}^{IN}\right) \tag{20}$$

In terms of designers, task time T of resource option m given task n is obtained by multiplying effort E by availability a, then adding waiting time w.

$$T_{n.m} = \left(E_{n,m} \times a_{n,m}\right) +\ updated\ w_{n,m} \tag{21}$$

Additionally, *'if'* statements can be added to effort and time equations to change their value as the number of iteration increases. For example, after four iterations learning improvement does not apply anymore. Cost for designers is the cost of the resource option cu multiply by effort E:

$$C_{n,m} = cu_m \times E_{n,m} \tag{22}$$

Additionally, when various resources are working on the same task, the time for the task is the longest taken by the any of the resources; and effort and cost is equal to the effort and cost of each resource used added together.

6.3.4.2   Computational BN model

Figure 47 illustrates a constructed computational BN model along with child nodes denoting their corresponding parent nodes. The model's relationships are indicated below.

CPT: Functions:

$cu = f (CC)$ $F = f (r)$ $t = f (CC, IN)$ $w = f (J, PP, CC)$

$r = f (CC, TR)$ $IF = f (F, IN)$

$C = f (t, cu)$ $T = f (t, w)$
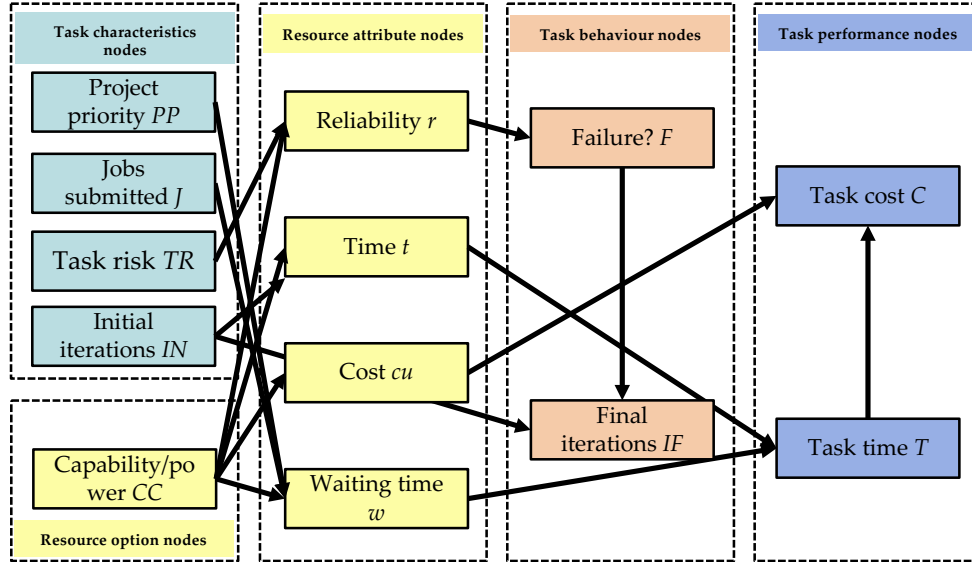
Figure 47. Computational BN model example

Task characteristics nodes

Project priority *PP* can be low, medium and high, which will influence on the waiting time to finish the task. Computational resources also need to indicate how many jobs *J* have been submitted for HPC, where high number of jobs could be reflected as extra waiting time. Initial iterations *IN* updates if iteration are triggered.

Resource option nodes

Each computational option can have different capability or power that defines the resource instance.

Resource attributes nodes

Computational resources have time values (triangular distribution equation) *t* and cost per unit *cu* associated with each resource instance. They can be modelled using CPTs.

Reliability *r*, given as percentage, indicates the probability of task iterating or failing. It combines iteration likelihood and inherent uncertainty of whether the computational or testing resource completes the job (e.g., breakdown during an overnight simulation). Reliability node *r* follows the value of the inherent task risk *TR* and a factor depending on the computational capability/power *CC*. It is modelled through the equation:

$$r_{n.m} = TR \times factor\ (CC_{n,m}) \tag{23}$$

Computational resources' waiting time depends on the number of jobs that the department has already requested HPC managers. The standard waiting time w of a resource option m is multiplied by a factor J depending on how many jobs have been already submitted. Waiting time w increases with the number of jobs sent to use HPCs, and it can be captured using CPTs or the next equation:

$$Updated\ w_{n,m} = w_{n,m} \times factor\ (J) \tag{24}$$

Computational and testing activities could have learning curves li depending on the task, if so it can be modelled through Equation (16).

Task behaviour nodes

Failure F node reduces reliability r, which depends on resource option, into deterministic states of either positive (iterate) or negative (does not iterate). The logic of this relationship is given by Equation (19).

Task process performance nodes

In terms of computational resources, activity duration T is the results of aggregating time t of a given resource m and the relevant waiting time w.

$$T_{n,m} = Tri\left(t_{n,m}\right) + updated\ w_{n,m} \tag{25}$$

Computational resources calculate task cost C as the cost of the resource instance cu and the time t that the instance needs to spend working on the task. Hence, cost for computational resources is equivalent to their value per unit cu multiply by the time used t:

$$C_{n,m} = cu_m \times Tri\ (t_{n,m}) \tag{26}$$

6.3.4.3 Prototyping and testing BN model

Finally, a prototyping and testing BN example is depicted in Figure 48 . The various child nodes indicating their parent nodes are presented below:

CPT: Functions:

$cu = f\ (Tes)$ $F = f\ (r)$ $t = f\ (Tes, IN)$ $IF = f\ (F, IN)$

$tl = f\ (Tes)$ $r = f\ (Tes, TR)$ $LS = f\ (tl, ET)$

$C = f\ (t, cu)$ $w = (PP, Tes, LS)$

$T = f\ (t, w)$
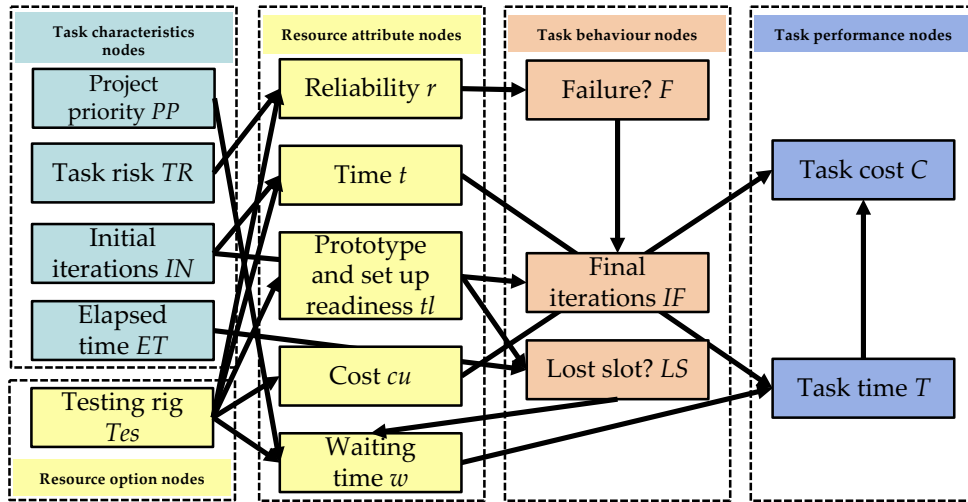
Figure 48. Prototyping and testing BN model example

Task characteristics nodes

Initial iterations *IN* updates if iteration is triggered. Elapsed time *ET* inputs the time already taken for the process to reach the current activity. Project priority *PP* can be low, medium and high, which will influence on the waiting time to finish the task.

Resource option nodes

Testing rig is defined by the option node *Tes*, which includes different instances as states if applicable.

Resource attributes nodes

Similarly, testing nodes have time values *t* as triangular distribution equations. Cost per unit *cu* can be cost per unit time or per testing slot usage.

Reliability *r*, given as percentage, indicates the probability of task iterating or failing. In case of testing resources, reliability combines iteration likelihood and inherent uncertainty of whether the prototype and rig complete the testing activity. Prototyping and testing resources defines reliability as the inherent task risk *TR* multiply by factor depending on the testing rig. It is modelled through the equation:

$$r_{n.m} = TR \times factor\ (Tes_{n,m}) \tag{27}$$

Testing resources include a time limit attribute *tl,* which defines a deadline to reach the activity or the testing slot will be lost (thus increasing waiting time).

Task behaviour nodes

Failure *F* node reduces reliability *r* into deterministic states of either positive (iterate) or negative (does not iterate). Again, the logic of this relationship is given by Equation (19). If the prototype, testing rig or design state are not all ready when the testing slot arrives,

extra waiting time w will be needed to reach the next slot. *'Lost slot'* node LS is capture through the next equation. It represents the logic that if elapsed time ET is larger than the time limit *tl,* then deterministic node *'lost slot' LS* will be *'true'*:

$$if\ tl < \text{Total T}\ ;\ then\ LS_{n,m} = true;\ otherwise\ LS_{n,m} = false$$
$$if\ LS = true;\ then\ w_{n,m} = w_{n,m};\ otherwise\ w_{n,m} = 0$$

(28)

Task process performance nodes

In terms of prototyping and testing resources, activity duration T is time t of given resource m plus the relevant waiting time w, already defined in Equation (25).

Finally, activity cost for prototyping and testing can be either the cost per unit time cu multiply by time usage t using Equation (26), which is the same as computational resources, or cost per used slot.

6.3.4.4 Total process performance

Total effort *Total E*, process duration *Total T* and cost *Total C* are the sum of the individual values for each task. This is done within the ASM framework using its built-in functionalities to model the following functions:

$$Total\ E = \sum_{i=0}^{n} E_{n,m}$$

(29)

$$Total\ T = \sum_{i=0}^{n} T_{n,m}$$

(30)

$$Total\ C = \sum_{i=0}^{n} C_{n,m}$$

(31)

6.3.5 Discussion of modelling assumptions

During the development of any model, the objective is to abstract the reality as accurately as possible. However, the paradigm for this research (Chapter 3) states that the capture of reality is often imperfect regardless of the effort invested. As already discussed, models need to be at least feasible for the intended purposes. Hence, some modelling assumptions were made:

1) The model captures variables that can be both qualitative and quantitate. Qualitative variables can be given a numerical factor to denote its impact on other variables following stakeholder's experience, but this often carries a degree of uncertainty.

2) The model assumes some values that can be different according to the organisation. For example: project priority, computational power, reliability in %, jobs submitted and licenses.

3) The discretisation of the continuous variables was necessary for BN inference capabilities.

The flexibility of BN offers the modeller the possibility to define a large number of situations. The method should be applicable to a wide range of different industries, thus the above relationships are intended to be a high level view of resource and task interactions, subjected to specific changes depending on the circumstances of the process to model. Thus, the presented relationship and behaviour, even though representative of the resource situations in engineering design that the author abstracted from the research, might vary depending on the organisation. Accordingly, it does not intend to be final but adaptable, and only offers a starting point. The method is intended to be captured in a wider *approach* that starts by studying the complexity of each organisation (Chapter 7). The process, company specifics, and industry should be taken into account and researched beforehand in order to model the interactions between the variables. In other words, *'activity behaviour'* should be adapted to the modelled situation, process and industry. For this reason, different workshops and interviews were set within Rolls-Royce plc as explained in previous chapters.

The next section explains the method implementation into a tool that can be used by process modellers.

6.4   Detailed implementation of resource management method

The method was implemented using CAM software for ASM process modelling, and Netica tool for BN resource modelling. Netica provides a convenient API to extend and interface with other software. Since the objective of the thesis is to deliver an overall approach, and not the tool itself, the implementation was done in conjunction with two other researchers in the author's group. The method's need, requirements, specific elements and simulation behaviour were provided by the author. A senior researcher helped with coding the tool extension given his extensive knowledge of CAM, and a second researcher was involved due to her experience using Netica's API.

The final extended tool went through various iterations where the author tested and improved the support method. This included validating the correct functioning of the modelling tool, BN embedded in task network, using simple models. Simulation results using the traditional ASM approach were compared with the newly developed support method. When no variation was included in the model, results were identical and confirmed the correct implementation of the tool.

The next section examines the method's detail design and computational implementation, including instructions regarding how to apply the method. The sub-sections are divided as follows: 1) Modelling the design process, which explains the structural modelling of the process using ASM; 2) Modelling activity characteristics, which are inputs that can be perturbed to define different scenarios; 3) Modelling resources, which illustrates the composition of resource BN models that are embedded within activities; 4) Exploring the impact of different variables, which gives examples of how the impact of resource attributes, task characteristics, behaviour and performance can be explored using BN's inference capability; 5) Linking the design process model to BN resource model, which details the developed functionalities to input and output data from the two models; 6) Setting up simulations, which indicates how simulation experiments can be specified; and 7) Summary of method capability, concludes by summarising the method's possible analyses.

6.4.1 Modelling the design process

Design processes are modelled as tasks, parameters, dependencies and iterations using ASM. Different process constructions and logic can be implemented due to the systems' modelling flexibility that allows: building iteration constructs, setting logic to different activity outcomes, depicting different granularities through hierarchical sub-processes, modelling process path behaviour, and implement resources as constraints amongst other functionalities.

Figure 49. Task network process (ASM) modelled with CAM

A pool can be defined with different types of resources and quantities. Then, resource allocation and constraints can be modelled using the *Resources tab* in CAM as shown in Figure 50. The modeller needs to define the type of resource and quantity needed. During a simulation, an activity can start if its precedent parameters are available and in the correct state for the task. At the same time, the task searches for the required resources starting with the highest priority. Once all resources and parameters are available, the

resources are allocated to the task and only returned to the pool when the activity is finished.

Figure 50. CAM tab to allocate resources from pool to tasks

As ASM only defines the process path and resource constraints, activities need to embed the corresponding BN that models its behaviour. The BN folder path for each task can be referenced under CAM's *"Notes"* tab. In this manner, the task is linked to the specific BN that has modelled its available resource instance options, activity behaviour, and impact on activity performance.
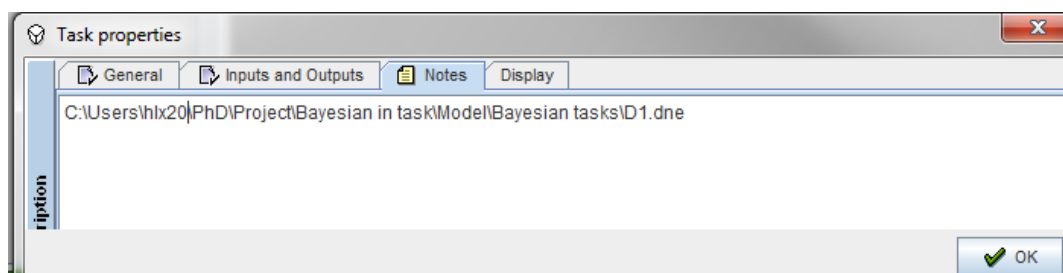
Figure 51. CAM tab to link the specific activity to its BN that holds the resources and behaviour of task

6.4.2   Modelling activity characteristics

Activity characteristics, resource options and task performance can be modelled as variables in CAM. They are also modelled within the BNs, and act as the linkage between the two models to provide the input data for BNs during a simulation. Figure 52 shows the variables implemented in ASM, they can set as model internal, dependant or independent variables. Resource options can be initially specified as independent variables in order to test the use of different instances. Furthermore, the model can appoint any other variable as independent. Process performance variables are also modelled in ASM,

and can extract the performance values from the BN node. The possibility of changing the values of the different variables, including activity characteristic nodes, is the basis of creating different simulation scenarios, thus a table defining and introducing different analyses is presented in Section 6.4.7.
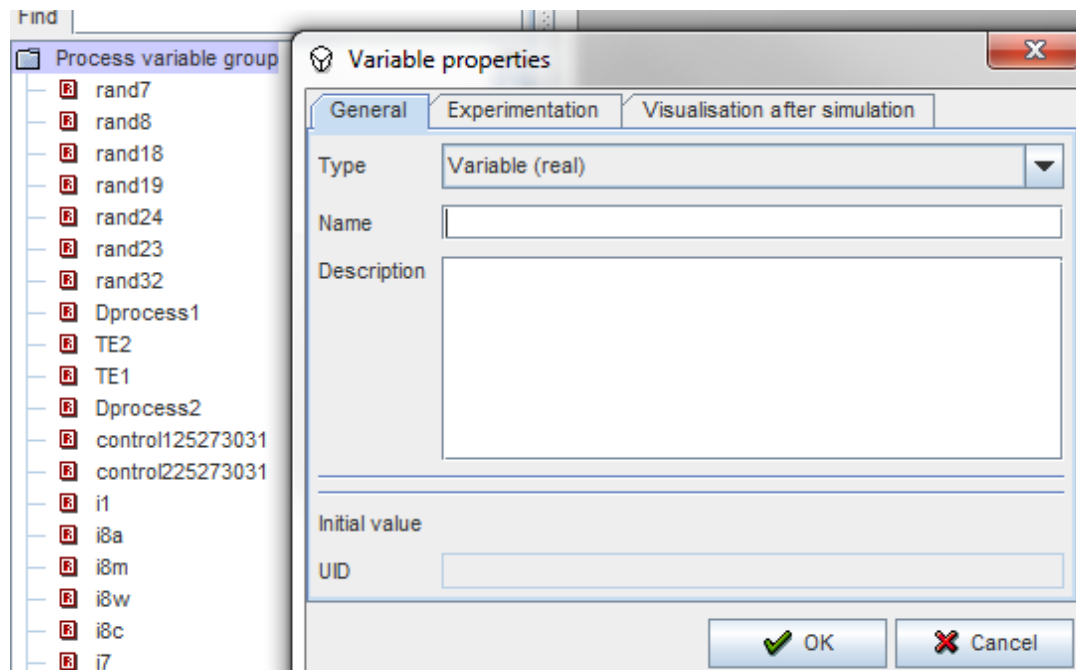
Figure 52. Variable modelling in ASM

6.4.3 Modelling resource's BN models

Resources are modelled as BNs using the Netica tool. The variables are captured as nodes and edges that define the conditional relationship between them. The modelling relationship can be found in Section 6.3.4. Figure 53 depicts examples of the different types of nodes that can be modelled, representing discrete, continuous or boolean states.
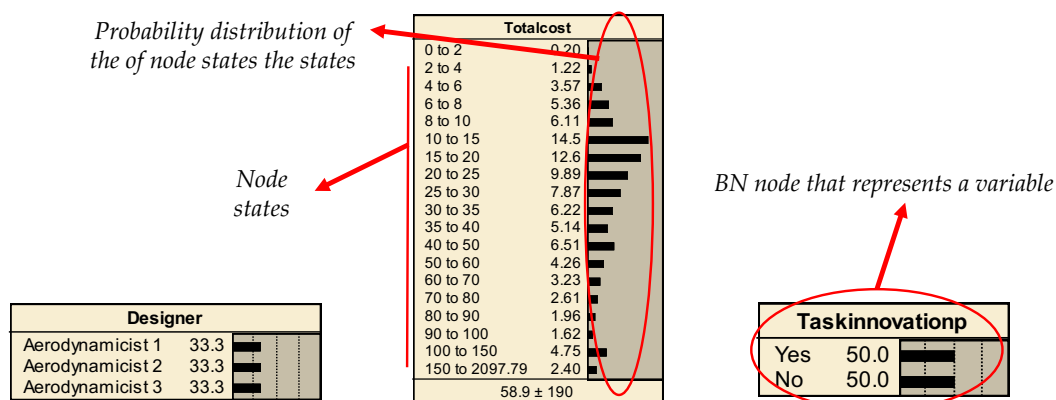
Figure 53. Different type of nodes. From left to right: discrete, continuous and boolean

The conditional probability between parent and child nodes can be modelled either as tables (CPTs) or equations.
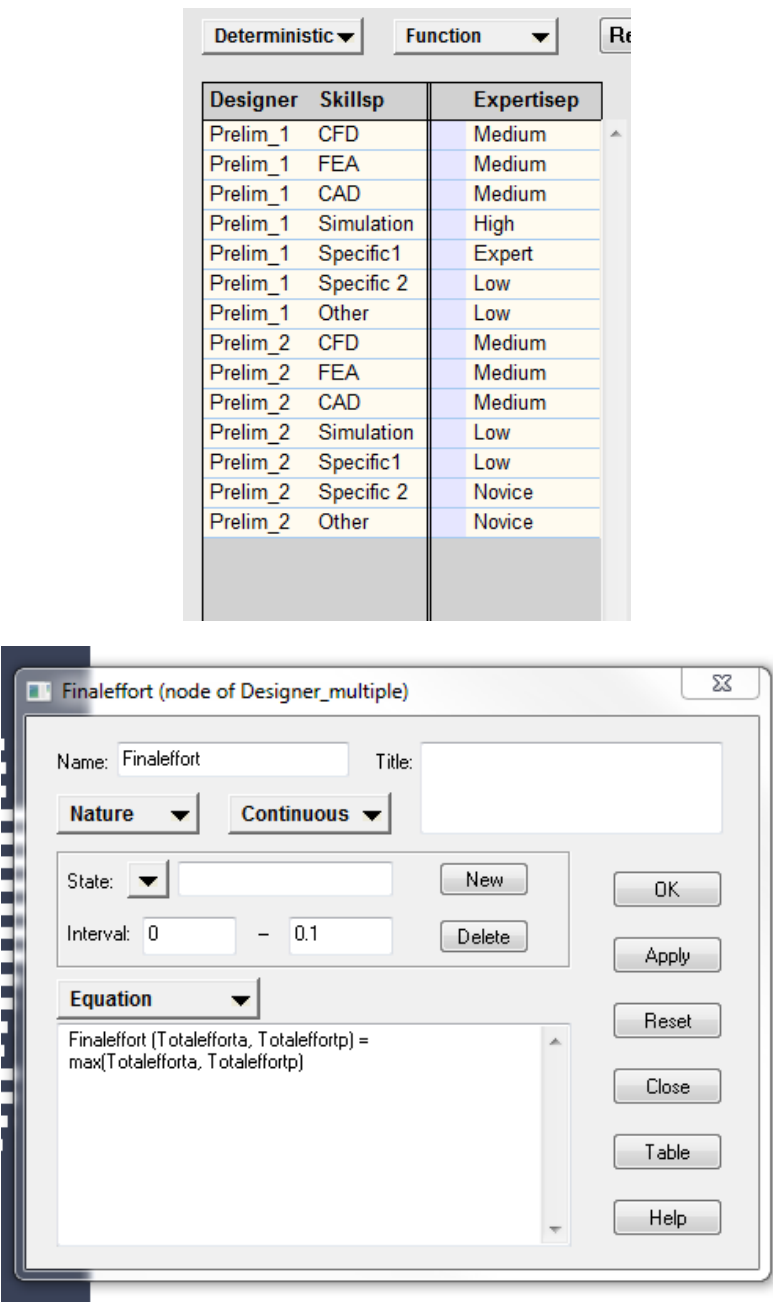
Figure 54. Different ways to input parent-child relationship. Top: CPT that defines designer's expertise on different skills. Bottom: Equation that defines effort

CPTs are used to indicate the conditional probabilities between one or multiple parent nodes with a child node. Due to the large number of combinations when more than two parent nodes are present, it could be more efficient to define the relationship as functional equations.

Sections 6.4.3.1, 6.4.3.2, 6.4.3.3 illustrate BN model examples of designer, computational, prototyping and testing resources respectively.

6.4.3.1   Designer model

Figure 55 presents a constructed BN example capturing three instances of aerodynamic designer. The model includes the different nodes that shape task behaviour and performance.
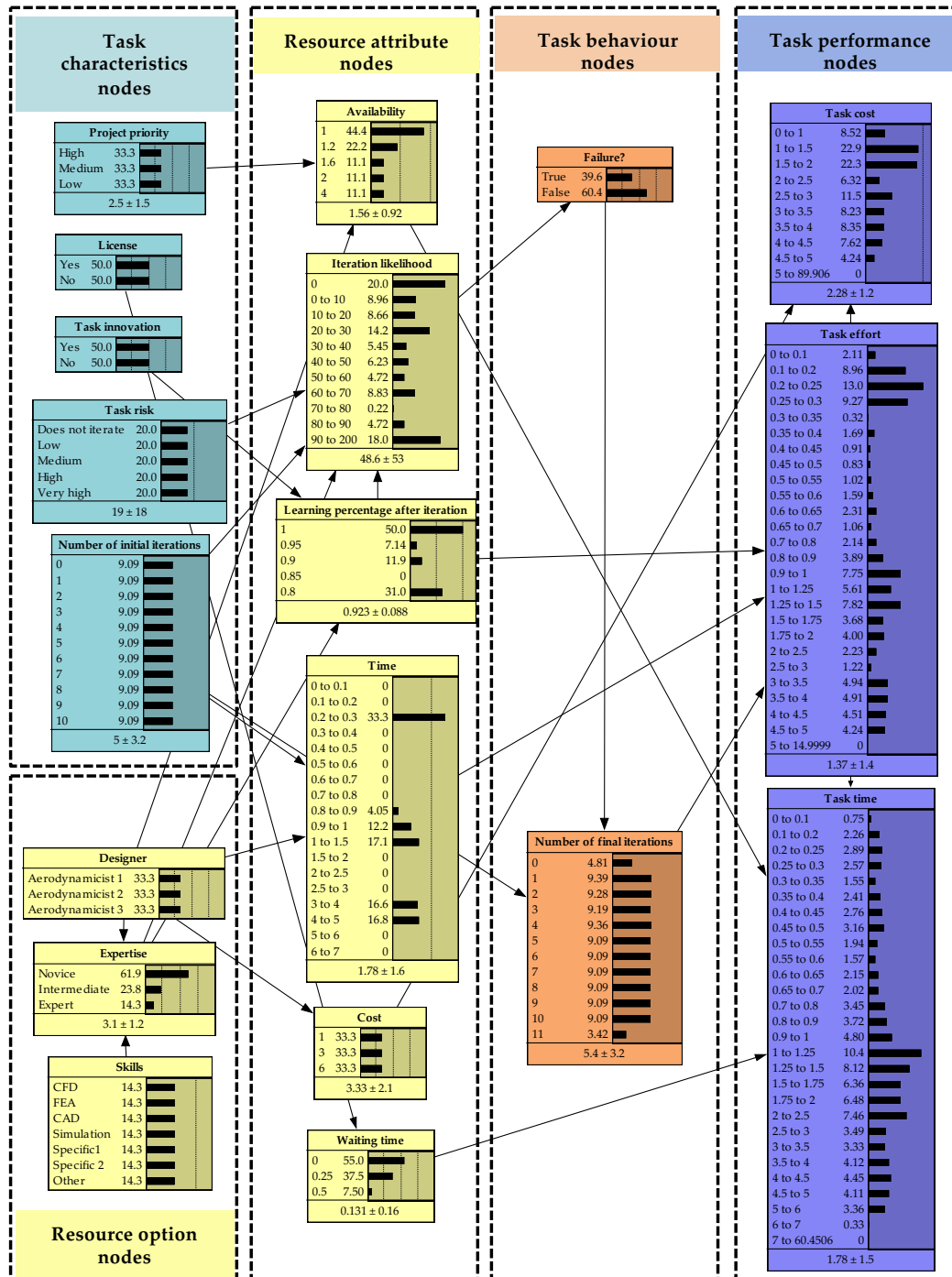
Figure 55. Constructed designer BN model

6.4.3.2   Computational model

Similarly, Figure 56 introduces a BN example of three choices for HPC depending on its number of cores (computational power). The model also includes the nodes that describe activity behaviour and performance.
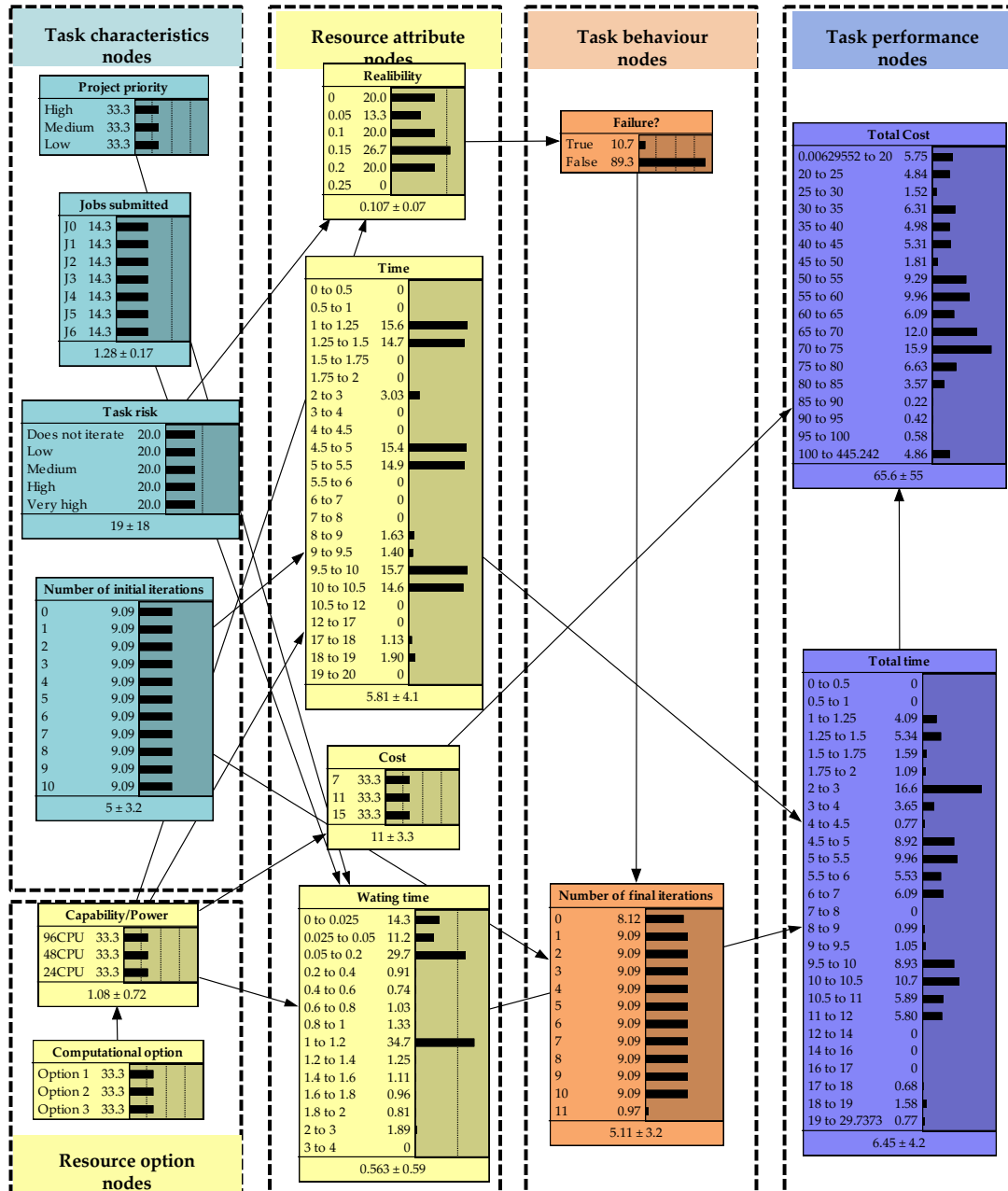
Figure 56. Constructed computational BN model

6.4.3.3 Prototyping and testing model

Figure 57 illustrates an example of prototyping and testing model. The node relationships were modelled according to Section 6.3.4.3.
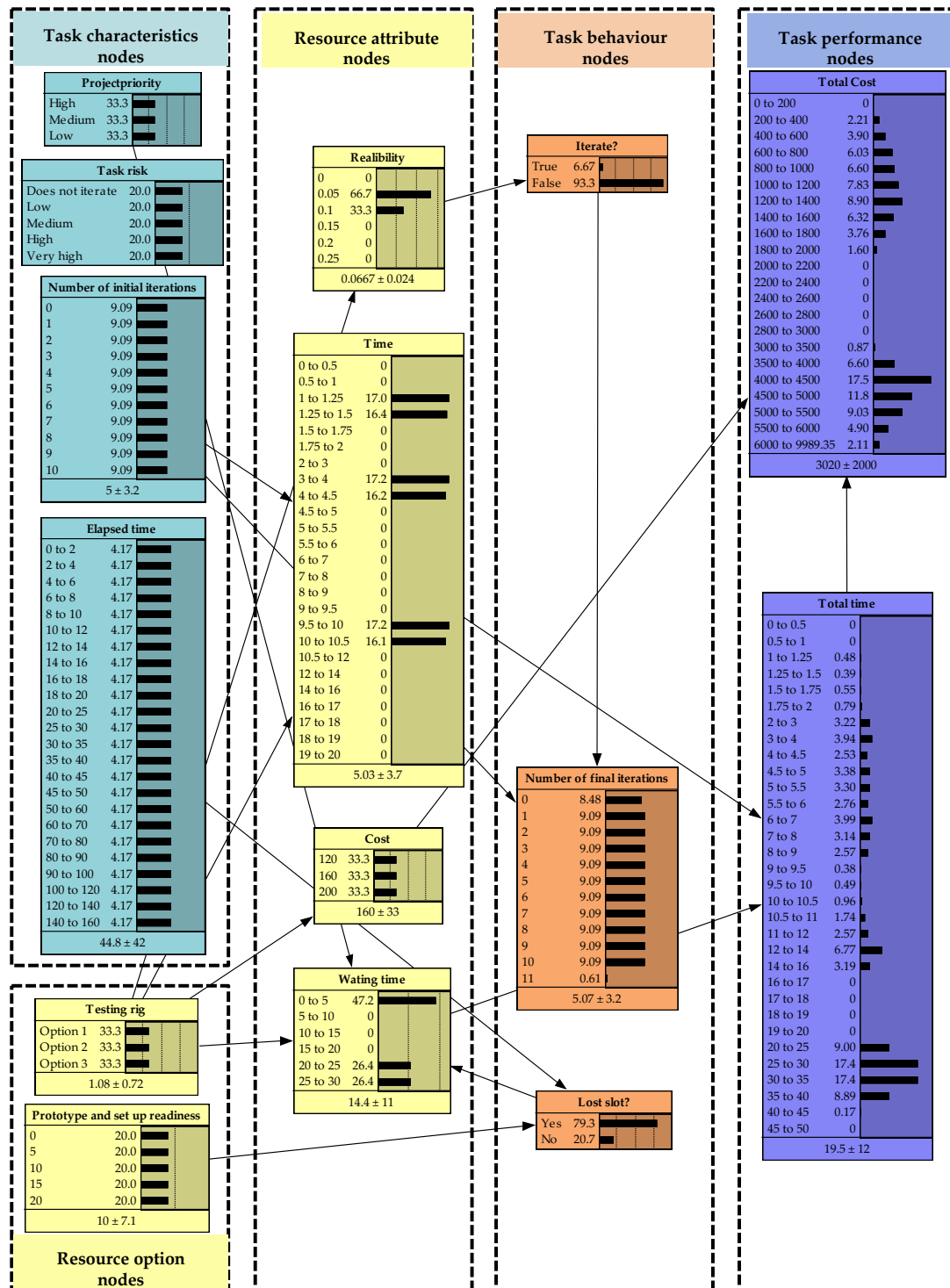
Figure 57. Constructed prototyping and testing BN model

6.4.4   Exploring the impact of different variables

Once BN models are constructed, inference can be used to explore the impact of different nodes on the conditional probabilities of the rest of nodes, hence enabling causal analysis. Each node state can be selected, *'setting a belief'*, resulting in updating the conditional probabilities of the remaining nodes through the Bayesian theorem shown in Equation (14). The graphical representation combined with the possibility to select the state of any node allows multiple scenarios to be studied in an understandable and easily visualisable way. The following figure explains how the setting of inputs on BN affects the performance outputs.
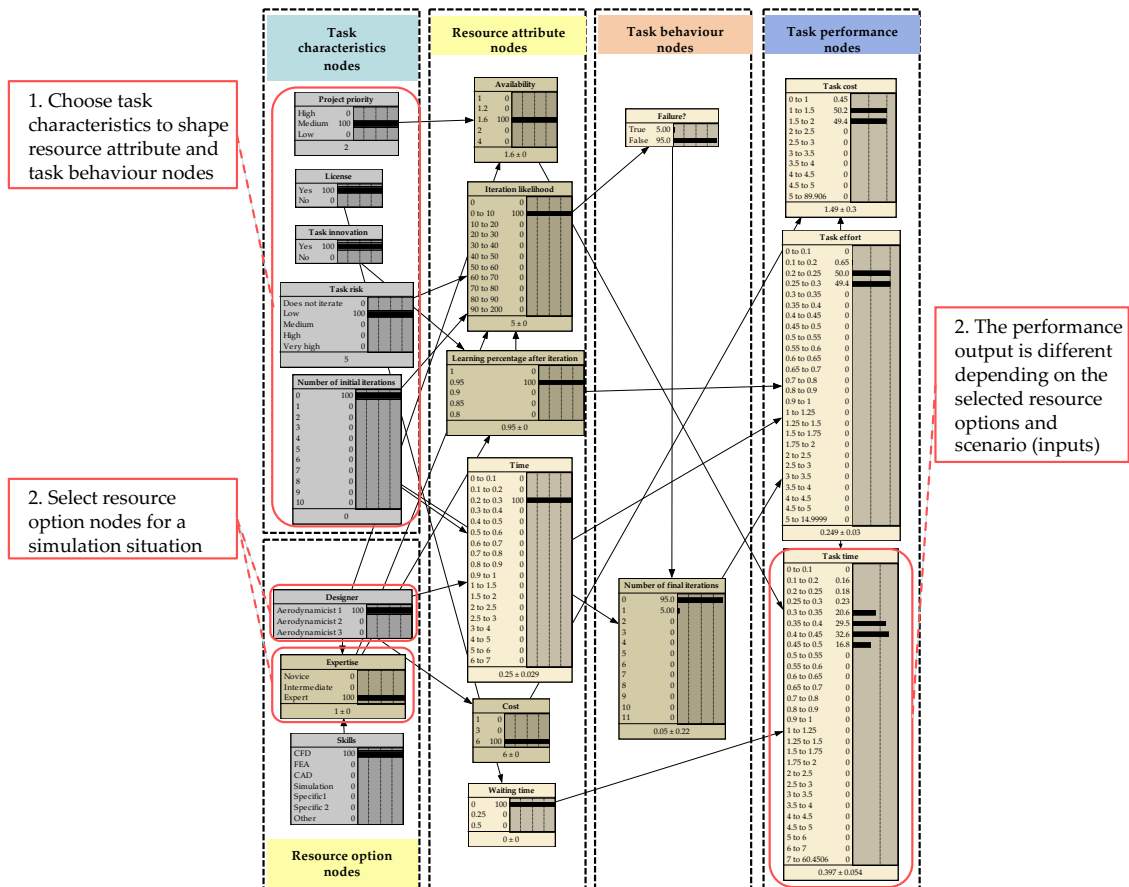
Figure 58. BN shows how the selection of different resources for the task impacts performance changes

Beliefs can be set on both causal and effect nodes, which enables to study the impact of any variable on the rest. Figure 59 shows another possible scenario, in which a task performance target is specified to perform diagnosis. After the BN is updated, the causal analysis can indicate the probability of achieving the performance aim by the different resource instances.
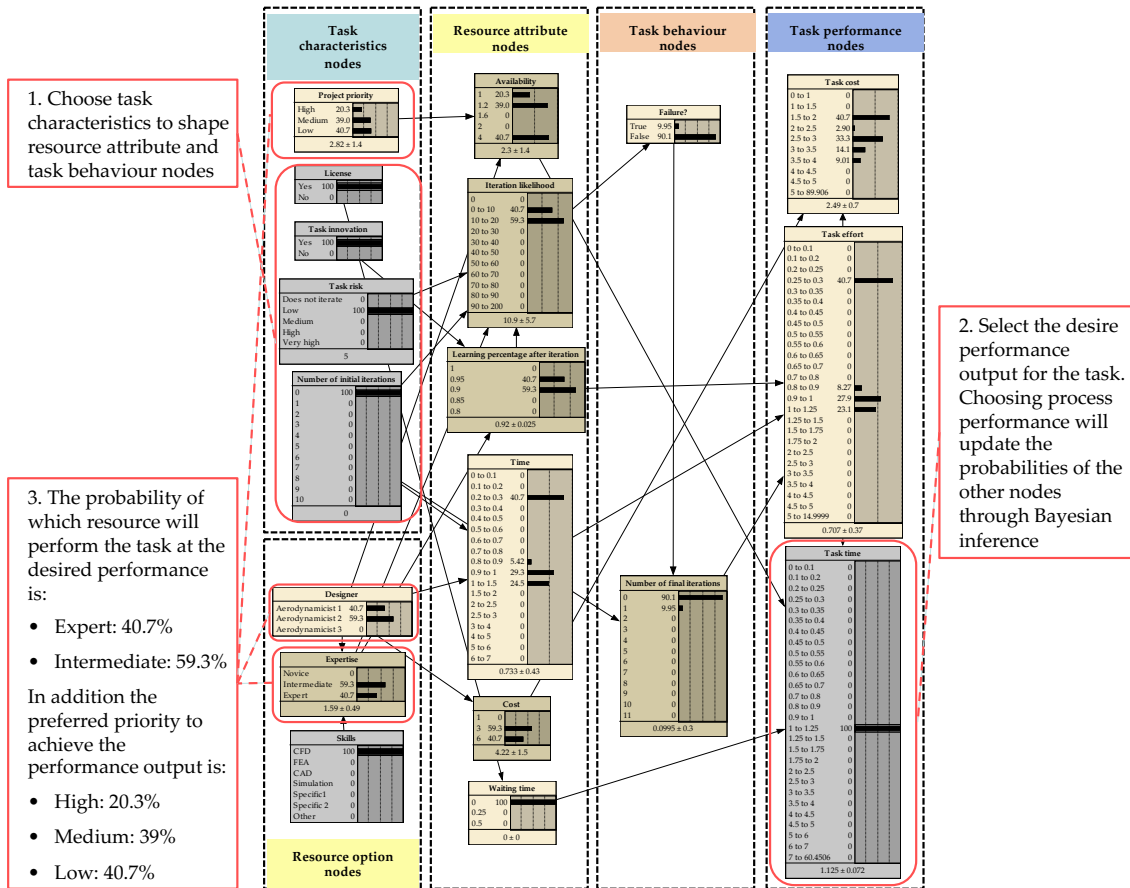
Figure 59. BN shows how selection of the desired performance target diagnoses the probability of resources that can attain the objective performance

6.4.5 Linking the design process model to BN resource model

CAM allows modellers to implement different process behaviour by creating variables and using them to write functions and logic. This is done through the *PreProcess* and *PostProcess* tabs under *Behaviour* properties of an activity. A number of predefined functions are available including Probability Distribution Functions for stochastic variables and *'if-then'* statements to implement logic.

In this context, three functions – *BNReader, BNWriter,* and *BNRetractor* - were developed to interface an existing BN engine (from Netica https://www.norsys.com/) within an ASM task network based process.

Firstly, the values of task's variables can be transferred into BN inputs by using the function *BNWriter* within *PreProcess* and *PostProcess* tabs. The extended function requires that each task variable must have the same name as its corresponding BN node. The BN then receives the input values from CAM through the *BNWriter* function, which requires to indicate the order of execution of the function, variable UID, and node name. The UID

is a specific code that is assigned to a vector variable in ASM that defines the BN variable, and can be found next to the variable when is selected.

>*BNWriter (a, b, "c")*
>
>*a*   *Order of execution of the function*
>
>*b*   *Variable code (UID) of the vector that holds the data to input into BN*
>
>*c*   *Comma separated input to BN as name, prefix, variable code*
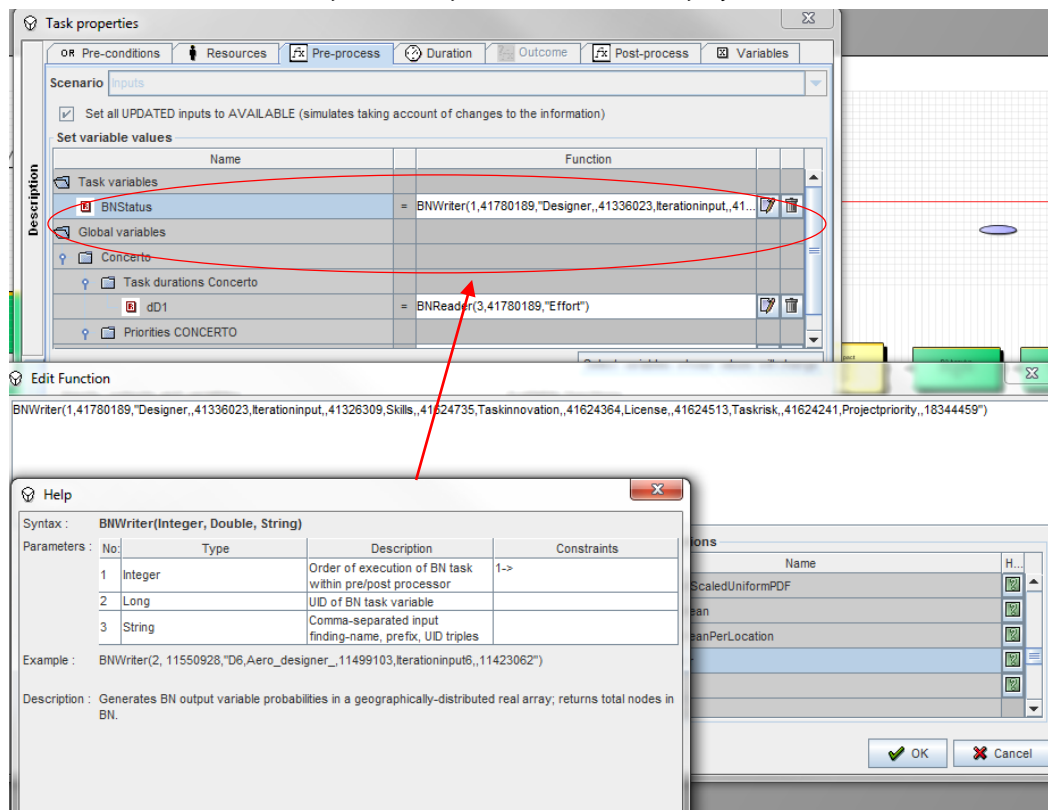
Figure 60. BNWriter function description and application using CAM

Secondly, in order to extract the desired values from its corresponding BN node, another function called *BNReader* was implemented in CAM. The function finds the specific node and extracts the value, at the same time re-updates the inference on the other nodes with the new set of beliefs. If a further value is read from another node, all probabilities are updated so the values extracted will correlate with each other.

>*BNReader (a,b,c)*
>
>*a*   *Order of execution of the function*
>
>*b*   *Variable code (UID) of the vector that holds the data to input into BN*
>
>*c*   *Comma separated output of the nodes to be extracted to the variable in CAM*
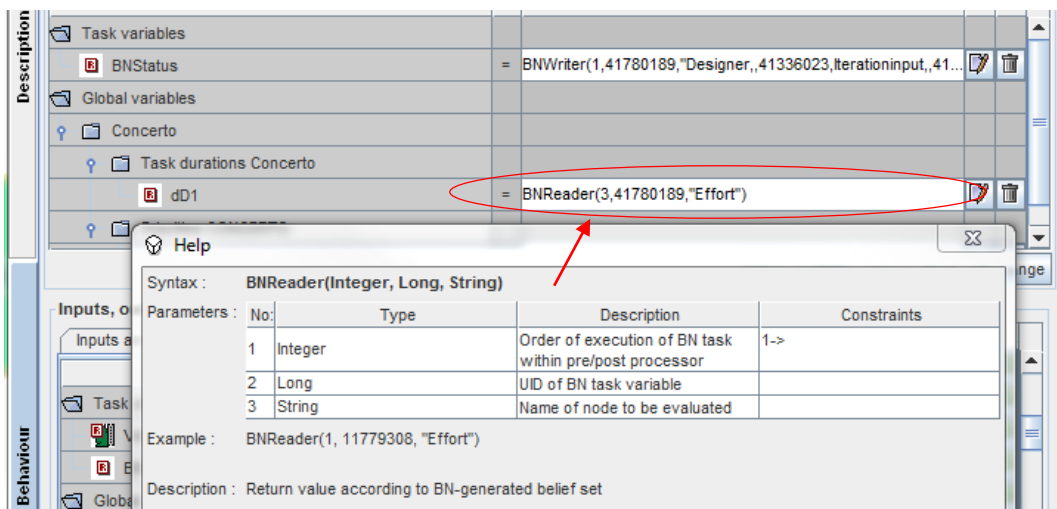
Figure 61. BNReader function description and application using CAM

The third function that was developed to implement BN within CAM was the *BNRetractor* function. The aim of the function is to retract the findings from BN output nodes and return the model to the initial setting in terms of conditional probabilities. Generally, the function should be used in the *Post Process* tab, bringing the BN back to the initial state for the task to be executed again if iterations are triggered.

> *BNRetractor(a, b)*

> a   *Order of execution of the function*
> b   *Variable code (UID) of the vector that holds the data to input into BN*
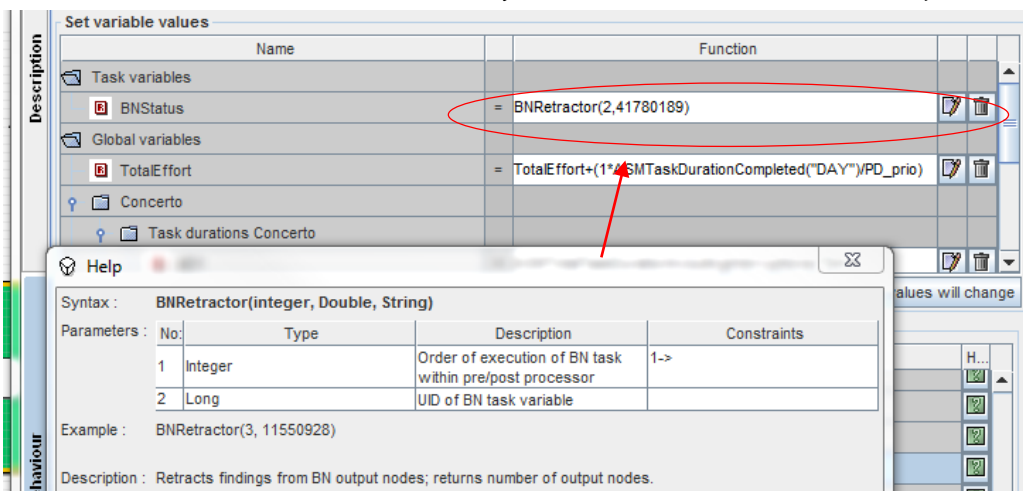
Figure 62. BNRetractor function description and application on CAM

The order of execution of these three functions must be specified. This enables the functions to be used multiple times in the same activity, extending the construction of simulation logic beyond the two steps of *PreProcess* and *PostProcess* settings. This is useful if

the activity undergoes multiple inferences in one simulation run. In addition, the order in which the inputs are written and read is important as it affects the inference process on other nodes. The BN model updates its conditional probabilities every time a variable is '*written*' or '*read*', both actions equivalent to setting a belief.

Finally, once the values are extracted from the activity, ASM uses its process simulator and functions (capturing elapsed time, current task time and number of iterations amongst others) to aggregate the total process performance.

6.4.6 Setting up simulations

Using ASM as process simulator, different scenarios can be tested by specifying independent variables in an experiment. At the same time, the number of Monte-Carlo runs can be indicated as shown in Figure 63.

Figure 63. Simulation experiment set up on CAM

The setting of simulation scenarios depends on the analysis objective. In general, as indicated in Section 6.1, the approach has both flexible resource allocation and preferred resource allocation capabilities. The procedure for the former involves setting up different resource options as independent variables. Subsequently, different combinations of resource instances can be simulated to study the output performance or the impact on any other variable (attribute, task characteristics, or behaviour). Activity characteristics

can also be specified: project priority setting, number of licenses, time dedication, quantity of resources, etc. The procedure for the later involves selecting the desired process performance for each activity to diagnose the probability of resource instances to achieve this (e.g., the project must be on time for a testing slot). In addition, due to the flexibility of the modelling approach, causal analysis can be performed to study the impact of any other variable, either attribute, activity characteristic or performance. Beliefs can be set on nodes to infer new output findings. Nevertheless, it is recommended to perturb a limited number of variables during each simulation. This enables to discern the influence on performance provoked by a specific variable while holding the rest constant.

6.4.7   Summary of method capability

The approach aims to support planning and scheduling through a resource management perspective. As stated in Chapter 4, design resources are affected by variables that influence availability and effectiveness. However, they often exhibit trade-off behaviours towards the three performance metrics (time, effort and cost). For example, more effective resources are generally more expensive or less available. Hence, analysis of the impact of resource attributes is focused on exploring the performance trade-offs to help resource management decision making.

The following analyses can provide insights for stakeholders by studying different scenarios and trade-off situations:

- Studying different resource combinations: This scenario can be set by changing resource options, either by simulating specific instances or full factorial of all possibilities. A high number of sensitivity analysis can be investigated by altering resource configurations. The analysis can provide insights on how each combination impacts the whole process, with the aim of finding feasible combinations that provide appropriate balance between performance trade-offs.

- Resource utilisation: Within each resource combination, the involvement of resource instances can be studied to identify the ones that exert a larger influence on the process. Examples are if the instance participates on a larger part of the process, it performs the most significant part (key activities), or there is substantial impact when the instance is replaced. Furthermore, since different resource types are defined in the model, the study of their involvement can potentially bring insights regarding both process and key resources. The outcome of the analysis identifies which resources can produce an important negative effect if missing. Hence, indicating the potential benefits of either acquiring more of these resources and/or investing on training the necessary skills.

- Identifying critical activities: Some activities can be more or less influenced by a change of resource options. The analysis is calculated upon the results of simulating different resource combinations. The range of performance values on activity performance can indicate resource sensitive activities. For the more resource sensitive activities, a possible way to manage them is to schedule them around the availability of key resources. For instance, a crucial task has a strong dependency to a specific expert designer. On the other hand, the less resource sensitive activities can be candidates to initiate new designers in the process.

- Studying the impact of different variables: Taking full advantage of BN diagnosis capabilities, different scenarios can be designed by setting belief on specific variables. In this manner, their influence on other variables can be studied. Examples include selecting the number of final iterations to study project priority, setting low availability and high cost to study waiting time. The analysis can be done at either activity level to investigate the influence of variables more granularly or at a process level.

- Achieving specific performance: Back propagation can be used to *'infer'* nodes to study the probability of attaining certain performance objectives by each resource instance. For example, if the tasks in the process need to finish by certain date, which resource instance has more possibilities to reach the objective.

Overall, the suggested method is thus, envisioned to be used for the investigation of various *'what-if'* scenarios during design process planning and execution. The presented list comprises examples of possible analyses.

There are other general analyses that are applicable but already studied by other approaches, hence not emphasised in this research. These include changing resource quantities, critical path, resource bottlenecks, etc. In addition, giving the flexibility of the approach in setting up scenarios, more analyses can be designed by stakeholders once they have defined managerial questions for which insights are necessary.

In summary, the method allows exploring different resource and process configurations to improve the process. Table 19 summarises the capability used during simulation of the model and subsequent analysis. The table can also be used as an analysis toolbox, providing guidance on the procedure taken and the potential results.

Table 19. Summary of potential analyses enabled by the model

Capability needed	Analyses	Procedure	Results
Flexible resource allocation	Studying different resource combinations	Predicting resource needs though sensitivity analysis	Feasible resource combinations after studying performance trade-offs
	Resource utilisation	Plotting the usage of each designer given the resource combination	Shows the involvement of different resource type (and instances). This can help identify key resources or skills needed for the process, proving insights regarding which areas to invest in training or acquire more resources
	Identifying resource sensitive activities	Plotting all the combinations per task against the desired metric	Identify which activities are more affected by resource changes. They can potentially be marked to allocate key resources first. On the other hand, if the activity is less sensitive, it can be a candidate to be performed by less effective resources
Preferred resource allocation	Studying the impact of different variables	Perturbing different variables (resource attributes, activity characteristics and behaviour) for a simulation scenario	Allows to quantify the impact of the different perturbed variables on resource attributes, activity characteristics and process performance. For example, studying the impact of project priority, number of iterations need, licenses, waiting time, etc.
	Achieving specific performance	Setting a specific target performance and investigating which resource instance can achieve it	Similarly, thanks to BN inference capabilities, causal relationships can be diagnosed to investigative which instance can reach the desired performance

6.5   Modelling procedure of the resource management model

The modelling procedure of the new approach, which aims to support project management planning, monitoring and re-planning, is shown in Figure 64. The modelling procedure is inspired by Wynn (2007)'s modelling method for ASM, the foundation of the current approach. The presented modelling method is an enhancement tailored to specifically highlight the role of resource management.
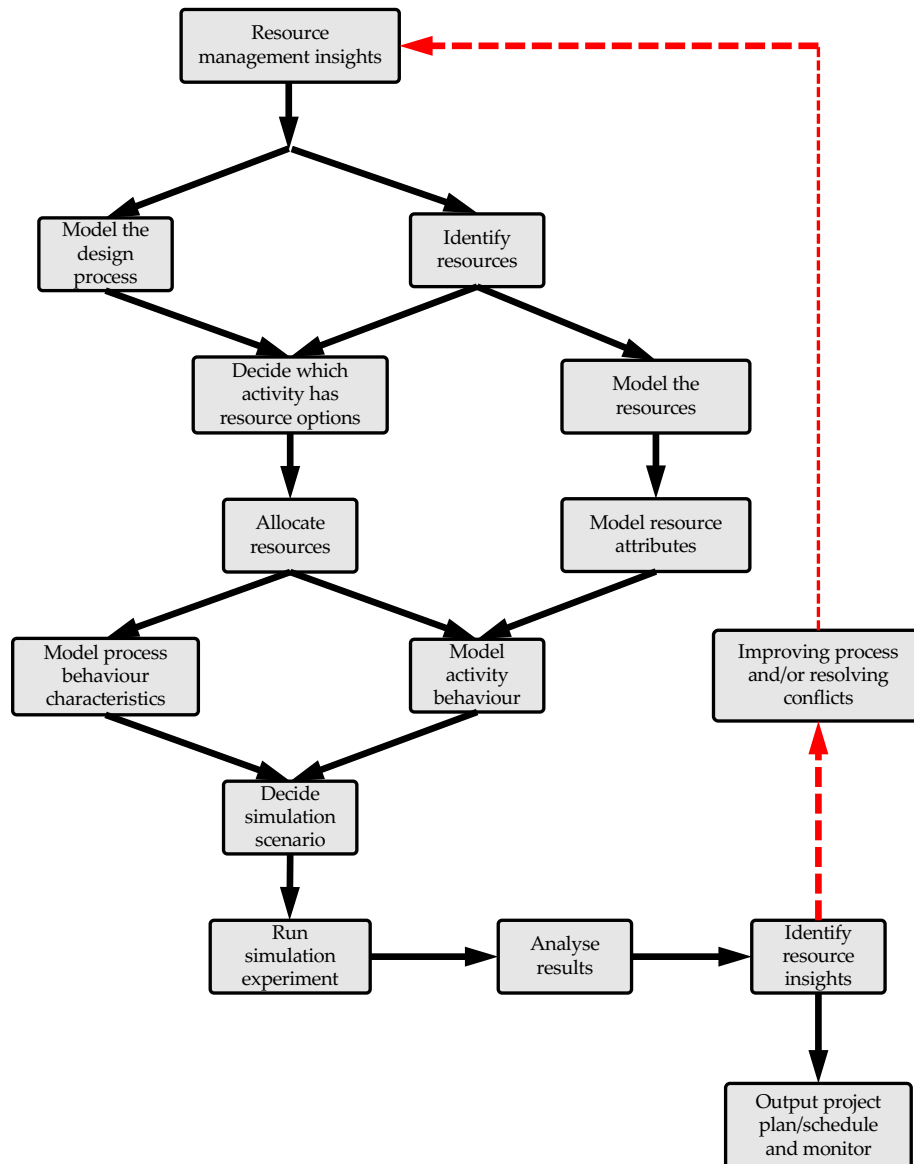
Figure 64. Modelling procedure of the method

The process starts when stakeholders require insights for resource planning and scheduling. The first step of the modelling method involves constructing the design process by specifying tasks, parameters, and iterations. The degree of granularity should be enough to extract both activity and process insights, and facilitate process monitoring.

On a parallel endeavour, the required resources are identified and subsequently modelled. Stakeholders must initially estimate the amount of resources available for the project in an effort to match resource requirements. These requirements are based on understanding of which resources (in terms of skills and expertise) and what quantities are needed to perform each activity. The forecasting process relies on information about scope of the task, required resource types, estimated available resource quantities, and resource calendars (PMI 2013). Then, resources are modelled, in which instances are characterised by their corresponding resource attribute values. In a parallel effort, the activities that allow different resource instances to perform it are identified. The process model can be populated with resources types and instances that will perform the activities. At this point, two steps can be done in parallel: 1) defining process path logic and 2) the activity behaviour through the relationships between resource attributes and activity characteristics. The activity behaviour should be adapted to the modelled situation, process and industry.

Different simulation scenarios can be defined to perform discrete event Monte-Carlo simulations. The outcomes represent the likelihood of the possible paths against the chosen metrics. Each process sequence can have a particular effect on the metrics. As any model based approach, the simulation can only be influenced by the parameters represented in the model. For instance, the model includes the known risks of iteration. However, they might be external factors that could provoke iterations or activity duration overrun. Thus, there are situations in which changes in the process or requirements could lead to re-planning. The modeller must decide whether the processes are acceptable depending on the criteria set for the project. These criteria should be abstracted to a level that allows comparison with the specified project performance metrics. Examples are to finish the project under a specific duration, budget, or to finish specific tasks under a set of milestones. The approach has a wide range of simulation scenario possibilities that can be explored. If none of the process paths are indicated as acceptable, there are underlying conflicts between individual project targets and the work plan. For example, the total duration of the projects exceeds the acceptable values; and given the current project and resource structures all possibilities to reduce it have been exhausted. Nevertheless, the results can help to identify the conflicting areas. For instance, identifying the critical bottleneck task or shortage of certain resources. The modeller must vary the process and/or resource configuration by relaxing the imposed constraints in the simulation model (Wynn 2007).

To conclude, the output plan and schedule can be used during the design process to monitor and evaluate the progress. Monitoring at different stages against the plan, milestones and performances metrics gives a sense of whether the project is generally on

track. Any incongruence with the actual process, the plan or set of plans serve as a black box to return and study where the conflict is located. Analysis of the simulation can indicate critical areas that need more attention. Management should encourage special emphasis on the success of those critical activities.

6.6 Summary

The chapter has introduced a novel method to aid resource management and gain insights for process improvement. The method extends the prototype model presented in Chapter 5, addressing all the derived functional requirements. Thus, the chapter answers **RQ4:** *What is a suitable concept(s) for a model for resource management that fulfils the set requirements?* and addresses **RQ5:** *How well does the model concept meets the set requirements?*

The chapter starts by introducing the evolution of resource management capabilities in assessing the use of different resource instances. There were embodied in concepts that abstract the capabilities of current approaches, static resource allocation, and the identified gaps in the field: flexible and preferred resource allocation. It was identified that an approach that can include both flexible and preferred resource allocation capabilities can address all the requirements in Chapter 5.

In order to do so, a novel method, which combines a task network approach (ASM) and a casual inference modelling method (BN) was presented. The method can assess the impact of different resource configurations to provide resource management insights and help decision-making. In summary, the approach provides:

1. Capability to capture design uncertainties;

2. Modelling the resources relevant for design processes (computational, designers, testing resources);

3. Providing the possibility to state different resource options for each activity;

4. Capturing design resource attributes and the relationships between tasks and resources. This means capturing resource attributes internal dynamics and influence on task performance;

5. Simulating multiple resource configurations (whole design space). Analysis should help improve project performance (time, cost, quality), devise insights on the effects of using different resources, and identifying critical resources and resource sensitive activities;

6. The method should ultimately allow to study causal relationships of any variable by setting beliefs, and investigating the updated probabilities.

As part of the method, the chapter details its fundamental elements and modelling relationships. It also explains the implementation and building of the model, as well as modelling procedure to aid stakeholders.

7 Application of support method

The current chapter applies the support method in two industrial case studies. The case studies were provided by Rolls-Royce plc, and combines complex design processes with a number of distinctive resources. The application of the method was carried out as part of the *resource management approach*, which comprises a number of steps aimed to investigate design resources and provide related managerial insights for process improvement. The approach is the one of the main contributions of this thesis and answers **RQ6:** *How can the model be used in an approach for resource management to improve design process planning?*

The subsequent application of the approach provides a basis for its evaluation, which is part of Descriptive Study II, and initially addresses **RQ7:** *How useful and usable is the developed resource management approach in industrial applications?* The main discussion regarding approach evaluation is elaborated in Chapter 8.

Section 7.1 introduces the approach taken to apply the resource management model with the objective of improving design process performance. Section 7.2 presents the Fan Subsystem case study, which includes its background, description of the process model, and analysis of results. Section 7.3 introduces the second case study, Turbine, with a similar structure. Section 7.4 briefly discusses the accuracy of the results, while Section 7.5 summarises the chapter.

7.1   Resource management approach for process improvement

The presented model (or support method) in Chapter 6 is part of an approach that embeds the application of the method in a clear step-by-step procedure. The approach is

the main outcome of the research and involves three stages: *Understanding the investigated organisation* in terms of their aims, processes and resources; *Application and analyses of the support method* in the relevant areas; and *Implementation of the resulting insights*.

The approach is detailed in Figure 65 and it is based on the author's own experience during the research. The author synthesised and refined the steps taken during research development. It also draws notions from application of modelling approaches in the design field such as Kerley *et al.* (2011), who applied ASM on industrial case studies. The aim is to provide an approach that encompasses empirical investigations; model construction and analysis; and insight implementation in the most efficient way.
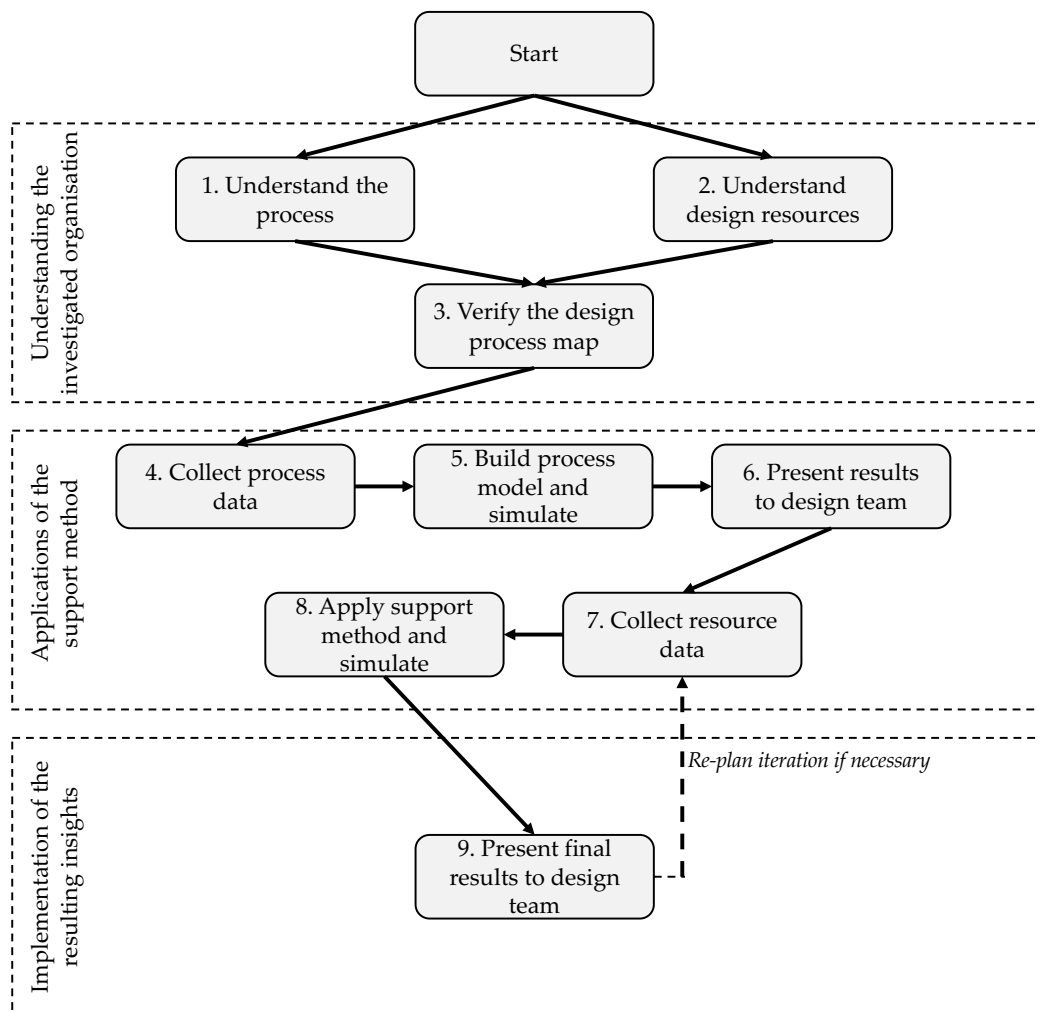
Figure 65. Resource management approach for process improvement

The following sub-sections details the resource management approach by explained the steps taken in each stage: understanding the investigated organisation, application of the support method and implementation of the resulting insights.

7.1.1   Understanding the investigated organisation

The approach starts when stakeholders in the organisation require resource management insights to improve process performance. During the first interaction with the relevant design team, the modeller should explain the approach, method, required data, analyses and potential insights.

1. Understand the process

The design process of each organisation might differ in its essence, hence the first step is to understand the organisation, its main objectives and the nature of their processes. During this step, discussion to align objectives and possible analyses can help define expectations. Finally, a schedule of interactions can be discussed to outline the necessary effort to deliver a successful collaboration.

2. Understand design resources

In a parallel effort, while gaining understanding about the processes, design resources should also be investigated. At this point, the modeller should be seeking to understand which design resources are key for the processes within the organisation. Section 4.4.2 explains the main requirements to distinguish design resources. At the top level they are required to deliver the design, then: 1) they have availability and 2) their effectiveness impact process performance metrics. Once the relevant resources have been identified, discussion should concentrate on understanding how they are managed (e.g., how they are requested and allocated, how they perform the activities, etc.). The understanding can be abstracted in relevant attributes that compose availability and effectiveness. This step elaborates the relationships that will later be modelled. The high level attributes and relationships presented in Chapter 4 and later abstracted in the model in Chapter 6 can be the starting point. However, this step can point out any different or specific behaviour that the investigated organisations possess. Therefore, the approach permits to adapt the model to various industries and situations.

3. Verify the design process map

Once a process has been chosen to apply the method, its design process map including activities, deliverables, parameters, iteration and path logic should be verified ahead of any modelling. Since the research focuses on evolutionary design processes, a reasonable assumption is that the process has been documented with some kind of process map, flowchart, Gantt chart or Microsoft Project file. Depending on the degree of detail of existing process maps, the verification effort can vary. It can range from just examining each activity with the team confirming the correct depiction of the process to develop a new process map. The latter can be done using other existing documents and additional

input from the design team. The step can be carried out as interviews or workshops to review the process representation. The aim is to carefully detect and fix potential inconsistencies, as well as understanding iteration and process path logic. Ideally the whole team should be present, or at least two design team members, during any verification or result assessment steps to increase objectivity while verifying the process map. Consensus between the designers should be reached in any discussion about data verification or results examination.

7.1.2 Application of the support method

The second stage of the approach involves application of the method once a basic understanding has been gained on the organisation, resources and process to model.

4. Collect process data

After the process map has been verified, process data can to be collected to build an ASM model that has the capability of *static resource allocation*. The data needed for each activity includes: time to finish the activity, iteration likelihood (if applicable), path logic (if applicable), type and quantity of resources (designers, computational, prototyping and testing), waiting time (if applicable). The data can also denote if any changes in these values are possible after iterating. If so, the new values should be collected. As explained in Chapter 5, duration values can be collected as probability distributions, for example triangular distributions (best, most likely and worst case). In anticipation for this step, a spreadsheet should be prepared beforehand, which can speed up data collection. The workshop is then focused on populating the spreadsheet with the help of the design team. ASM, a proven research model, is used to draw first insights about the process.

5. Build process model and simulate

Using the CAM tool, an ASM model with static resource allocation capability is built with the data collected in the first workshop. Monte-Carlo simulations can be run on the model to provide basic performance metrics such as process duration and effort in the form of frequency distributions. The design team can validate the plausibility of these first results and ensure that the process data and model construction is accurate, or at least fit for its intended purpose. First insights can include the best, worst, and most likely frequency distribution of process duration amongst other analyses.

6. Present results back to design team

The plausibility of the results is verified with the design team. This step allows to: 1) give initial insights about the process to stakeholders; 2) verify the correct building of the

process model and logic; and 3) provide results that can be compared against the new model to verify its correct functioning. The model is built using ASM with the CAM tool, a proven model and academic tool respectively. Firstly, the generated simulation results can provide a first set of insights to the design team. The modelling and data collection are susceptible of rework if results are not reasonable as assessed by the design team. Secondly, the verification of the plausibility of simulation results ensures that the process logic and first set of data are correct. Thirdly, it provides a set of results that can be compared with the resource management method.

7. Collect resource support method data

A second workshop to collect the remaining necessary data for the approach is performed. The basic model, *static resource allocation*, has verified the correct building, path logic and behaviour of the model. This next step can be entirely focused on resource management. The second workshop enhances the ASM model to add resource specific data. This includes the necessary resource attributes, which can be captured with two set of tables in the form of spreadsheets. Again, they are prepared beforehand and populated during the workshop with the design team. Before the second workshop, it is necessary to investigate the designer's skills necessary for the process in order to build the spreadsheet. The first set of tables involves the type of resource and instances. Each instance has a specific expertise in the different skills, time dedication, waiting time and available quantity. The second table involves detailing how each instance modifies the original time to perform the activity, iteration likelihood, waiting time (e.g., how jobs affect computational waiting time), learning curves, etc. The remaining attributes are also collected or abstracted from the understanding gained during step 2.

8. Apply support method and simulate

After the second set of data is collected, the new model including both ASM process and BN resource models can be built. The procedure to construct the model, which allows both *dynamic resource allocation* and *preferred resource allocation*, can be found in Section 6.5. The extended model can be simulated with the same instances as the ASM static resource allocation to verify that results are similar when no perturbation is present. Subsequently, different analyses can be performed at both activity and whole process level by changing resource instance options and other variables.

7.1.3   Implementation of the resulting insights

The final section of the approach involves discussing the findings from the analyses that can lead to more *'what-if'* scenarios, re-planning the process and/or implementation of insight for process improvement.

9.   Present final results to design team

The final results and insights are discussed with the design team. Due to the great number of possible trade-off analyses and *'what-if'* scenarios, the first results are likely to trigger more specific questions and analyses. The design team must assess the relevancy and plausibility of the analysis results based on experience. Once the necessary and satisfactory insights are gathered, the design team can decide any implementation actions for process improvement. Stakeholders must evaluate the feasibility of implementing the different insights and act accordingly. The approach is intended to be iterative and re-plan can be triggered if more scenarios or analyses are required, going back to previous steps to collect data.

7.2   Fan Sub-system

The organisation background and objectives were presented in Chapter 4. To recap, Rolls-Royce plc works in a bid system with limited resources and is continuously looking to improve its design processes in terms of: time (process duration), cost (effort and cost), and quality. Preliminary design work involves the generation of first designs from the Preliminary Design division that are further enhanced by different Sub-system divisions, all coordinated by a Central Division. The Fan process is one of the Sub-systems in which the support method was applied following the approach in Section 7.1[4].

The first few interviews with the Sub-system team is also part of the exploratory case study that comprises Chapter 4 and covered until the third step of the approach. The first data collection workshop was conducted with designers of the Fan Sub-system team to populate the corresponding spreadsheet. A constructed ASM model and analysis of results were verified by the team. Then, the author coordinated with one of the designers to construct the appropriate spreadsheet for the second data collection. Subsequently, a workshop focused on gathering specific data for the approach was carried out in half a day. The data collection involved five designers from different process areas. The analyses performed and results were discussed with designers from the team.

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[4] Steps 1-6 of the approach were conducted with Daniel Shapiro, another Ph.D. student at the EDC at the time, focused on developing a different design support method.

Hereafter, Section 7.2.1 details the background and process description, and Section 7.2.2 presents analysis results.

7.2.1 Case study background and process description

The Fan Sub-system design process is part of the preliminary jet engine design of Rolls-Royce plc explained in Chapter 4. The case study comprises 26 tasks involving five types of designers, and HPC resources. The process, necessary resources and possible instances are depicted in Figure 66.

In essence, this process starts with a set of three activities conducted by preliminary designers to produce different fan blade concepts and blade geometry based on the functional requirements from the Preliminary Design team, each of these activities requiring specific tools to be used. The concepts are further studied by aerodynamic designers focusing on aero-thermal properties. Then, mechanical properties are generated and refined in the areas of stress and impact analyses as well as manufacturing assessment. The suitability of Rolls-Royce plc and its processes as case studies has been discussed in Chapter 4. To enforce confidentiality, the name and description of activities and parameters are not explicitly shown except for the code name. Some characteristics of the fan process are detailed below:

- In broad terms, the duration of the process can take several months;
- Resources comprise designers from different departments (preliminary, aerodynamics, mechanical, stress, impact), and HPC resources;
- Three options per designer type and HPC cores were present in the process;
- When an intermediate designer executes a task, an extra 15% of expert designer's effort is necessary to supervise the task. When a novice executes a task, an extra 30% of expert's effort is needed;
- Baseline scenario was the combination of using all *intermediate* designers and *medium* cores.

The performance metrics used for this process and indicated as relevant by the design team are:

- *Process duration or total time:* Elapsed duration of whole process measured in days.
- *Total Effort:* Measured in person-days.
- *Total human cost/computational cost:* Cost is calculated by multiplying effort by a weight (three for novice, six for intermediate, and nine for expert). Computational cost is measured as time of computational resources multiply by the number of cores used (depends on the activity and computational power needed).
- *Task time:* Measured in days.
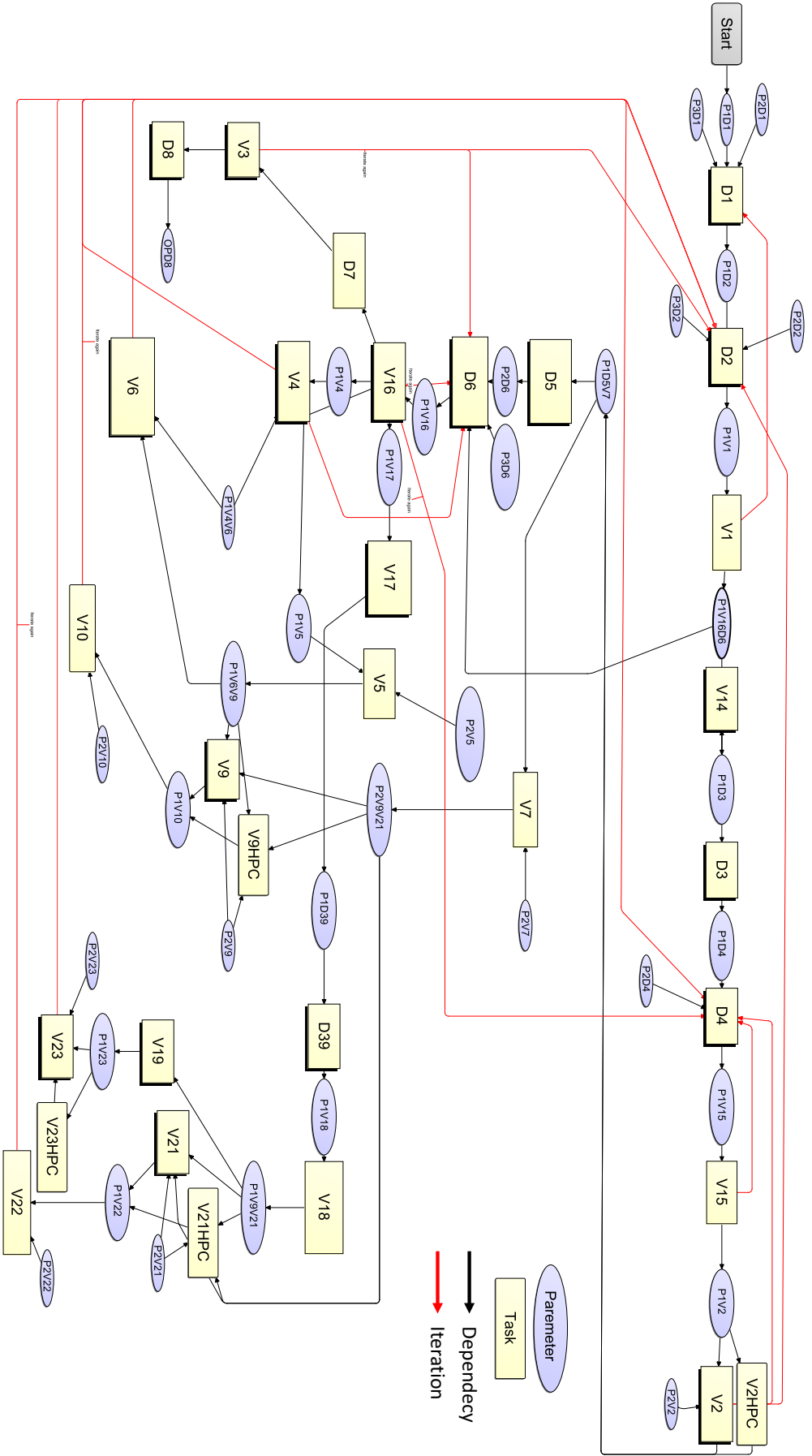
Resource	Instance options	Activities (Quantity)
Preliminary		D1(1), D2(1), V1(1), V16 (1)
Impact	1.Expert 2.Intermediate 3.Novice	V14 (1), V17 (1), V7(1), V9(1), V16(1), V10(1), V21(1), V22(1)
Aerodynamic		D3(1), D4(1), V15(1), V2(1), V16(1)
Manufacturing		V3(1), D8(1)
Mechanical		D5(1), D7(1), V16(1), V5(1), D39(1), V18(1), V19(1)
Stress		V4(1), V6(1), V23(1)
HPC	1.High cores 2. Medium cores 3.Low cores	V2C(X cores), V9C(X cores), V10C(X cores), V21C(X cores), V22C(X cores), V23C(X cores)

Figure 66. Process map of fan preliminary design process and designers' allocation; descriptions of activities and parameters replaced with code names to maintain confidentiality

'*Time dedication*' for an expert designer ranges from 50% to 100%, and dedication decreases as expertise increases. '*Time'* to task completion ranges from two hours to one week depending on the task and designer expertise: typically, expert designers complete the tasks faster than intermediate designers, which in turn are faster than novice designers. Time values were specified as triangular distributions. HPC time ranges from one day to two weeks, also depending on task and number of cores used. Similarly, '*iteration likelihood'* value ranged from 5% to 100% (with learning after iterating) depending on designer and task. Learning after iteration, which corresponds to '*learning curves*', ranges from 0% to 50% depending on designer and task.

The number of jobs already submitted to HPC from the same department determines how long the current job has to wait. Depending if the number of jobs submitted is low, medium or high, '*waiting time'* varies from half a day to a week. When no job has been submitted there is no waiting time. In this case, it is assumed that no jobs are pending. Finally, the priority of the project itself can affect process performance: medium priority is the default setting. As priority decreases, designers time working on the activities may decrease to 75% or 50%. All possible resource combinations of the model are tested through Monte-Carlo simulation runs and the analyses discussed in the following sections used the mean of 2,000 simulation runs.

7.2.2   Analysis of results

The analyses performed, as introduced in the analyses summary in Chapter 6, can be classified in five sub-sections: 1) Studying different resource combinations; 2) Resource utilisation; 3) Identifying resource sensitive activities; 4) Studying the impact of different

variables; 5) Achieving specific performance. At the start of each sub-section, the analysis and method used is explained. Then results and insights are presented. A brief summary with insights and recommendations is included at the end of the case study.

7.2.2.1 Studying different resource combinations

The objective is to identify resource combination with improved performance in terms of effectiveness through different trade-off analyses. Firstly, all 729 resource combinations are plotted in three different graphs depicting improvement compared to baseline of: cost against process duration; cost against effort; and process duration against effort. Secondly, a table filters the resource combinations that have relative improvement in all performance metrics (process duration, effort, and human and computational cost). Thirdly, three tables are introduced with the best 16 resource combinations in terms of process duration, human effort and cost respectively.

Figure 67 depicts all 729 resource combinations: each point represents a specific resource combination as percentage improvement in cost (*x*-axis) and process duration (*y*-axis) against baseline scenario. The figure characterises the whole design space in terms of resource instance options. Similarly, Figure 68 illustrates all 729 resource combinations as a percentage of improvement in cost (*x*-axis) and effort (*y*-axis), and Figure 69 as a percentage of improvement in process duration (*x*-axis) and effort (*y*-axis).
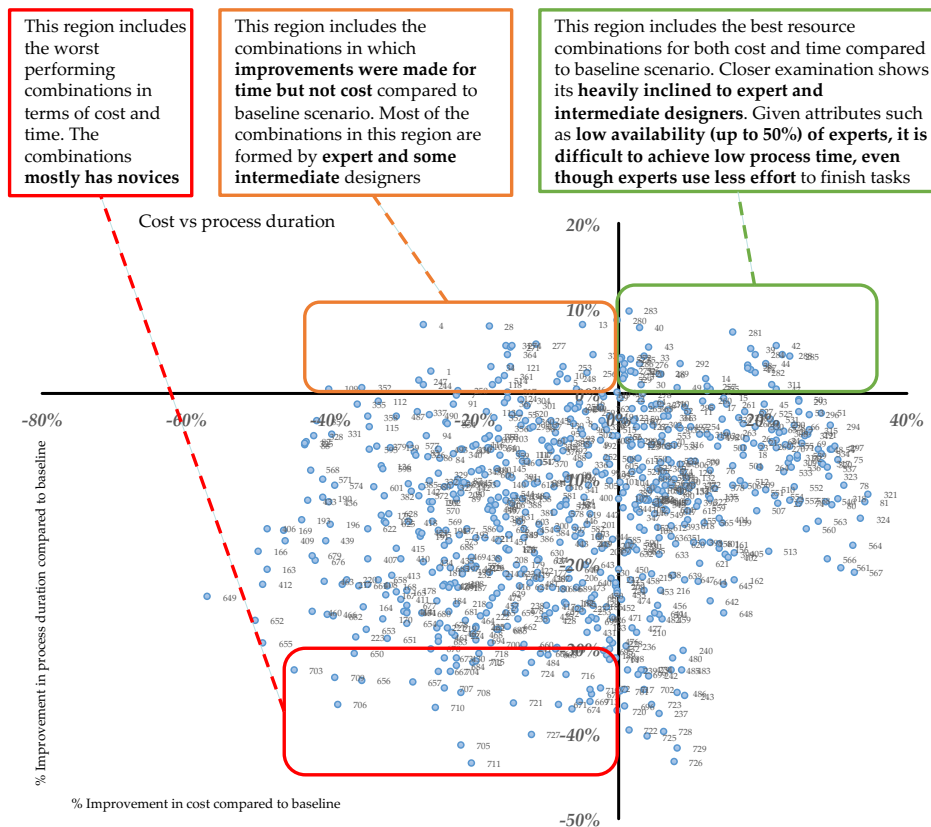
Figure 67. Fan: Improvement in cost vs improvement in process duration

This region includes the worst performing resource combinations in terms of effort compared to baseline scenario.

This region includes resource combinations in which **improvements were made for effort.** Since this represents the actual effort spent on the tasks by the designers **without accounting for attributes such as time dedication** (expert designers are less available and hence increases elapsed time), the combinations are **more evenly scattered** than the process duration vs cost graph. The combinations has **designers that can improve the performance of all intermediate designers, mostly by including some experts.**

Figure 68. Fan: Improvement in cost vs improvement in human effort

In contrast, **performance output for effort is evenly distributed as expected.** The set of combinations with any **experts seems to outperform the baseline scenario, their expertise allows them to finish the tasks faster.** At the same time, combinations with less experts or intermediate designers seems to take more effort to complete the tasks.

As already seen, improvements over baseline combination for process duration seems **difficult achieve given low timed dedication of experts during a medium priority project.**

Figure 69. Fan: Improvement in process duration vs improvement in human effort

The three areas that can be distinguished in Figure 68 corresponds to the combinations that use high, medium and low number of HPC cores. The number of cores and discretisation of the simulation drives the cost improvement and the shape of the figure.

Table 20 shows resource combinations that have relative improvement in cost, effort and time against baseline. Given the resources attributes and the trade-off nature of the different metrics, only 17 combinations had overall improvements. The table indicates the designer type and instance (E for expert, I for intermediate, and N for novice), and HPC and instance (H for high number of cores, M for medium and L for low).

Table 20. Fan: Resource combinations with improvements in cost, effort and time

Combination	Aero	HPC	Impact	Mech	Prelim	Stress	% Improvement of cost	% Improvement of human effort	% Improvement of comp cost	% Improvement of process duration
				Resource type						
Baseline	I	I	I	I	I	I	0	0	0	0
14	E	H	E	I	I	I	12%	18%	23%	2%
30	E	H	I	E	E	N	3%	2%	22%	1%
32	E	H	I	E	I	I	2%	9%	24%	2%
35	E	H	I	E	N	I	2%	6%	23%	4%
38	E	H	I	I	E	I	18%	7%	23%	3%
40	E	H	I	I	I	E	3%	10%	28%	8%
41	E	H	I	I	I	I	19%	4%	22%	3%
43	E	H	I	I	N	E	4%	8%	29%	5%
257	I	H	E	I	I	I	12%	16%	22%	1%
272	I	H	I	E	E	I	1%	10%	24%	4%
275	I	H	I	E	I	I	1%	7%	23%	2%
280	I	H	I	I	E	E	0%	9%	26%	8%
281	I	H	I	I	E	I	16%	3%	22%	7%
283	I	H	I	I	I	E	2%	7%	26%	10%
284	I	H	I	I	I	I	19%	2%	22%	5%
523	N	H	I	I	E	E	1%	6%	14%	4%
526	N	H	I	I	I	E	2%	4%	15%	3%

Summary of resource instance frequencies of the above combinations					
Aero	HPC	Impact	Mech	Prelim	Stress
E: 47% I: 41% N: 12%	H: 100%	E: 12% I: 88%	E: 30% I: 70%	E: 35% I: 53% N: 12%	E: 35% I: 59% N: 6%

The resulting combinations above are the ones with positive improvement for all metrics. They are as expected, since trade-offs between cost, time and effort led most combinations to have intermediate designers with some experts to improve the baseline scenario. Too many experts would be too costly, but a large number of novices will not provide enough effort and process duration improvement. Due to the importance of preliminary designers, combinations 30, 38, 272, 280, 281 and 523 are probably the most feasible ones. In addition, combination 280 has the highest improvement in process duration of ~8% compared to baseline. High number of cores for HPC and intermediate impact and mechanical designers have a large presence.

Table 21 includes the best 16 resource combinations (all combinations are available, 16 are shown to illustrate the analyses) that have relative improvement in process duration

against baseline. The table indicates the resource type and instance, and complements with information of percentage improvement on the remaining performance metrics.

Table 21. Fan: Best 16 resource combinations with improvement in process duration

Combination	Aero	HPC	Impact	Mech	Prelim	Stress	% Improvement of cost	% Improvement of human effort	% Improvement of comp cost	% Improvement of process duration
Baseline	I	I	I	I	I	I		0	0	0
283	I	H	I	I	I	E	2%	7%	26%	10%
280	I	H	I	I	E	E	0%	9%	26%	8%
13	E	H	E	I	I	E	-5%	23%	26%	8%
4	E	H	E	E	I	E	-27%	26%	25%	8%
28	E	H	I	E	E	E	-18%	16%	27%	8%
40	E	H	I	I	I	E	3%	10%	28%	8%
281	I	H	I	I	E	I	16%	3%	22%	7%
277	I	H	I	E	N	E	-11%	11%	28%	6%
42	E	H	I	I	I	N	22%	-6%	22%	6%
274	I	H	I	E	I	E	-15%	12%	27%	6%
31	E	H	I	E	I	E	-15%	14%	27%	6%
43	E	H	I	I	N	E	4%	8%	29%	5%
271	I	H	I	E	E	E	-15%	16%	28%	5%
39	E	H	I	I	E	N	19%	-6%	21%	5%
284	I	H	I	I	I	I	19%	2%	22%	5%
364	I	M	I	I	I	E	-15%	7%	5%	4%

Summary of resource instance frequencies of the above combinations

Aero	HPC	Impact	Mech	Prelim	Stress
E: 50% I: 50%	H: 93% M: 7%	E: 13% I: 87%	E: 50% I: 50%	E: 31% I: 55% N: 14%	E: 75% I: 13% N: 2%

The combinations above are the 16 best ones in terms of process duration improvement, with 283 (~10%) and 281(~8%) as the best two. Combinations 13, 4 and 28 also present an improvement of ~8%. However, many experts result in deterioration of cost performance. The presence of experts is significant for stress designers. In a slightly less degree expert presence is also high for aerodynamic, mechanical and preliminary designers. An interesting point to note is that improvements in process duration does not always correlate with improvements for effort. Resource frequencies of the combinations are summarised at the bottom of Table 21.

Table 22 includes the best 16 resource combinations that have relative improvement in cost against baseline. As expected, the combinations with more novices have higher improvements in cost. However, these combinations do not show any improvements on effort or process duration. HPCs with high number of cores still show improvement in terms of cost, a possible explanation is that their computational speed offsets their cost. The combinations in Table 22 indicate a higher correlation between effort and process durations than other combinations with more intermediate or expert designers. A possible explanation could be that novices have 100% time dedication in all project priority situations. In contrast, intermediate and expert designers are less available. Resource frequencies of the combinations are summarised at the bottom of Table 22.

Table 22. Fan: Best 16 resource combinations with improvement in cost

	Resource type						% Improvement of cost	% Improvement of human effort	% Improvement of comp cost	% Improvement of process duration
Combination	Aero	HPC	Impact	Mech	Prelim	Stress				
Baseline	I	I	I	I	I	I			0 0	0
321	I	H	N	N	I	N	35%	-37%	25%	-12%
81	E	H	N	N	N	N	34%	-41%	25%	-13%
324	I	H	N	N	N	N	34%	-45%	23%	-15%
567	N	H	N	N	N	N	33%	-49%	10%	-21%
564	N	H	N	N	I	N	33%	-45%	11%	-18%
78	E	H	N	N	I	N	32%	-42%	22%	-11%
561	N	H	N	N	E	N	31%	-43%	11%	-21%
75	E	H	N	N	E	N	31%	-38%	24%	-8%
318	I	H	N	N	E	N	31%	-41%	22%	-12%
297	I	H	I	N	N	N	30%	-22%	25%	-6%
77	E	H	N	N	I	I	30%	-28%	25%	-7%
80	E	H	N	N	N	I	30%	-33%	24%	-13%
294	I	H	I	N	I	N	30%	-17%	25%	-4%
54	E	H	I	N	N	N	30%	-20%	25%	-7%
323	I	H	N	N	N	I	29%	-37%	23%	-10%
566	N	H	N	N	N	I	29%	-39%	10%	-20%

Summary of resource instance frequencies of the above combinations

Aero	HPC	Impact	Mech	Prelim	Stress
E: 38% I: 38% N: 24%	H: 100%	I: 19% N: 81%	N: 100%	E: 19% I: 31% N: 50%	I: 25% N: 75%

Table 23 shows the best 16 resource combinations that have relative improvement in human effort against baseline.

Table 23. Fan: Best 16 resource combinations that have relative improvement in human effort against baseline

	Resource type						% Improvement of cost	% Improvement of human effort	% Improvement of comp cost	% Improvement of process duration
Combination	Aero	HPC	Impact	Mech	Prelim	Stress				
Baseline	I	I	I	I	I	I	0	0	0	0
163	E	L	E	E	E	E	-49%	30%	15%	-21%
1	E	H	E	E	E	E	-26%	30%	26%	2%
82	E	M	E	E	E	E	-43%	29%	5%	-6%
406	I	L	E	E	E	E	-49%	28%	14%	-16%
325	I	M	E	E	E	E	-43%	28%	4%	-6%
409	I	L	E	E	I	E	-46%	27%	16%	-17%
166	E	L	E	E	I	E	-50%	27%	14%	-19%
85	E	M	E	E	I	E	-42%	27%	4%	-3%
244	I	H	E	E	E	E	-27%	27%	24%	1%
91	E	M	E	I	E	E	-23%	26%	6%	-1%
4	E	H	E	E	I	E	-27%	26%	25%	8%
328	I	M	E	E	I	E	-42%	25%	4%	-5%
169	E	L	E	E	N	E	-46%	25%	15%	-16%
7	E	H	E	E	N	E	-22%	25%	26%	0%
568	N	M	E	E	E	E	-43%	25%	-7%	-9%
2	E	H	E	E	E	I	-9%	24%	22%	-3%

Summary of resource instance frequencies of the above combinations

Aero	HPC	Impact	Mech	Prelim	Stress
E: 63% I: 31% N: 6%	H: 31% M: 38% L: 31%	E: 100%	E: 94% I: 6%	E: 56% I: 31% N: 13%	E: 94% I: 6%

As expected, combinations with higher improvement in effort, which means less effort required to finish the process, are the ones with higher number of experts. Combination 1, with experts and high number of cores for HPC, performs well compared to baseline in terms of effort. Process duration improvement is not that significant due to the low availability of experts. In addition, having experts in the team comes with significant cost, up to ~50% negative improvement compared to baseline in the case of 166. It seems that many combinations have human effort improvements but negative process duration. A possible explanation could be due to the use of low or medium cores HPC or low time dedication of expert designers. Expert impact, mechanical and stress designers seem to have a large presence.

To conclude resource combination analysis, Table 24 compares the performance improvements between key combinations (baseline, all experts, all novices, best and worst, etc.). The difference is calculated by subtracting values of the combinations in the first column with each combination in the top row and dividing it by the baseline value of each metric.

Table 24. Fan: Comparison of performance improvements between key combinations

Key combinations and improvement over baseline

		Resource type							Human effort	Computational cost	Process duration
	Combination	Aero	HPC	Impact	Mech	Prelim	Stress	Cost			
	Baseline	I	I	I	I	I	I	-	-	-	-
All experts/high cores	1	E	H	E	E	E	E	-26%	30%	26%	2%
All novices/low cores	729	N	L	N	N	N	N	8%	-49%	-1%	-42%
Best process duration	283	I	H	I	I	I	E	2%	7%	26%	10%
Best cost	321	I	H	N	N	I	N	35%	-37%	25%	-12%
Best human effort	163	E	L	E	E	E	E	-49%	30%	15%	-21%
Low performance	711	N	L	N	E	N	N	-20%	-31%	-5%	-44%

Difference between the combinations (first column minus top row) divided by baseline

Cost difference

	Baseline	1	729	283	321	163
Baseline						
1	26%					
729	-8%	-34%				
283	-2%	-27%	7%			
321	-35%	-61%	-27%	-33%		
163	49%	23%	57%	50%	83%	
711	20%	-6%	29%	22%	-28%	-28%

Effort difference

	Baseline	1	729	283	321	163
Baseline						
1	-30%					
729	49%	78%				
283	-7%	23%	-56%			
321	37%	67%	-12%	44%		
163	-30%	-1%	-79%	-23%	-68%	
711	31%	61%	-17%	38%	62%	62%

Comp cost difference

	Baseline	1	729	283	321	163
Baseline						
1	-26%					
729	1%	27%				
283	-26%	0%	-28%			
321	-25%	1%	-27%	1%		
163	-15%	11%	-16%	12%	10%	
711	5%	31%	4%	32%	20%	20%

Process duration difference

	Baseline	1	729	283	321	163
Baseline						
1	-2%					
729	42%	44%				
283	-10%	-7%	-51%			
321	12%	14%	-30%	22%		
163	21%	23%	-21%	30%	9%	
711	44%	46%	2%	53%	23%	23%

▨ Significant increase (negative performance)
▨ Significant decrease (positive performance)

Table 24 highlights the largest positive or negative differences between some of the resource combinations. More comparisons between combinations can be studied at the request of the design team.

7.2.2.2   Resource utilisation

Figure 70 assesses the amount of involvement of the different designers in the process and displays the studied key combinations (the data for other combinations were simulated and can be displayed at the request of the design team). Figure 70 shows that impact, mechanical and stress designers are highly involved in the process. Due to confidentiality, the exact values are not included. However, they were reported to the design team to increase visibility and quantify how much the use of more effective resources (less effort) can impact on cost. In addition, depending on the resource type and instance, the correlation between effort and process duration values can vary.
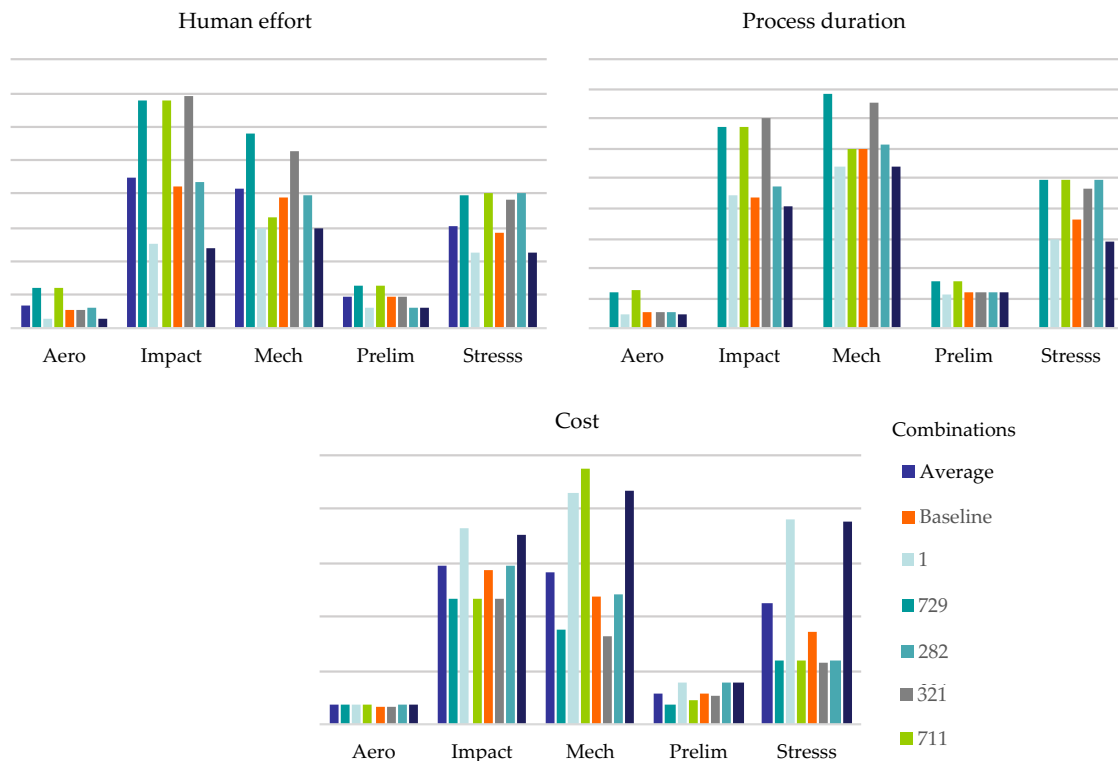
Figure 70. Fan: Resource utilisation for some selected combinations in terms of process duration, effort and cost. Values are not shown due to confidentiality

The results quantify the involvement of different designers, as well as the performance difference between the instances. Impact designers shows a significant difference in effort depending on the instance chosen. Instances of aerodynamic designers have different outputs in terms of effort and duration, but similar in cost. This could be due to experts having higher cost per unit values and taking less time, which evens out with novice taking longer and having lesser cost per unit value.

7.2.2.3 Identification of resource sensitive activities

Figure 71 shows all possible 729 resource combinations plotted with process activities in the *x*-axis and task duration in the *y*-axis (blurred due to confidentiality). Resource sensitive tasks can be identified by virtue of their distinctive performances depending on different combinations, indicating increased susceptibility to resource changes.

Different resource combinations time performance in each task
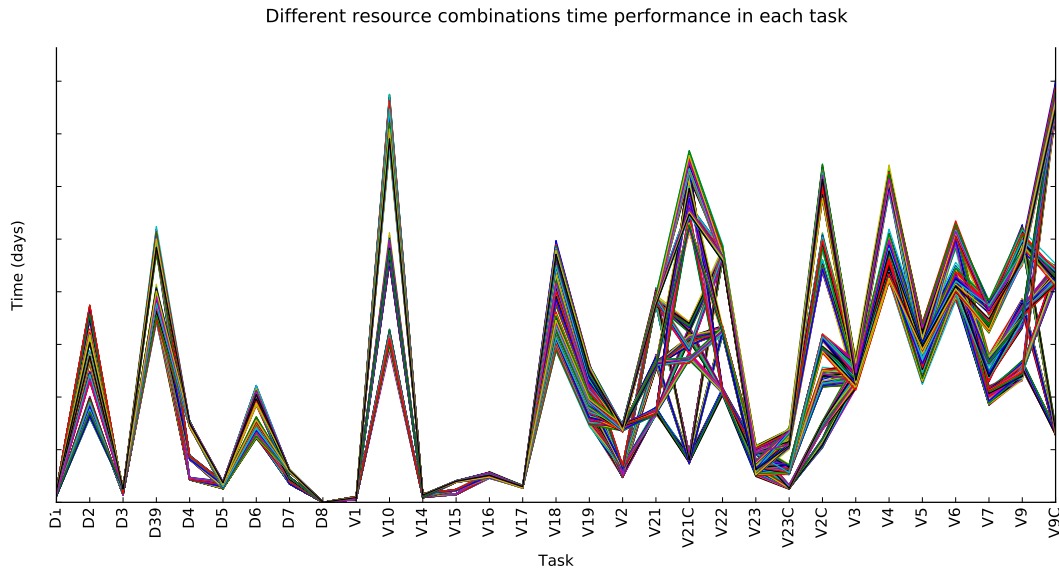
Figure 71. Fan: Task time of different resource combinations. Values are not shown due to confidentiality

Time is set as the total time taken to finish the activity including iterations, lack of availability, etc. It seems that HPC tasks V21C, V23C, V2C and V9C are sensitive to the number of cores used. Activities D2, D39, V18, V21, V22, V4, V7, V9 and V10 are more sensitive to a change of designer instance. Activities D4, D6, V2, V19, V2, V5, V6 and V23 have a medium sensitivity to a change of designer option. Activities D1, D3, D5, D7, V14, V19, V1 and V15 are less sensitive to a change of designer option, while activities V16, V3, D8, and V17 did not have resource instance options. However, activities V1 and V15 are mainly verification activities, that leaves activities D1, D3, D5, D7, V14 andV19 as prospects to introduce new designers or novices to the process with low negative performance impact.

7.2.2.4 Studying the impact of different variables

Previous analyses identified time dedication (availability) as a key attribute that drives process duration. Experts are usually less available, although their effectiveness are better than intermediate or novices. In this context, project priority has a strong influence on availability and time dedication. Table 25 analyses the impact of changing project priority on process performance. The new simulated scenario with high project priority was compared with the medium project priority scenario (all previous analyses were

medium project priority). High priority situations require designers to have full time dedication on the current project, as opposed to medium or low priority, in which designers could be working on other projects.

Table 25. Fan: Impact of changing project priority, medium vs high

	Combination	Aero	HPC	Impact	Mech	Prelim	Stress	Process duration difference in %
	Baseline	I	I	I	I	I	I	-9%
All experts/high cores	1	E	H	E	E	E	E	-30%
All novices/low cores	729	N	L	N	N	N	N	-1%
Best process time	283	I	H	I	I	I	E	-10%
Best cost	321	I	H	N	N	I	N	-10%
Best human effort	163	E	L	E	E	E	E	-27%
Low performance	711	N	L	N	E	N	N	-9%
Biggest difference in process duration	2	E	H	E	E	E	I	-45%

Table 25 shows the performance difference for some selected combinations (all other combinations have been simulated and available at request of the design team). A change in project priority mainly affects process duration. The difference between cost, effort and computational cost are similar, hence not included in the table. The most significant improvements are given by combinations 2, 1 and 163, which comprise mostly expert designers. The performance difference for novices is negligible since they are already fully dedicated to the process. In addition, the use of extra 30% of experts' effort if a novice performs the tasks could lead to situations in where the effort used by experts is the same as if they were performing the task. To illustrate the point, a task requires either one day of expert's effort or three days of novice's effort. In the situation in where the novice performs the task, the expert still has to contribute almost a day of effort. The importance of experts can be seen when comparing key combinations. During a medium project priority situation, a combination of experts can complete the process with less effort than a combination full of novices. However, due to a lack of availability in medium priority situations, the effort improvements do not correlate to process duration improvements (e.g., combination with all experts has a 30% improvement in effort but only 2% in process durations).

7.2.2.5   Achieving specific performance

Further analyses can be provided by investigating the results of constraining a desired performance for a task and diagnose the probabilities of different designers to reach that performance. The most resource sensitive activities were selected and a limit for task duration and/or cost were imposed on them to investigate, using BN capabilities (inference), which resource and project priority has a bigger probability to attain the desired

performance. Due to confidentiality, the actual performance aim set for each activity (duration, cost or effort) used to infer the BN is not shown.

Table 26. Fan: Setting performance aims to diagnose the impact on the probability of reaching it by resource instances and project priority

Activity	Resource instance probability to reach desired performance			Project priority probability to reach desired performance		
	Expert	Intermediate	Novice	High	Medium	Low
D2	55.5%	44.5%	0%	44.5%	55.5%	0%
D39	0%	100%	0%	100%	0%	0%
V18	59.1%	40.9%	0%	100%	0%	0%
V21	9.75%	83.8%	6.49%	57.4%	42.6%	0%
V22	86.8%	13.2%	0%	98.1%	1.87%	0%
V4	37.5%	38.5%	24%	50.9%	42.2%	6.94%
V7	31.8%	55.2%	31.8%	61.8%	38.2%	0%
V9	51%	48.5%	0.55%	74.3%	25.4%	0.27%
V10	100%	0%	0%	100%	0%	0%

7.2.2.6   Analyses summary

Some key insights and recommendations from the results:

- In a medium priority situation, the recommended combinations to achieve improvements in effort (up to 19%), cost (up to 18%) and process duration (up to 10%) are combinations 30, 38, 272, 280, 281 and 523. The combinations comprise expert preliminary designers, and mix of intermediate and expert for the other roles.

- In a medium priority situation, to maximise process duration (~10% compared to baseline) a mix of intermediate and expert designers seems more suitable (see breakdown in Table 20) due to low availability of experts.

- As expected, combinations with more novices show the best improvements in cost compared to baseline (up to 35%).

- The effort needed for experts to finish the process is considerable less than for intermediate or novices, with improvements up to 30%.

- HPC seems a crucial resource, with the use of high number of cores providing better performance.

- It is recommended to increase time dedication of expert designers as much as possible, with the possibility of reaching improvements of 45% in process duration for combination 2 and 30% for combination 1.

- Impact, mechanical and stress are highly involved in the process (Figure 70). Activities D1, D3, D5, D7, V14 and V19 are less resource sensitive and prospects to introduce new designers or novices to the process with low negative performance impact.

7.3   Turbines Sub-system

A second case study to apply the support method was conducted using the approach in Section 7.1[5]. The subject of the second case study is the Turbine Sub-system preliminary design process at Rolls-Royce plc.

7.3.1   Case study background and process description

The second case study is presented in Figure 72 and Figure 73 with the corresponding design resource types and instances. The process involved activities in cooling, stress, lifing, vibrations, weight and cost, which refine deliverables to output fuel burn, thrust, weight and cost, into a turbine geometry (2D-aerofoil of the turbine blade) for Central Division as part of the bid process. Again, descriptions and activity names were replaced by a code name. The characteristics of the process:

- In broad terms, the duration of the process can take several months;
- Resources comprise different types of designers (aerodynamic, blade, cooling, mechanical, stress and sub-system), with three options of each designer type;
- When an intermediate designer executes a task, an extra 15% of expert designer's effort is necessary to supervise the task. When a novice executes, an extra 30% of expert's effort is needed;
- Baseline scenario was the combination of using all *intermediate* designers.

The performance metrics used for this process and indicated as relevant by the design team are similar to the ones in the fan process: *process duration* (days), *effort* (person-days), *human cost* (unit-cost times effort), and *task time* (days). '*Time dedication*' for an expert designer ranges from 60% to 100% and decreases with expertise. '*Time*' of task completion ranges from two hours to one week depending on both task and designer's expertise. Similarly, '*iteration likelihood*' values range from 5% to 90%. Learning after iteration, which corresponds to '*learning curves*', ranges from zero to 20% also depending on designer and task. Finally, the priority of the project itself can affect process performance: it is assumed that medium priority is the default setting.

All possible resource combinations of the model were tested through Monte-Carlo simulation runs. The analyses discussed in the following sections used the mean of 2,000 simulation runs.

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[5] Steps 1-6 of the approach were conducted with Daniel Shapiro, another Ph.D. student at the EDC at the time, focused on developing a different design support method.
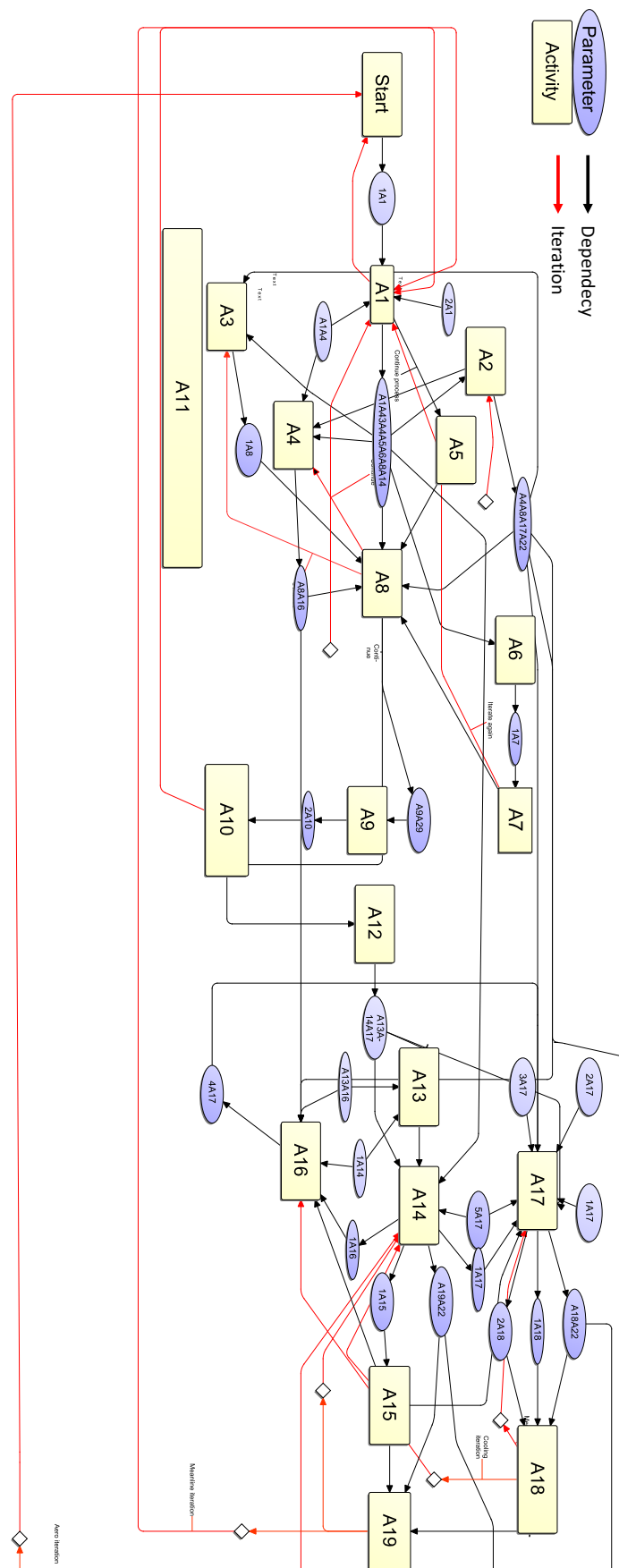
Figure 72. Process map of turbine preliminary design process (Part 1)
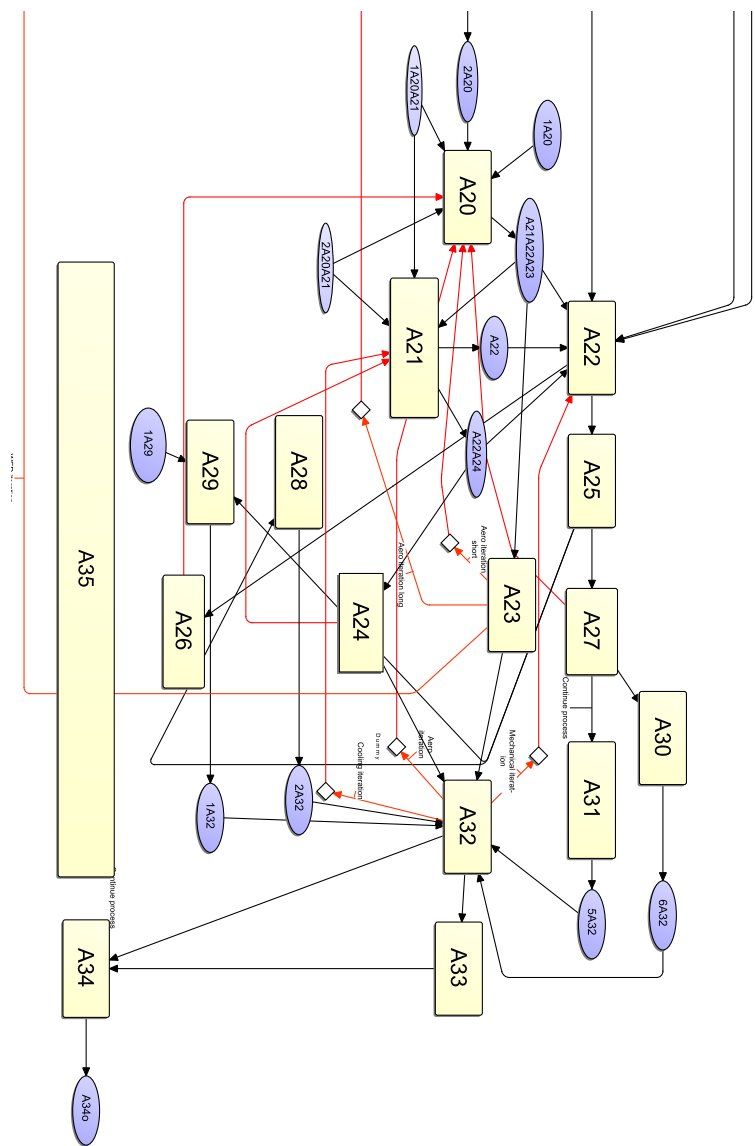
Resource	Instance options	Activities (Quantity)
Cooling		A8(1), A10(1), A19(1), A32(1), A34(1), A4(1), A16(1), A21(2), A24(1)
Sub-system		A8(1), A10(1), A19(1), A32(1), A34(1), A3(1), A9(1), A26(1), A28(1), A29(1)
Aerodynamic	1.Expert 2.Intermediate 3.Novice	A1(1), A8(1), A10(1), A12(1), A13(1), A14(1), A15(1), A20(1), A23(1), A33(1), A19(1), A32(1), A34(1)
Blade		A25(1)
Mechanical		A6(1), A7(1), A30(1), A2(1), A8(1), A17(1), A18(1), A31(1), A10(1), A19(1), A32(1), A34(1)
Stress		A27(2), A8(1),

Figure 73. Process map of turbine preliminary design process and designers' allocation (Part 2); descriptions of activities and parameters replaced with code names to maintain confidentiality

The preliminary turbine design process had a variety of different design resources compared to fan, and was also a good candidate for the application of the resource management approach. However, a second case study that included more design resource types (besides the six different designers) would have been ideal. This is typical of processes in the next stages of the engine design in Rolls-Royce plc. Nevertheless, given time constraints in finding case studies, and the interest within the organisation and design team, the turbine sub-system was presented as a feasible case study. However, due to special circumstances in the organisation, access to the team was rather more difficult during the last steps of the approach. Hence, sometimes it was necessary to estimate data collection values to be later verified by the team.

7.3.2 Analysis of results

As the fan case study, analyses are classified in five sub-sections: 1) Studying different resource combinations; 2) Resource utilization; 3) Identifying resource sensitive activities; 4) Studying the impact of different variables; and 5) Achieving specific performance.

7.3.2.1 Studying different resource combinations

Due to space considerations, the plots of all resource combinations are not included. However, the whole design space was simulated and results are available for designers in case any specific combination needs to be studied. This section includes: a table that filtered resource combinations that have relative improvements in all performance metrics (process duration, human effort, and cost); and three tables that present the best 10 resource combinations in terms of process duration, cost and effort respectively.

Table 27 shows resource combinations that have relative improvement in all performance metrics. The table includes designer type and instance of the combinations.

Table 27. Turbine: Resource combinations with improvements in cost, effort and time

	Resource type						% Improvement of cost	% Improvement of human effort	% Improvement of process duration
Combination	Aero	Blade	Cooling	Mech	Stress	Sub-system			
Baseline	I	I	I	I	I	I			
442	I	N	I	I	E	E	0.0%	0.4%	1.8%
206	E	E	I	I	N	I	0.3%	0.0%	8.5%
198	E	E	I	E	N	N	0.2%	1.1%	9.0%
135	E	I	I	N	N	N	0.9%	1.1%	4.1%

Summary of resource instance frequencies of the above combinations /o

Aero	Blade	Cooling	Mech	Stress	Sub-system
E: 75% I: 25%	E: 50% I: 25% N: 25%	I: 100%	E: 25% I: 50% N: 25%	E: 25% N: 75%	E: 25% I: 25% N: 50%

Only four combinations showed improvements compared to the baseline for all performance metrics. This gives a sign of the heavy trade-off situation between the metrics. Resource frequencies of the combinations are summarised at the bottom of Table 27.

Table 28 includes the best 10 resource combinations that have relative improvement in process duration compared to baseline and resource frequencies of the combinations are summarised at the bottom.

Table 28. Turbine: Best 16 resource combinations with improvement in process duration

| Combination | Resource type | | | | | Sub-system | % Improvement of cost | % Improvement of human effort | % Improvement of process duration |
	Aero	Blade	Cooling	Mech	Stress				
Baseline	I	I	I	I	I	I			
82	E	I	E	E	E	E	-16%	30%	22%
163	E	N	E	E	E	E	-13%	26%	22%
1	E	E	E	E	E	E	-19%	34%	22%
88	E	I	E	E	N	E	-13%	24%	21%
2	E	E	E	E	E	I	-17%	33%	21%
7	E	E	E	E	N	E	-15%	28%	21%
166	E	N	E	E	I	E	-12%	22%	21%
164	E	N	E	E	E	I	-12%	24%	21%
4	E	E	E	E	I	E	-17%	31%	21%
83	E	I	E	E	E	I	-15%	28%	21%

Summary of resource instance frequencies of the above combinations

Aero	Blade	Cooling	Mech	Stress	Sub-system
E: 100%	E: 40% I: 30% N: 30%	E: 100%	E: 100%	E: 60% I: 20% N: 20%	E: 70% I: 30%

It seems that experts in aerodynamic designers, cooling and mechanical roles are key for a fast process: an improvement between 21%-22% can be achieved compared to baseline. However, the trade-off in cost seems to be between 12%-19% decrease in performance.

Table 29 includes the best 10 resource combinations that have relative improvement in cost against baseline and summarise the frequency of resource instances.

Table 29. Turbine: Best 16 resource combinations with improvement in cost

| Combination | Resource type | | | | | Sub-system | % Improvement of cost | % Improvement of human effort | % Improvement of process duration |
	Aero	Blade	Cooling	Mech	Stress				
Baseline	I	I	I	I	I	I			
729	N	N	N	N	N	N	20%	-38%	-35%
728	N	N	N	N	N	I	19%	-36%	-33%
720	N	N	N	I	N	N	19%	-35%	-32%
727	N	N	N	N	N	E	18%	-34%	-32%
719	N	N	N	I	N	I	18%	-33%	-29%
648	N	I	N	N	N	N	18%	-33%	-34%
726	N	N	N	N	I	N	18%	-35%	-35%
725	N	N	N	N	I	I	17%	-33%	-32%
723	N	N	N	N	E	N	17%	-31%	-34%
711	N	N	N	E	N	N	17%	-33%	-30%

Summary of resource instance frequencies of the above combinations					
Aero	Blade	Cooling	Mech	Stress	Sub-system
E: 100%	I: 10% N: 90%	N: 100%	E: 10% I: 20% N: 70%	E: 10% I: 20% N: 70%	E: 10% I: 30% N: 60%

Improvements in cost of 17%-20% are conditioned with a decrease in effort and duration performance of around 30%. The combinations mainly feature novices in key roles such as aerodynamics, cooling, blade and mechanical designer.

Table 30 shows the best 10 resource combinations with relative improvement in effort against baseline and summarises the frequency of different instances. The combinations with more experts, especially in aerodynamics, blade, stress, and cooling roles can provide 29% of effort improvement. Process duration improvement is also present, but a decrease in cost performance of between 15%- 19% is the trade-off.

Table 30. Turbine: Best 16 resource combinations that have relative improvement in human effort against baseline

	Resource type						% Improvement of cost	% Improvement of human effort	% Improvement of process duration
Combination	Aero	Blade	Cooling	Mech	Stress	Sub-system			
Baseline	I	I	I	I	I	I			
1	E	E	E	E	E	E	-19%	34%	22%
2	E	E	E	E	E	I	-17%	33%	21%
10	E	E	E	I	E	E	-16%	32%	21%
4	E	E	E	E	I	E	-17%	31%	21%
3	E	E	E	E	E	N	-16%	31%	19%
11	E	E	E	I	E	I	-15%	30%	20%
82	E	I	E	E	E	E	-16%	30%	22%
19	E	E	E	N	E	E	-15%	30%	17%
5	E	E	E	E	I	I	-16%	29%	20%
13	E	E	E	I	I	E	-15%	29%	20%

Summary of resource instance frequencies of the above combinations					
Aero	Blade	Cooling	Mech	Stress	Sub-system
E: 100%	E: 90% I: 10%	E: 100%	E: 60% I: 30% N: 10%	E: 70% I: 30%	E: 60% I: 30% N: 10%

To conclude resource combination analysis, Table 31 compares the performance improvements between key combinations.

Table 31. Turbine: Comparison of performance improvements between key combinations

Key combinations and improvement over baseline

		Resource type						Cost	Human effort	Process duration
	Combination	Aero	Blade	Cooling	Mech	Stress	Sub-system			
	Baseline	I	I	I	I	I	I	-	-	-
All experts/Best duration	1	E	E	E	E	E	E	-19%	30%	22%
All novices/Best cost	729	N	N	N	N	N	N	20%	-38%	-35%
Overall improvement	198	E	E	I	E	N	N	0.2%	1.1%	9.0%
Best human effort	82	E	I	E	E	E	E	-16%	30%	22%

Difference between the combinations (first column minus top row) divided by baseline

<div style="display:flex">

Cost difference

	Baseline	1	729	198	82
Baseline					
1	19%				
729	-20%	-39%			
198	0%	-19%	20%		
82	16%	-3%	36%	16%	

Effort difference

	Baseline	1	729	198	82
Baseline					
1	-34%				
729	38%	72%			
198	-1%	33%	-39%		
82	-30%	4%	-68%	-29%	

</div>

Process duration difference

	Baseline	1	729	198	82
Baseline					
1	-22%				
729	35%	57%			
198	-9%	13%	-44%		
82	-22%	0%	-57%	-13%	

🟥 Significant increase (negative performance)
🟩 Significant decrease (positive performance)

7.3.2.2   Resource utilisation

Figure 74 assesses the amount of involvement of the different type of resources in the key combinations that have been investigated.
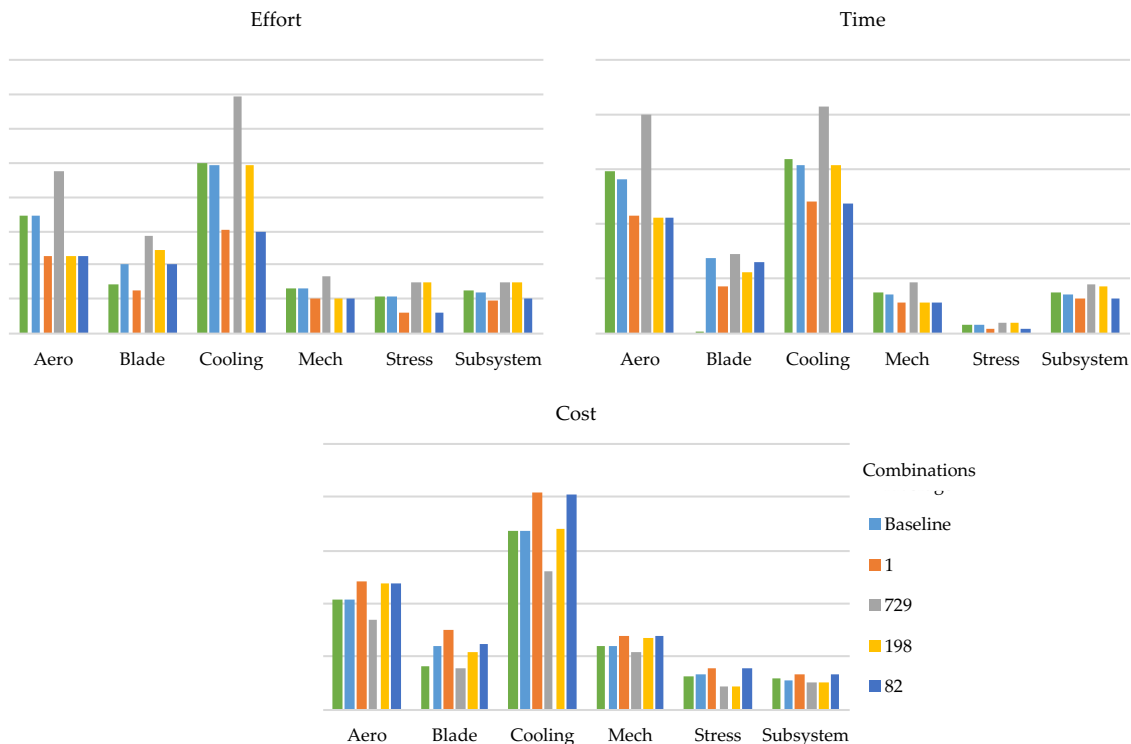
Figure 74. Turbine: Resource utilisation for some selected combinations in terms of process duration, effort and cost. Values are not shown due to confidentiality

As expected, it shows that aerodynamics and cooling designers have high involvement during the process. This is followed by mechanical and blade, that also exhibit a larger

performance difference depending on the instance. Similarly, to the first case study, due to confidentiality the exact values are not included.

7.3.2.3 Identifying resource sensitive activities

Figure 75 shows all possible 729 resource combinations plotted with process activity in *x*-axis and task duration in *y*-axis. Resource sensitive tasks can be identified in this figure by virtue of their distinctive performances depending on different resource combinations, indicating increased susceptibility to resource changes.
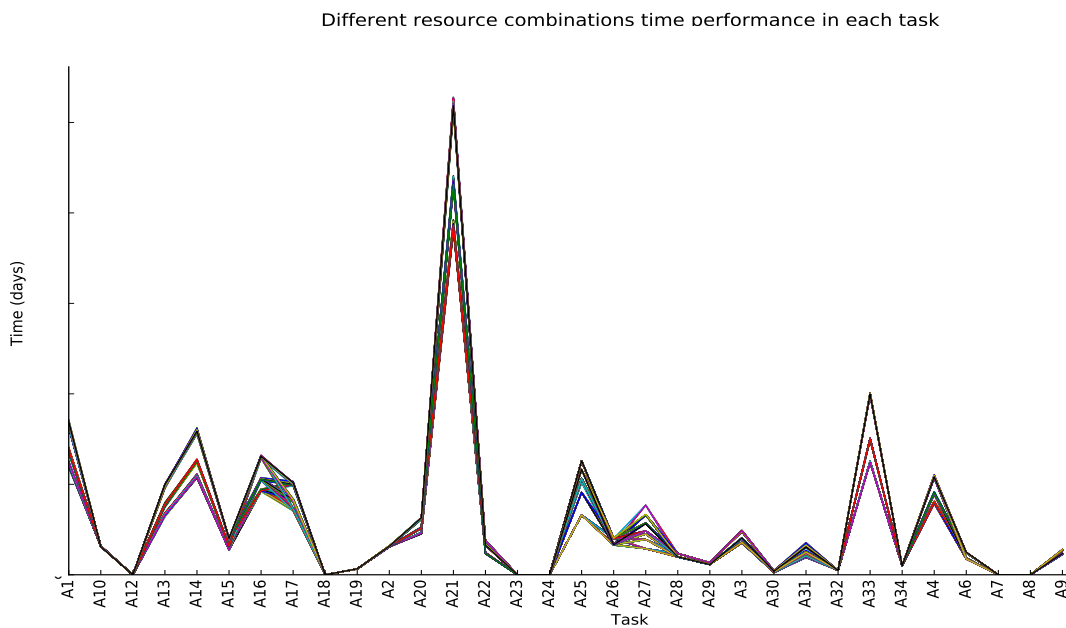
Figure 75. Turbine: Task time of different resource combinations. Values are not shown due to confidentiality

A21 is one of the main generation activities performed by two cooling engineers. The possible iteration of A21 yields in the activity having a relative higher duration compared to other tasks. Activities A1, A13, A14, A16, A21, A25, A27 A33, and A4 are more sensitive to a resource change. To a lesser degree activities A15, A20, A22, A3 and A31 are somehow sensitive to a resource instance change. Finally, activities A2, A10, A17, A18, A19, A26, A28, A29, A30, A32, A34, A6 and A9 are less sensitive. Certain activities such as A12, A23, A24, A7 and A8 were verification activities performed either by a single designer or the whole team on an on-going basis during the process and did have a specific time associated. In a similar manner A10, A19, A32 and A34 were team decision activities with time associated. Excluding these activities, it leaves A2, A18, A26, A28, A29, A30, A6 and A9 as potential activities that are less sensitive to resource changes.

7.3.2.4 Studying the impact of different variables

The section analyses the effects that changing project priority have on process performance. The new simulated scenario with high project priority was compared with the medium project priority scenario. High priority situations require designers to have full time dedication on the current project, as opposed to medium or low priority, in which designers could be working on other projects. The analysis investigates the performance difference between the high and medium project priority scenarios. Table 32shows the performance difference for some selected combinations.

Table 32. Turbine: Impact of changing project priority, medium vs high

	Combination	Aero	Blade	Cooling	Mech	Stress	Sub-system	Process duration difference in %
	Baseline	I	I	I	I	I	I	
All experts/Best duration	1	E	E	E	E	E	E	-55%
All novices/Best cost	729	N	N	N	N	N	N	-29%
Overall improvement	198	E	E	I	E	N	N	-37%
Best human effort	82	E	I	E	E	E	E	-55%
Biggest difference in process duration	163	E	N	E	E	E	E	-55%

The difference between cost and effort is similar, hence not included in the table. The most significant improvements of around 55% are given by combinations 1, 82 and 163, which comprise mostly expert designers.

7.3.2.5 Achieving specific performance

The most resource sensitive activities were selected and a limit for task duration and/or cost were imposed on them to diagnose, using BN capabilities (inference), which resource and project priority has a bigger probability to attain the desired performance.

Table 33. Turbine: Setting performance aims to diagnose the impact on the probability of reaching it by resource instances and project priority

Activity	Resource instance probability to reach desired performance			Project priority probability to reach desired performance		
	Expert	Intermediate	Novice	High	Medium	Low
A1	78.5%	20.5%	1%	83.2%	16.7%	0.69%
A13	100%	0%	0%	100%	0%	0%
A14	100%	0%	0%	100%	0%	0%
A16	32%	37.3%	30.7%	35.3%	64.7%	0%
A21	88.8%	11.2%	0%	98%	2%	0%
A25	97.6%	2.41%	0%	100%	0%	0%
A27	82.8%	16.7%	0.5%	86.7%	13.3%	0%
A33	77.7%	22.3%	0%	91.1%	8.87%	0%
A4	94.6%	5.4%	0%	100%	0%	0%

The results show that attaining those performances can sometimes depend on the possibility of incorporating a specific designer. For example, A13 and A4 require expert designers in a high priority situation. Key resources might have to scheduled first to these tasks to achieve the desired performance. Other tasks are more flexible, such as A16, in terms of designer and priority.

7.3.2.6   Analyses summary

Some key insights and recommendations from the results:

- In a medium priority situation, the recommended combinations to achieve improvements in effort (up to 1.1%), cost (up to 0.9%) and process duration (up to 9%) are combinations 442, 206, 198 and 135. The combinations comprise expert aerodynamic designers; intermediate for cooling; and mix of intermediates, novices and experts for the other roles.

- In a medium priority situation, to maximise process duration (up to 22% compared to baseline) expert designers, especially in the roles of aerodynamics, cooling and mechanical seems more suitable (see breakdown in Table 30).

- A very similar situation is necessary to improve effort (up to 34%), with aerodynamics, blade and cooling designers heavily inclined to be performed by experts.

- As expected, combinations with more novices show the best improvements in cost compared to baseline (up to 20%).

- It is recommended to increase time dedication (a form of availability) of expert as much as possible with the possibility of reaching improvements of 55% for combinations 1, 82 and 163.

- Aerodynamic and cooling designers have high involvement in the process, followed by blade and mechanical.

- Activities A2, A18, A25, A26, A27, A28, A29, A30, A6 and A9 are less resource sensitive and can be prospects to introduce new designers or novices to the process with low negative performance impact.

7.4   Discussion of accuracy of results

This section examines the accuracy of the analysis results in the fan and the turbine case studies by discussing: 1) the appropriate construction of the model; and 2) the statistical error of the Monte-Carlo simulations. The implications of the results for industry is discussed in Section 8.1.4.

The appropriate construction of the model involves: the accuracy of the collected data, the correct functioning of the implemented tool, the actual modelling and plausibility of

the results. The process map verification, step 3, was verified with the design team. Furthermore, the team's experience and expertise in their design process minimises the risk of having the wrong process structure and path logic. Furthermore, verification discussions reached team consensus, which increases objectivity. Similarly, during data collection in steps (4 and 7), experts or owners of each specific part of the process populated the spreadsheet. Whenever it was possible, more than one designer was present to increase confidence on the collected data. The correct functioning of the implemented tool was studied during its implementation, in which the new functionalities were tested with simple models to examine that the model behaved correctly. The simple models increase their complexity until the author determine that the tool enhancement was fit for its purpose. The actual modelling and plausibility of results were examined in two steps, 6 and 9. Step 6 involved verifying the plausibility of the results from the ASM model. The established status of the ASM framework combined with the consensus of the whole team in terms of assessing the results confirmed the appropriate construction of the model until this point. This culminates in step 9 in which the results of final support method were verified: the plausibility of results was positively assessed by designers in the team. The Fan Sub-system followed all the mentioned steps. However, given unforeseen circumstances in Rolls-Royce plc and time constraints imposed on the design team, the Turbines case study was only able to initially perform step 9, a situation that the author could not control.

The second component of examining the accuracy of results concerns with statistical error in the simulations. An aspect of this is related to the probabilistic nature of the underlying process models, which were populated with values that are not deterministic, different possible paths, iterations, etc. The other aspect is the nature of Monte-Carlo simulations. During the building of the model, test runs suggested that results stabilised after 500 runs. However, both case studies were simulated with 2,000 runs in all the different combinations (729 in both cases) and each scenario. The simulation errors were: in the fan case study, the 95% confidence intervals were less than $\pm5\%$ /$\pm6\%$ around the average effort and process duration simulation results for the combinations checked (confidence intervals are wider for cost values since they have a bigger range). In the turbine case study, the 95% confidence intervals range less than $\pm3\%$ /$\pm4\%$ around the average simulation results for effort and process duration for the combinations checked. They seem reasonable given the range of results. These statistical errors can be decreased as the number of simulation runs are increased.

As acknowledged by other authors such as Shapiro (2017) and Hamraz (2013), the accuracy of design process results can seldom be objectively evaluated in its entirety. However, the building of the model and final results should provide enough insights to the design team. Hence they were useful and adequate for design practice.

7.5 Summary

The current chapter addressed **RQ6:** *How can the model be used in an approach for resource management to improve design process planning?* It also provided a basis for **RQ7:** *How useful and usable is the developed resource management approach in industrial applications?* which is addressed in the next chapter.

The main contribution of the thesis is presented as an approach that has three sections: *Understanding the investigated organisation*; *Application and analyses of the support method*; and *Implementation of the resulting insights.* The approach is divided in nine steps: understand the process, understand design resources, verify the design process map, collect process data, build ASM model and simulate, present results to design team, collect resource data, apply support method and simulate, and present final results to design team.

The approach was applied on two case studies in Rolls-Royce plc to extract significant insights for decision making in terms of resource management. Analyses included: 1) Studying different resource combinations; 2) Resource utilization; 3) Identifying resource sensitive activities; 4) Studying the impact of different variables; and 5) Achieving specific performance. Each cases study introduced the pertinent description of the process and its characteristics. Then results were presented and summarised at the end of case study. The chapter is part of Descriptive Study II from the DRM, the followed methodology.

8 Discussion and evaluation

In this thesis, the role of design resources has been investigated from both a theoretical (Chapter 2) and empirical perspective (Chapter 4). The key factor was identified as managing design resources to determine effective resource combinations given, for example, trade-offs between availability and efficiency attributes. Requirements emerged from the gained understanding from project stakeholders to guide the development of a support method that can aid in this endeavour (Chapter 5). These requirements are related to modelling the design process, modelling resources and attributes, and implementation of analysis. Following the requirements, a support method (model) was conceived and refined in Chapter 6. The model was embedded in an approach that was applied to two case studies from Rolls-Royce plc (Chapter 7), which are the basis for evaluation in this chapter. Thus, the research undergoes an initial evaluation as part of DS-II to address **RQ7:** *How useful and usable is the developed resource management approach in industrial applications?*

The current chapter reviews the implications of the research, evaluates the project, and discusses research limitations and future work. The thesis is discussed as a whole in Section 8.1 to relate key findings with the overall research context and results. This includes the importance of design resources, understanding of design resources and attributes, impact of the appropriate resource instances on process performance and implications for industry and research community. Section 8.2 evaluates the work in three sub-sections: support evaluation, application evaluation and success evaluation. Section 8.3 discusses the limitations of the current research, while Section 8.4 presents opportunities for further research. Finally, Section 8.5 summarises the chapter.

8.1   Discussion of the research

This thesis started with the overarching research question of - *How can resource management be utilised to improve planning and execution of complex design processes?* that motivated investigations in literature review (Chapter 1 and 2). In addition, a hypothesis was introduced: *An efficient approach (support method) will provide insights on resource management for decision making.*

Consequently, the results of the literature review shaped the underlining statements that guided the research:

- Resource management is a key factor to improve design processes;
- Current support methods could be enhanced with different resource types and instances to provide managerial insights;
- Design resources must be further studied in order to provide concise information on how to abstract them.

A comprehensive Descriptive Study was necessary to understand the current situation. Therefore, an exploratory case study in Roll-Royce plc was carried out to investigate and characterised design resources, in addition to their management and attributes. Empirical investigations in Chapter 4 supported literature findings and consolidated a list of resource types and attributes. It also confirmed the value of support methods that can provide detailed resource management insights for process planning and execution. Furthermore, both literature and empirical investigations provided pragmatic targets in the form of functional requirements to develop the support.

Therefore, this research was set to attain the overall goal by investigating, developing, and refining the needed support method in Chapters 5 and 6. The final model was embedded in an approach that provided a step-by-step procedure for its application (Chapter 7). The approach was based on the author's experience during his research and examples of previous work that involved developing modelling approaches (Wynn 2007; Hamraz 2013) or applying them (Kerley *et. al* 2011).

Before the research is evaluated, the next sub-sections discuss different aspects of this thesis. Firstly, the importance of design resources as a topic of investigation. Secondly, the process of improving the knowledge about design resources and attributes. Thirdly, the exploration of the impact of appropriate resource instances on design processes. Finally, implications for industry and research community were outlined.

8.1.1   The importance of design resources

On the outset of this research, during Chapter 1, the role of resources in the organisation and particularly in design processes was defined. The results characterised design resources by virtue of:

- Resources are required to undertake the design process;
- Resources are limited and their effectiveness impact process performance;
- Planning resource utilisation is complex due to the multiple types of resources (i.e., human designers, effort, simulation engines, etc.) and their attributes.

The inherent complexity and uncertainty of design processes led to believe that resource management (estimating, allocation and scheduling design resources) was a key concern for organisations (Section 1.2.4). Chapter 1 also concluded that different methods could be feasible and effective in supporting resource management. Therefore, Chapter 2 investigated these approaches and identified that design process modelling fits the intended goal of this research, proving detail day-to-day insights for decision making.

Discussions in the initial chapters of the thesis (Chapters 1, 2 and 4) confirmed the importance of designers as primary drivers of design processes. Yet, it also greatly emphasised the important role of other key resources such as computational, prototyping and testing. The need of accounting for all key design resources could enhance the usefulness of resource management approaches. Both literature review and empirical studies characterised attributes of these resources that influences the outcome of process performance. However, few approaches were able to capture that the influence on performance could greatly differ depending on the resource instance chosen. The impact of design resources and attributes exhibit a trade-off behaviour on performance due to the different availability and effectiveness of their instances. This adds to the inherent complexity of design processes. Hence, the topic of managing design resources, which could have seen as a simple endeavour, is not trivial.

8.1.2   Understanding design resources and attributes

This thesis includes a comprehensive DS-I, hence an empirical study in Chapter 4 was used to complement literature investigations. The primary purpose was to further understand design resources and attributes beyond the investigated literature. The exploratory case study was able to extend the knowledge gained regarding design resources (as studied by different approaches) and provided with a characterisation that consolidated all previous findings: key design resources can be classified as, but not limited to, human designers, computational resources, prototyping and testing resources. Equally, resource attributes were also characterised and extended during the empirical study.

The final resource attribute list elicited during the empirical study also englobed the attributes found in literature. The underlining role of design resources in the process and the significance of their attributes were analysed to develop requirements to distinguish them in Section 4.4.2. The primary requirement refers to whether the resource is necessary to the design process, *'required to deliver the design'*, and sub-requirements regarding its *'availability'* and *'impact'*: 1) *They have availability*; and 2) *Their effectiveness impact process performance metrics*.

The aforementioned design resources and attributes list was intended to be as exhaustive as possible, providing high level and general descriptions of both. However, the author acknowledges that other organisations could have a different characterisation that fits their purpose better, or display more types of design resources. Therefore, the requirements to identify design resources can act as a guideline for modellers in other organisations and situations. Towards the same purpose, the first stage of the approach in Section 7.1.1, *understanding the investigated organisation*, reiterates to the prospect modeller the key role of fully comprehending the resources to be modelled.

There is an unavoidable degree of subjectivity in characterising and abstracting the investigated subject. However, the author intended to keep this at minimum by presenting the rationale from literature and empirical study to thesis supervisor, academics, and industrial designers from the investigated organisation. In addition, the approach ensures that each modeller will examine the resources and attributes of the processes to be modelled.

8.1.3   Impact of the appropriate resource instance on design processes

The importance and key aspects of resource management was explored in Chapters 1 and 2. The previous sections have discussed the value of a support method that can study the impact of different resource instances on performance. The goal is to explore appropriate resource combinations for the process. However, before this can be abstracted into a model, the actual behaviour of different types of design resources had to be investigated. This was done through empirical investigations in Chapter 4 that presented the interrelationships between resource attributes and task characteristics. They were later abstracted into variables that comprised mathematical functions in Chapter 5, and refined in Chapter 6.

As acknowledged by designers during empirical studies, different instances can have distinctive impact on process performance. This confirmed the potential benefit of testing different resource instances and extracting insights from analyses. In Chapter 5, the development of the support method was guided by functional requirements in three

areas: design process modelling, resource modelling requirements and resource management analyses. The functional requirements were extracted from Chapters 1, 2 and 4. They were systematically addressed during the development of the support method, which was completed in Chapter 6. The final approach, which the model is part of, was developed to examine the impact of appropriate resource combinations on design processes. The approach was able to:

- Increase understanding of different resource types of and their attributes that define effectiveness in process performance;
- Quantify the trade-off of using alternative resource instances on activity and process performance;
- Increase understanding of the impact of resource attributes in process performance;
- Contributing to develop and improve process plans by estimating resource needs, allocating and scheduling resources.

The approach was applied to two case studies from Rolls-Royce plc as part of DS-II of the DRM methodology. The outcome of the application serves as evaluation, presented in Section 8.2.

8.1.4   Implications for industry

The study of the impact of design resources in the process has some important contributions to industry stakeholders. The results are able to quantify the performance output of different resource instances. Subsequently, it prescribes the combinations that can provide an improvement in one or more performance metrics. Achieving overall improvement is not trivial due to the trade-off behaviour between the metrics. There are several positive implications for industry.

- In the presence of different resource instance options, the results help managers to select appropriate resources;
- The analysis can increase visibility on the possible performance increase that can be achieved;
- If objectives were set, results can indicate if they are plausible to attain;
- Stakeholders can identify key activities, the ones that are more resource sensitive that need more attention and the ones that are less sensitive that can be candidates to introduce new designers;
- Results can show which key resources are needed, recommending increase their availability, acquiring more or training the required skills;

- The diagnosis capabilities of the approach enable to assess the impact of different activity characteristics or resource attributes. In this manner, the drivers of the process can be identified.

For example, in the case studies, the high implication of experts in different projects for the organisation could sometimes mean that even though they need less effort to perform activities, the duration could still be significant. Then the approach diagnosed, for key activities, the right level of project priority and expertise to offset low availability. Another possible solution was to acquire or train designers in the needed skills. To conclude, a large number of *'what-if'* analyses can be performed by decision makers to aid decision making in different situations.

8.1.5   Implications for research community

The importance of design resources has been acknowledged by the research community. Much of this is represented with work in process models and theoretical studies regarding designers (Chapter 2). However, a large amount of work is being focused on other aspects of the process such as process architecture or the study of iterations (e.g., Ahmadi *et al.* 2001; Browning and Eppinger 2002; Yassine *et al.* 2003; Smith and Eppinger 1997a, 1997b; Ko *et al.* 2010). Holding these elements constant and perturbing the different aspects related to design resources have been somehow overlooked. This research hopes to bring some light on the possibilities and stimulate further research in this front. The 'ad-hoc' modelling of process performance and resources attributes is not limited to the analyses presented in this thesis, there is an opportunity for more *'what-if'* situations to be studied with BN capabilities.

Furthermore, the importance of other design resources besides designers, often not properly characterised, has also been highlighted. Their influence on completing design processes seems critical and further study is an opportunity for the design research community. Chapter 2 identified that these resources (computational, prototyping and testing) have not been fully addressed by previous work. Thus, this thesis is biased towards studying the impact of instances of these resources on process performance. The next natural step is to take a more holistic view looking into extending the approach to study variations of task sequencing, the impact of socio-technical attributes, how to improve communication, etc.

Finally, the use of BN for design research has also been a feature in this thesis. Modelling BNs in tasks to better understand the complex relationships of resources can be applied

to modelling frameworks to study (and diagnose) other design characteristics. In summary, the advantages of the method can be further applied in the field. More detail on opportunities for further research is presented in Section 8.4.

8.2 Evaluation of the research

Overall, this research complemented literature review with empirical investigations during the Descriptive Study phase. The combination of inputs from existing literature with findings from industry provides a basis on the validity of the classification of resources and attributes, the foundation of the Prescriptive Study support method. The importance of validation roots on that results can only be assumed during development of the method (DRM).

The approach developed was applied to two case studies to extract insights for process improvement. The section aims to demonstrate that the case studies' results provide an initial evaluation for this research, indicating that the approach is suited to model design resources and prescribe insights that might be of value for decision makers. A comprehensive evaluation would need to extend the application of the approach by independent modellers to multiple organisations across different industries. DRM (Blessing and Chakrabarti 2009) acknowledges that evaluating the support is difficult because design processes take longer than the duration of Ph.D. projects. Sometimes the implemented insights only emerge in a few years. DRM recognises that ideal evaluation is often not possible for Ph.D. projects due to limitations such as time, repeatability and access constraints. Nevertheless, an initial evaluation can provide some validity to the approach. According to the DRM, three evaluation types can be conducted:

1. The *support evaluation* involves verification, assessing that the support method fulfils its requirements;
2. The *application evaluation* assesses the support in terms of applicability and usefulness in addressing the key factors;
3. The *success evaluation* validates the usefulness of support in achieving the stated goals.

The next sub-sections assess the method in the terms of support, application and success evaluation.

8.2.1 Support evaluation

Support evaluation is a pre-requisite for the next two types of evaluation and should start during PS. The author conducted support evaluation as a continuous assessment

and refinement of the correct functionalities of the method during the development phase. Support evaluation ensures that the resulting support method addresses all the requirements. It also reviews the research as a whole at the academic and industrial level. The elements of this evaluation involved:

- Testing during development: The proper functioning of the developed features for the support was constantly tested as explained in Section 7.4. During implementation, the new functionalities were tested individually and in conjunction with a predictable simple model. Chapters 5 and 6, in which the prototype model evolved to the final support, exemplify how functional requirements were assessed on an on-going basis to refine the method. Chapter 5 presented a prototype model that was enhanced in Chapter 6 to address all the functional requirements (see discussion in Section 6.1.1) and incorporate the feedback from academic and industrial review.

- Academic review: Internal academic reviews consisted on regular discussions regarding the research, theory, method development, refinement and application, with thesis supervisor. Formal stage reviews were present in the form of examinations at the end of the first and second year of the Ph.D. External academic reviews included informal discussions with other members of the research community during workshops and conferences. The presented concepts resonated with their understanding of design resources. In addition, the results from literature investigations and empirical studies, the foundation of the support, were published in Xin Chen *et al.* (2014). The detailed method and prototype model was published in Xin Chen *et al.* (2015), and the final support method in Xin Chen *et al.* (2016).

- Industrial review: Continuous interactions with industry collaborator encompassed quarterly reviews, in which the method concept, the detailed method and its application results were discussed. In addition, the same discussion took place with different design teams involved in the research from the empirical study in Chapter 4 to the application of the method in Chapter 7. Finally, all the published work was submitted for review in Rolls-Royce plc. The support method paper was presented by a designer in the organisation to his colleagues given the interest generated in the work.

Overall support evaluation was positive based on the positive feedback from academic and industrial review, and correct functioning of the method.

8.2.2   Application evaluation

Similarly, application evaluation is necessary before any success evaluation can be conducted. Application evaluation was mainly assessed through successfully applying the support method to two case studies (Chapter 7). The aim of the evaluation consists on assessing the applicability and usability of the intended support to produce managerial insights on resource management, covering the general requirements set in Chapter 5.

The method was first applied in a simplification of one of the case studies, fan sub-system. Making it a simple model ideal to initially assess method applicability and usefulness of the possible analyses. The same model was constructed with ASM and compared with the prototype model (Chapter 5), and then the new support method. The assessment of its usefulness was done by comparing the enhanced number of analyses that were possible with the prototype model, and in a larger degree the final support. These analyses were presented to the industrial organisation to confirm their practical usefulness. Subsequently, the support was applied on the two larger case studies. As aforementioned, an ideal evaluation involves applying the method to two processes in different industries. However, given the project set-up with the industry collaborator and sponsor, both case studies were carried out in the same organisation. Nevertheless, the case studies have some core differences: they were carried out in two different sub-systems with different teams, they focused on different engines, they were conducted in two different cities, and they displayed different resources and iteration complexity.

Regarding the models' usability, related to GR1-Ease of application, it can be argued that a certain face validity is given since the model was developed by extending existing tools, ASM and Netica. Cambridge Advanced Modeller (CAM), which is the software used to model ASM, has been extensively validated by Wynn (2007), where the efforts of two Ph.D. students using CAM were thoroughly recorded. Furthermore, CAM is a recognised academic research tool that have been used as part of other research work (Wynn *et al.* 2014; Shapiro *et al.* 2016). Netica's usability has also been proven due to its commercial software status.

Usability of the current approach can be also studied through the effort taken to apply it. In terms of the modelling, the effort was approximately a week for each case study. This can vary with the modeller's experience with the method. The previous steps in the approach, such as the data collection with spreadsheets involved around four to six engineers in two workshops of approximately half a day to one day. The first steps are the ones that can greatly vary depending on the existing information or data regarding the process map, the granularity chosen or the complexity of the process amongst other factors. The value gained from the application of the process should outweigh the potential effort invested. Most of the effort is related to the understanding of the organisation and

process. Thus, if the modeller was part of the organisation and owner of the process, the potential effort greatly diminishes. Nevertheless, the prospective benefits from applying the whole approach not only lies on the application of the model, as argued in the next section, but also on the understanding that designers gained from the first steps. Finally, the processes in evolutionary design are likely to be executed repeatedly with some changes for different design projects. If these changes are not major, such as process restructuring because new methods or tools are introduced, the process models are likely to be re-used with new data. Hence the author argues that GR2- Effort needed was also fulfilled successfully.

The results obtained from the models were of enough quality to produce detail managerial insights, as shown in the case studies in Chapter 7, initially covering GR3-Accuracy of results in terms of producing insights. There were also presented in an actionable manner to provide a positive impact on performance, thus fulfilling GR4-Comprehensibility of results. Nevertheless, more case studies should be conducted to provide a deeper assessment of the general requirements.

To conclude, the method's application evaluation can be judged as positive, an initial validation of the approach.

8.2.3   Success evaluation

This section assesses the usefulness of the approach in improving the specified measurable success factors (time, effort and cost). For a comprehensive success evaluation, ideally the approach has to be applied to a process, analysis from results devised and insights implemented. The subsequent process improvement should be measurable and compared with the existing situation. DRM describes the whole process to be challenging due to the extended time of complex industrial projects, the ambiguity in comparing the outcome situation against a past one, amongst other factors. Alternatively, an initial success evaluation was applied, which is intended to assess the success of the approach by examining plausibility of the results and functional usefulness. This is a method often conducted by other researchers in the field (Shapiro 2017; Hamraz 2013) for initial success evaluation. The current research had the overall goal of improving resource management in design processes by:

- Increasing understanding of different type of design resources and their attributes that define effectiveness in process performance: During the application of the approach, the understanding of design resources and its implication on process performance was greatly enhanced. Chapter 2 studied design resources from

an academic perspective through approaches used to managed them and Chapter 4 increased understanding of different types of resource and their attributes empirically.

- Quantifying the trade-off impact of using alternative resource instances on activity and process performance: The application of the approach enabled a series of analyses that quantify the performance of different resource combinations taking into account their trade-offs. The approach was successful in: 1) Studying different resource combinations in Section 7.2.2.1 for fan and Section 7.3.2.1 for turbine; 2) Specifying resource utilisation in terms of performance in Section 7.2.2.2 for fan and Section 7.3.2.2 for turbine; 3) Identifying resource sensitive activities in Section 7.2.2.3 for fan and Section 7.3.2.3 for turbine.

- Increasing understanding of the impact of different variables and resources attributes in process performance: The approach enabled the study of the impact of variables at various levels of granularity by setting up different scenarios or using the diagnosis capabilities of the approach (which is provided by BN model). Successful examples are: 1) Assessing the impact of different variables such as project priority in Section 7.2.2.4 for fan and Section 7.3.2.4 for turbine; 2) Specifying different performance aims for key activities to diagnose the impact on project priority and the feasibility of resource instances to achieve the performance objectives in Section 7.2.2.5 for fan and Section 7.3.2.5 for turbine.

- Contributing to develop and improve process plans by estimating resource needs, allocating and scheduling resources: The results were summarised into actionable managerial insights with the aim of reducing effort, cost and duration during process planning and execution. The insights were presented in Section 7.2.2.6 for fan and Section 7.3.2.6 for turbine.

The analysis results from the fan case study were discussed with the lead engineer that deemed them as plausible and interesting: "*It seems to make sense – it is all a question of balancing the use of expert resource which is generally of low availability and higher cost against plentiful novice resource*". The insights from the analyses to improve process performance were based on the numerical quantification of the trade-offs of using different resources instances, as intended by the stated goals. The engineer from the team commented on the insights and the possible implementation to help decision making: *"I find slides 16-18 (feasible resource combinations depending on trade-offs) interesting. It tells you how to use your resource if you want to focus on reducing overall elapsed time, human cost or human effort"*.

In addition, there are some benefits from applying the approach beyond the extraction of insights from simulations. The steps taken to understand and verify the process, understand resources and their relationships, and collecting the relevant data also served

to improve planning visibility. It developed a common understanding for designers in the team that were not used to participating in design planning. The improved visibility was acknowledged by designers during the case studies and can potentially enhance communication and collaboration between designers. It is also noteworthy that during interviews and workshops designers sometimes engaged in discussions to deepen their knowledge of the technical implications of each other's work.

The initial evaluation demonstrated that the approach has practical usefulness in providing insights for managerial decision making. This confirms the initial hypothesis, concluding the initial validation.

The approach has been initially assessed in terms of support, application and success with the conclusion that it fulfils the stated requirements, it is applicable to industry and the insights are useful for process planning and execution.

8.3   Research limitations

The section discusses the methodological, model, implementation, case studies and success evaluation limitations:

- Methodological: Epistemologically the current research falls into the realist paradigm, in which the author has tried to capture the reality as objectively as possible but acknowledges that is not entirely possible. Hence, there is some unavoidable subjectivity in the research during different steps including the interpretation and abstraction of resource attributes, derivation of requirements, and choice of some aspects of the method development. However, the author tried to keep this subjectivity to a minimum by providing the rationale behind the research from three areas: 1) Literature review; 2) Empirical study; 3) Discussions with academics and industry experts.

- Model: The first model limitation is the number of variables used in the approach (comparatively more than the original situation). The presence of too many variables could potentially add uncertainty to the final results. However, the analyses are focused on looking for performance changes when different resource combinations are used to identify trends rather than absolute values. The second model limitation is related to its potential complexity if the number of activities or resource combinations are too large. This could lead to a significant computational effort to simulate the process. However, the conducted case studies displayed reasonably complex processes and the approach was applied successfully. Yet, it important for the modeller to consider this factor and evaluate the potential effort needed against the benefits of applying the approach.

- Implementation: The implementation of the approach was conceived using a number of different tools, which could decrease the usability of the method. The approach extended the CAM tool, used to model the design process, by interfacing it with Netica, which is used to model the BN. Subsequently, the results are analysed using Microsoft Excel. Hence, the initial tool to model the approach and analyse the results could be further enhanced into a final software to boost its usability.

- Case studies: As discussed, two case studies were conducted in the same organisation. The case studies also display the same types of non-human resources. Ideally, more case studies should be conducted across different organisations using distinctive type of design resources to evaluate the approach comprehensively. Application evaluation detailed the effort invested in data collection and modelling. However, the overall duration of a case study (including searching for a suitable case study, setting up, understanding the organisation, review interactions) lasted between six months and a year for each case. Thus, due to time limitations two case studies seem reasonable for the current work. Furthermore, the case studies were conducted in the same organisation due to the set-up of the project with the industrial collaborator. Nevertheless, the approach is applicable to other organisations and situations and further case studies can be conducted as part of future work.

- Success evaluation: As stated, DS-II included an initial evaluation of the research. A more comprehensive DS-II should follow the implementation of insights in the process and assess its performance. Nevertheless, for the reasons stated, initial evaluation was sufficient for the type of DRM project chosen in the methodology chapter (Chapter 3).

- Applicability of the method: A limitation of the research could be the difficulty a-priori in assessing if the value of the potential insights outweighs the complexity and effort to build the model. In this context, this research has argued that the insights extracted exceeded the effort taken to conduct two case studies, but more work is needed at this front. In addition, the applicability of the method to other industries and companies should be further investigated. Although, as explained, the approach was designed specifically to be applied to different industries and organisations, more case studies are needed to confirm this.

8.4   Opportunities for further research

Further research comprises opportunities to address limitations, opportunities in design resource research and opportunities to take advantage of the model's capabilities for other projects.

- Opportunities to address limitations: Addressing the implementation and evaluation limitations by enhancing the tool into a final software and applying the approach to different organisations. For a comprehensive evaluation, the approach should be applied by independent practitioners in the organisation, recording and evaluating its applicability and usefulness. The devised insights should be implemented and followed to comprehensively examine the success of the approach.

- Opportunities for resource research: The developed approach enables insights to be drawn on selecting the ideal resource instances for the process. This is done by identifying the level of effectiveness needed for the activity and process as a whole. Another opportunity is to study processes with multidisciplinary skilled resources that can alternatively perform different activities in the process. For example, scheduling a process in which a team with a fixed number of designers that have multiple skills at different levels of expertise. Some activities can indicate the resources that have the necessary skills or capabilities to perform it, from which one will be selected. The investigations will focus on testing the different resource scheduling possibilities and allocation policies. For this to be feasible, the model has to be enhanced with OR allocation capabilities so multiple resources from the pool can perform the same activity. Initial work at this front has been developed by the author of this thesis. A prototype model has been defined and initial implementation was conducted with the help of a researcher from the author's group. Further research will be focused on testing the approach. This extension seems especially relevant for SMEs, in which a small multidisciplinary team has multiple skills and competences performing activities interchangeably during the project. Finally, another interesting opportunity is to extend the current research into a multi-project resource scheduling approach, a natural extension of the current research.

- Opportunities to take advantage of the model capabilities: Another opportunity for further research consists of using the outcome results from the simulations to build a BN model for the whole process. The potential diagnosis capabilities of BN are thus extended beyond the modelling of resources. On another stream, the capabilities of BN, mainly the capture of complex conditional relationships, the

representation of uncertainty and the capability of diagnosis, can be further applied to other elements of the design field. This thesis has focused on design resources, but there is an interesting opportunity to incorporate BN to other aspects of design.

8.5 Summary

In this chapter, the research is discussed as a whole with respect to the importance of resources as a topic, how the work has enhanced the understanding of design resources and its attributes, and how the approach enabled investigations of the impact of different resource combinations. The implications of this thesis for industry and the research community were also outlined.

In addition, the thesis was initially evaluated in DS-II, the last stage of DRM. Therefore, addressing **RQ7:** *How useful and usable is the developed resource management approach in industrial applications?* The conclusion led to believe that the research and developed approach had a positive contribution to the field having proved its applicability and usefulness.

Finally, research limitations regarding methodology, the model itself, tool implementation, case studies and further validation was outlined. Opportunities for further research concluded the chapter.

9 Conclusion

This chapter revisits research questions, key findings and contributions. In addition, final remarks conclude the thesis.

The research is founded upon three main points: 1) the literature investigations; 2) the empirical studies; and 3) the experimental exploration conducted in two case studies to provide resource management insights. The first two points were the basis of a resource management approach that enabled exploring the implications of different resource characterisation on process performance. The approach was applied to extract the insights for the third point.

The methodology followed, DRM, was presented in Chapter 3 and guided all the stages of the research and presented a series of research questions. Section 9.1 revisits the research questions and summarises the key findings and contributions. Finally, Section 9.2 concludes the thesis.

9.1 Key findings and research contributions

This section revisits the seven research questions (RQs) underlining the thesis and summarises the key findings and research contributions. The general objective of the research was to improve design process management by improving design resource management.

To attain the objective, the following principal research question derived in Chapter 1 guided the research **RQ0**: *How can resource management be utilised to improve planning and execution of complex design processes?*

Initial literature review in Chapter 1 provided a hypothesis for the research: *An efficient approach (support method) will provide insights on resource management for decision making.*

Hence, the thesis was set to answer the seven granular research questions systematically. The results of the research are presented below outlining research findings and contributions:

RQ1: *What are the different types of design resources and the current methods to support their management?*

The question was addressed with literature review in Chapter 2, which identified relevant methods leading to the first research contribution:

Design resource management model classification. A number of approaches in engineering design, process modelling, ABMs, queuing models, activity network models and SD were classified in terms of their aim, the resources they manage and resource attributes included.

At the same time, answers to RQ1 consolidated different characterisations of design resources by the reviewing models and empirical findings in an organisation. Hence, the following contribution was made:

Characterisation of design resources. Bringing together the lists of resources found in literature in Chapter 2 and empirical study in Chapter 4. The refined list included designers, computational, prototyping and testing resources as a high level description. A more detailed classification depending on the granularity of the resource description was also provided. For example, designers can be sub-classified by roles, expertise, etc.

RQ2: *What key attributes can describe the impact of resources on process performance?*

Literature review extracted key resource attributes modelled by different approaches. In addition, the exploratory case study expanded the understanding of crucial resource attributes by studying how design resources are managed in the organisation. The combination of both attained the following contributions:

Design resource attributes list. Resource attributes were also characterised and consolidated for models in literature and empirical investigations. These were divided into fundamental, designers, computational, prototyping and testing attributes. The attributes define the relationships between resources and activities which moulds the influence and impact on process performance.

A set of requirements to identify design resources in different organisations and industries. The gained understanding was discussed to develop these requirements. The primary requirement refers to whether the resource is necessary to the design process,

'required to deliver the design', and sub-requirements regarding its *'availability'* and *'impact'*: 1) *They have availability*; and 2) *Their effectiveness impact process performance metrics*.

Both literature review in Chapter 2 and industry study in Chapter 4 indicated that an approach including a resource management model was suitable to address the objectives of this thesis, leading to:

RQ3: *What are the requirements for a model that might enable prediction of the resource impact on process performance?*

RQ3 was answered by systematically deriving requirements for the development of the model from literature review and exploratory case study, leading to the fifth research contribution:

A comprehensive list of 12 requirements to guide model development. The list comprises four functional requirements for design process modelling, five for resource modelling and three for resource management analyses.

RQ4: *What is a suitable concept(s) for a model for resource management that fulfils the requirements in RQ3?*

A prototype model was developed to incorporate the functional requirements to assess the possible usefulness of the support in Chapter 5. Subsequently, further understanding was gained to answer RQ4 with the following contribution:

Resource management support concepts according to resource allocation capabilities. The three concepts presented were *static resource allocation*, *flexible resource allocation* and *dynamic resource allocation*. Discussion regarding how each concept addresses the functional requirements answered RQ4 and introduced model building structures, which directed the final model development.

RQ5: *How well does the model concept meets the requirements in RQ3?*

To answer RQ5, the chosen model concepts were detailed: ASM to model the process and BN to model resources. It was implemented computationally using CAM and Netica respectively (Chapter 6). This leads to the seventh research contribution:

Resource management model. The final support method combined a design process model with resource BN models. The model addressed all the functional requirements and answered RQ5.

RQ6: *How can the model be used in an approach for resource management to improve design process planning?*

The model was included in an approach in Chapter 7, a main contribution of this thesis:

The resource management approach. One of the main outcomes of the research that involves three stages: *Understanding the investigated organisation in terms of their aims, processes and resources*; *Application and analyses of the support method in the relevant areas*; and *Implementation of the resulting insights*. The approach intends to guide the modeller through the application procedure, subsequently gain understanding and provide insights for process improvement.

RQ7: *How useful and usable is the developed resource management approach in industrial applications?*

RQ7 was answered by applying the approach in Chapter 7 to two industrial case studies. To evaluate the usefulness and usability of the approach in industry, the outcome of the two case studies in Chapter 7 was evaluated in Chapter 8. Hence, the last contribution of this thesis:

Initial evaluation of the approach. The support method, application and success evaluation demonstrated that the approach was useful and usable in industrial applications. During evaluation, opportunities to complete a comprehensive evaluation and further research were outlined.

In summary, by answering the RQs, the thesis was able to initially address RQ0. Whilst this is inevitably a partial answer, it provides a means to improve planning and execution of complex design processes using a resource management approach. The further work section in the previous chapter outlines a guideline to further answer the overarching research question. In conclusion, the thesis achieved the research objective of improving design process management by enhancing resource management.

9.2   Concluding remarks

Design processes are inherently complex endeavours that can integrate thousands of designers and multiple resources within a careful designed plan. Traditionally, researches have paid more attention to the study and management of designers, and have overlooked other resources such as computational, prototyping and testing resources during planning stages.

The thesis highlights that resource management in design processes is not trivial. It is continuously challenged by the inherent complexity and uncertainty of design processes and the necessity of utilising the appropriate resource for each task. However, the impact of different resource instances on performance exhibit a trade-off behaviour towards the main metrics of effort, cost and duration. Hence, it is paramount to provide methods

that can help decision making on how to balance their availability, effectiveness, and cost.

Consequently, this thesis aimed to improve process management by developing a resource management approach that enables to gain understanding of design resources and attributes, quantify the trade-off impact of different resource instances and attributes, and provide resource management insights for planning and execution. The approach includes resources such as designers, computational, prototyping and testing resources and allows testing different combination of their instances.

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Appendix

Prototype model results

Table 34. Prototype model combinations improvement in cost, effort and process duration

Combination	Aerodynamics	Mechanical	Preliminary	HPC	Time process duration	Total cost	Total effort
1	Expert	Expert	Expert	High	54%	23%	60%
2	Expert	Expert	Intermediate	High	36%	27%	35%
3	Expert	Intermediate	Expert	High	51%	38%	54%
4	Expert	Intermediate	Intermediate	High	31%	38%	33%
5	Expert	Intermediate	Intermediate	High	31%	38%	33%
6	Expert	Novice	Intermediate	High	24%	37%	23%
7	Expert	Expert	Expert	Medium	47%	-8%	51%
8	Expert	Expert	Intermediate	Medium	24%	-8%	23%
9	Expert	Intermediate	Expert	Medium	42%	3%	45%

10	Expert	Interme-diate	Interme-diate	Medium	13%	3%	13%
11	Expert	Novice	Expert	Medium	36%	2%	36%
12	Expert	Novice	Interme-diate	Medium	1%	2%	-2%
13	Expert	Expert	Expert	Low	34%	-67%	38%
14	Expert	Expert	Interme-diate	Low	-1%	-64%	-4%
15	Expert	Interme-diate	Expert	Low	23%	-53%	25%
16	Expert	Interme-diate	Interme-diate	Low	-4%	-53%	-4%
17	Expert	Novice	Expert	Low	3%	-56%	1%
18	Expert	Novice	Interme-diate	Low	-10%	-55%	-13%
19	Interme-diate	Expert	Expert	High	47%	25%	52%
20	Interme-diate	Expert	Interme-diate	High	28%	27%	26%
21	Interme-diate	Interme-diate	Expert	High	42%	37%	45%
22	Interme-diate	Interme-diate	Interme-diate	High	25%	38%	26%
23	Interme-diate	Novice	Expert	High	36%	36%	36%
24	Interme-diate	Novice	Interme-diate	High	9%	36%	6%
25	Interme-diate	Expert	Expert	Medium	38%	-11%	42%
26	Interme-diate	Expert	Interme-diate	Medium	10%	-11%	7%
27	Interme-diate	Interme-diate	Expert	Medium	34%	0%	37%
28	Interme-diate	Interme-diate	Interme-diate	Medium	0%	0%	0%
29	Interme-diate	Novice	Expert	Medium	28%	0%	27%
30	Interme-diate	Novice	Interme-diate	Medium	-6%	-1%	-9%
31	Interme-diate	Expert	Expert	Low	23%	-72%	27%

32	Interme-diate	Expert	Interme-diate	Low	-9%	-73%	-12%
33	Interme-diate	Interme-diate	Expert	Low	5%	-60%	7%
34	Interme-diate	Interme-diate	Interme-diate	Low	-10%	-59%	-11%
35	Interme-diate	Novice	Expert	Low	-3%	-60%	-5%
36	Interme-diate	Novice	Interme-diate	Low	-16%	-60%	-20%
37	Novice	Expert	Expert	High	28%	24%	32%
38	Novice	Expert	Interme-diate	High	-4%	25%	-8%
39	Novice	Interme-diate	Expert	High	23%	36%	25%
40	Novice	Interme-diate	Interme-diate	High	-8%	35%	-10%
41	Novice	Novice	Expert	High	3%	34%	0%
42	Novice	Novice	Interme-diate	High	-14%	34%	-19%
43	Novice	Expert	Expert	Medium	9%	-15%	12%
44	Novice	Expert	Interme-diate	Medium	-14%	-15%	-17%
45	Novice	Interme-diate	Expert	Medium	-5%	-6%	-5%
46	Novice	Interme-diate	Interme-diate	Medium	-17%	-3%	-19%
47	Novice	Novice	Expert	Medium	-9%	-5%	-13%
48	Novice	Novice	Interme-diate	Medium	-23%	-4%	-28%
49	Novice	Expert	Expert	Low	-11%	-80%	-9%
50	Novice	Expert	Interme-diate	Low	-25%	-77%	-29%
51	Novice	Interme-diate	Expert	Low	-15%	-67%	-15%
52	Novice	Interme-diate	Interme-diate	Low	-30%	-70%	-32%
53	Novice	Novice	Expert	Low	-21%	-68%	-25%
54	Novice	Novice	Interme-diate	Low	-35%	-70%	-41%

Data collection tables

The first data collection in step of the approach was done with the following example table. The table can be repeated if rework values are different.

Table 35. Basic process data

| Activity | Durations (BC, MLC, WC) | | Iteration likelihood % | Resources | |
	Waiting time (days)	Time (days)		Type	#
1	0, 1, 1.5	1, 4, 7	15	Aero	1
2	-	2,5,6	-	Stress	2

The second data collection in step of the approach was done with the following example tables. The first set of tables are related to different resource types and instances.

Table 36. Data for designer instance

Resource (instance)	# available/ cost	Time dedication % change with priority	Skills	Expertise (Expert, Intermediate, Novice, None)
Stress (Expert)	2/ 6 per unit time	100%- High 50%-Medium 20%- Low	FEA	Expert
			Stress analysis	Expert
			CFD	Novice

Table 37. Computational resource instance

Resource (instance)	Capability/power # cores	Number Jobs	Waiting time (days)
HPC	34	1-4	2
		4-7	4
		+7	7

Table 38. Testing instance

Resource (instance)	Testing conditions	Testing and prototype set up readiness (days)	Limitations on booking/ waiting time
Testing	Location	3	Specific months/ if slot is lost wait for 10 days

The modeller should collect the relevant data, since not all resources has all the attributes. It is advised to work with designers from the team to develop the right spreadsheets.

The last table is related to the activities performed by the different instance:

Table 39. Data collection for the support method

Activity	Resource instance	New iteration likelihood/ Reliability	Time modifier (as % improvement)	Learning curves (as % improvement)
1	Impact (Expert)	10%	30%	0%
	Impact (Intermediate)	20%	0%	5% in first 3 iterations
2	HPC (20 cores)	5%	0%	-
	HPC (40 cores)	5%	100%	-