A STUDY TO IDENTIFY ENGINEERING DESIGN RESOURCES IN COMPLEX PRODUCT DEVELOPMENT PROJECTS

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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. In order to achieve this, it is necessary to identify and understand the different resources required. This paper attempts to do so through insights drawn from interviews in an aerospace company. Firstly, it investigates what elements have been considered design resources by current modelling approaches and how the approaches have managed resources. Secondly, interviews identified that key design resources does not only include designers but also computational, testing and prototyping resources. Thirdly, the paper introduces resource attributes that can impact on resource availability and their effectiveness on process performance. Fourthly, it proposes a set of requirements to distinguish design resources from company resources. Finally, it advocates for having allocation flexibility to balance all these resources within the process, requiring new approaches for planning and scheduling that can model resources along with their attributes.

Keywords: Resources, Process modelling, Requirements, Design engineering, Enterprise resource planning

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Product development (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). The rising complexity of new products (Lindemann et al., 2009), tight competition, and higher customer expectations demand better processes with shortened delivery times and lower budget. Appropriate resources are not only required to produce a quality product, but also have a significant impact on both project cost and duration. However, design processes are highly uncertain: multiple and unexpected changes yield in iterations and rework that cannot be anticipated at the beginning of a project. In this context, managing resources may become cumbersome. In principle, adding more resources could reduce time to market while increasing cost, but reality of resource planning is notably more complex. Furthermore, resources to complete a project are usually limited, making its allocation a crucial decision making point. In this competitive environment, appropriate management of resource is a key factor to success: estimating and planning of needed resources; allocation; and scheduling.

Design process modelling and simulation can reduce this uncertainty and aid estimation of the cost and duration of design projects by considering rework and iterations probabilities associated to each design task. They can be used to aid resource planning and scheduling, in which different configurations and behaviour of processes can be set up to investigate cost-effective improvements (Bell et al., 2007). Simulations could help to quantify the effects of resource allocation and utilisation amongst other analyses. However, a better understanding of resources and their impact on performance could provide more accurate estimations. To obtain an extensive view of possible resources involved in the design process, product development literature has been investigated. In parallel to this, interviews in a prominent international aerospace company have been conducted in order to obtain additional industrial insights. It appeared that resources involved in the design processes of the company are not exhaustively addressed by investigated research works.

This paper has threefold objectives: 1) to propose an extended list of resources usually involved in design processes, 2) to detail which of their attributes could influence the design process performance and should be considered in design process simulations and 3) Propose a set of requirements to distinguish design resources in complex PD. Also it advocates for the need to balance resources.

Section 2 will focus on identifying what elements have been considered engineering design resources by current modelling approaches and how they have been managed within the process. Section 3 presents our empirical study, in which the company's needs are summarised and interviews were used to understand and categorise the range of resources present in industry. Additionally, different resource attributes that affect their availability and impact process performance are introduced. In Section 4, the authors discuss requirements to be defined as engineering design resources. Section 5 advocates the need to balance resources by having allocation flexibility. Finally, the conclusion summarises the contributions and proposes future work.

2 BACKGROUND

2.1 Resources in product development and engineering design

A PD project is one of the first stages of a product's lifecycle that starts when a market opportunity is identified until the production of the product (Browning and Ramasesh, 2007). In PD, Ulrich and Eppinger (2004) 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 organisation level, one of the major challenges on running multiple projects is the management of shared resources. Overloading designers and other resources could drastically decrease productivity. Thus, at the project level, the challenge is to estimate and decide the amount of resources needed. Although not mentioned explicitly in Ulrich and Eppinger (2004), the authors could abstract from it that other resources could also include information from customer feedback and relationships (Chapter 4), legal resources such as patents or licenses (Chapter 6), or market research resources to evaluate projects or technology (Chapter 3).

Engineering design processes are part of PD projects and refer to the method by which new products are created (O'Donovan, 2004). Hammer (2001) stated that: "*A process is an organized group of related tasks that work together to create a result of value*". In engineering design, Cross (2000) has studied how designers think and design. It mentions resources such as equipment, facilities, and

materials used, amongst others. Resources have mentioned explicitly or implicitly throughout the literature as elements assumed to be known by the reader but have not been formally categorised.
At the design level, a successful design process relies, amongst other points, on an organisation applying the right resources to the right activities in the correct order. Similarly, team communication can be considered paramount for a process to work efficiently (Crowder et al., 2012). The project will set the aims, requirements, and constraints for the design process to produce the appropriate product.

2.2 Challenges related to resource management in PD and design processes

Uncertainty, ambiguity, and risk are inherent in PD and design processes (Pich et al., 2002). Thus, they are characterised with high iterations, and multiple interdependent activities executed as a multidisciplinary effort (Browning et al., 2006). In this context, process modelling is often used to describe and analyse the process with the aim of offering insights that could aid managerial decisions (Wynn, 2007). Moreover, a model provides the perfect scenario to conduct what-if analysis thanks to its process simulation capabilities (Wynn, 2007). Different configurations and behaviour of processes can be set up to investigate cost-effective improvements (Bell et al., 2007). During planning, managers need to estimate, plan and schedule the necessary resources to be available at the right time.

2.3 Resources in design process modelling

Typical business approaches such as Gantt charts or tools such as Microsoft Project can analyse resource allocation and produce schedules. Nevertheless, they do not capture the complexity and uncertainty of design processes. Basic project management tools have capabilities directed to modelling certain characteristics (e.g. time constraints). The challenge lays on incorporating the uncertainties of design, which requires models that allows iterative analysis (Wynn et al., 2007). Many models can be found in literature; examples of prominent reviews are Browning and Ramasesh (2007) and Wynn (2007). This section focuses on understanding what elements have been considered as resources in process modelling and how such models predict, allocate and schedule resources.
Some task networks model considers resource as a '*constraint'*, i.e. as elements needed to be in place to execute activities but limited in number or availability. Tasks network models divides 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. Belhe and Kusiak (1996) extended IDEF3 to schedule design activities with precedence and multiple resource constrains. CPM and PERT has been used to model processes with tasks competing for the same resources. It allows identifying the critical path to subsequently analyse where and how much resources are needed to minimise delay risks. DSM has been used by Cho and Eppinger (2005) for resource scheduling in an advance simulation model. It introduces a weighted parameter to decide heuristically which tasks are more important to execute first in case of resource competition. Signposting (Clarkson et al., 2000) and ASM (Wynn, 2007) can use resources as constraints during process path Monte-Carlo simulations. Other task network models have the capability of estimating the necessary amount of resources. Resources are thus treated as '*effort'* or any other implicit element that could converge a task or process. Ullman et al. (1997) developed a technique that aids in the decision of where to invest 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. Lee et al. (2004) extended DSM to calculate how much resources will be needed to finish a design process in a desire number of iterations. Yassine et al. (2003) used DSM to study design churns. The discovery of churns can avoid a vicious cycle of fire fighting by allocating resources to the identified bottleneck tasks.
Other approaches have been more concerned with supporting communication, coordination and negotiation of decisions between stakeholders in the design process rather than the structure of the processes. These approaches normally involve *'human designers'*; and sometimes *'tools'* used during the process. Agent Based Models (ABMs) falls in this category, it consist on 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). They are able to model the interaction of design teams including different designers behaviour and coordinating tasks for resources. Some ABMs frameworks uses a centralised coordinator to allocate tasks based on the needs of the task, capabilities of the resource, and the state of the process. An example is Agent-based Process Coordination, which helps decision making in planning and task sharing. It includes a coordinator agent and service agents (CAD, FEA,

etc.) (Madhusudan, 2005). Jin and Levitt (1996) extended the Virtual Design Team (VDT), a multi-agent modelling framework to assess different configurations of design processes using discrete-event simulation. Crowder et al. (2012) developed a collaborative agent based model for simulating teamwork in Integrated Product Teams (IPT). 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. CPiW developed by Wynn et al. (2014) can predict the resulting resource requirements and schedule risk of a design process after an externally imposed process change. The model uses agents as *'resources that perform the activities'*. Additionally, Joklegar et al. (2005) have researched resource allocation policies using System Dynamics model.

2.4 The problem

Despite all the literature involving resources in design process modelling, often what is considered a resource is not clarified. There is a lack of formal classifications of different type of resources in design literature due to the broad definition of the term. Most approaches acknowledge the existence of resources as a constraint for task execution. They were not concisely defined, just merely elements needed to perform the activities. For instance Ullman et al. (1997) aids on deciding were to add resources without mentioned what kind of resource. It could have been referring to designers, money, effort, etc. In addition, the approaches that mention and model resources characteristics often refer to designers. Agent based methods sometimes incorporated tools, however they are usually concerned with improving interactions between designers (or designer and tools) rather than structural analysis of the process. Traditionally, many researchers have studied the performance of designers (Ahmed et al., 2007; Crowder et al., 2012). In contrast, 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. In order to improve the way in which projects are planned, allocated and scheduled, it is necessary to better understand the different resources and how their characteristics influence design process performance. Thus, the first step was to investigate design resources and its significant attributes through a preliminary case study.

3 STUDY

3.1 Industrial needs, context and objectives

This study is part of a larger research that ultimately aims to enhance resource planning and scheduling methods in complex product design. 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 process is run and coordinated by a Central Division (CD), 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 for more detailed work on specific parts of the product. The process is highly iterative and interchanges information between divisions and with customers through CD. 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. 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:

- Total duration: 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. Subsequently, the final product must be delivered on time to avoid any financial penalties
- Quality of product: Due to the end use of the product, its quality cannot be compromised.
- Total project cost: Needs to cut cost expenditure to improve profitable.

The objective of this paper is to understand what elements can be considered as design resources and abstract the significant attributes that can influence the performance outcome of design activities in terms of quality, time and cost. Product development in aerospace industry needs the integration of thousands of engineers and it is coupled with high uncertainty, risk and iterations. Furthermore, the company presented a large variety of resources in their process. This company therefore features all the characteristics of a complex design process and could potentially provide interesting insights.

3.2 Methodology

Fifteen interviews were conducted with a main focus on early stage design. Five interviews were focus on understanding *Preliminary Design* phases, in which further stages were also discussed to provide a better understanding of the process. Another three interviews on understanding the design process along with allocation of designers, and two interviews on computational resources. Finally, detailed interviews were conducted on one of the *Sub System* divisions, focusing on the design process and management of resources. The rationale was to provide a more complete picture by investigating both high and detailed level of the process. Interviews have been recorded and transcribed. First five interviews were conducted as exploratory meetings and the last ten were conducted as semi-structured structure interviews following a set of developed interview guides. They were conducted by one of the authors and another researcher with one or more interviewees in sessions ranging between 1.5 to 4 hours. Additionally more insights were drawn during a visit to testing facilities.

4 UNDERSTANDING THE RANGE OF RESOURCES IN INDUSTRY

4.1 Design resources as observed in industry

Our empirical study was used to help contextualise and categorise design resources into a practical range of resources presented in industry. Current modelling approaches have widely researched into human designers and elements that constrain the design process. However, interviews emphasised that a large proportion of the actual practical work involves a whole range of other resources such as computational resources, testing and prototyping resources.

In the current stage of the research, the main types of design resources derived from industry are:

- '*Human designers*': Comprised by 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. It also includes active elements performing the activity independently. They were present in the company as hardware (High Performance Computers (HPC), stations, grids, desktops), software (dedicated to FEA, CFD, etc.), licenses, and network.
- '*Prototyping resources*': Prototypes will 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.

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. This includes design clarification, conceptual design, embodiment and detailed design (Hales and Gooch, 2004). Since it cannot be uncorrelated from product development and may lead to design iterations, the authors included testing. The interviews confirmed having the described resources participating in the design process, thus having a high level of relevancy towards industry. Figure 1 shows a proposed categorisation of practical design resources found in the company and examples of relevant classifications. The list is not final and additional resources could be added as research advances.

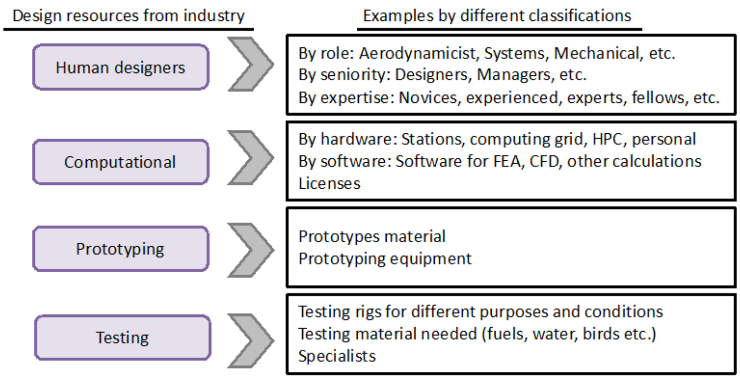

Figure 1. Design resources in industry and examples of classification

4.2 Design resources allocation and characteristics

Having specified the resources involved in design processes, the present section investigates the characteristics of resources through their attributes and briefly explains their allocation in preliminary design as described in the interviews. The authors aimed to develop a list of resource attributes that can affect process performance in terms of total time, cost and quality output during allocation and execution of tasks. They were developed and refined by reference to the literature and authors' experience. The list was limited to attributes that can impact on resource availability and produce different effectiveness in process performance output. During interview discussions they were validated, and the importance of each of them were discussed and contextualised for the company.

After elicitation of fundamental attributes that refer to all design resources, the allocation of each particular type of resource is described and specific attributes are explained.

4.2.1 Fundamental resource attributes

The allocation of resources is done at different levels. At preliminary design level, when a project starts at CD request, different departments will negotiate with project owners how much designers and other resources they need. Depending on bid urgency and level of detail, more or less resources will be allocated to a project. The complexity of adjusting the availability of all resources involved is a key issue for managers. Projects require the right resources, in the right amount, and for the time needed.

Fundamental attributes of resources include resources *'capabilities'*, *'quantity available'*, *'time'* needed to finish (or allocated to) a specific task, *'calendar availability'*, *'time window to book'* them, and *'cost'* of utilising them. Resource capabilities will determine the degree at which is capable of competently performing and successfully completing a task. Additionally, they have to be available at a required point in time, which can be indicated by its calendar of availability. Supplementary information in calendars could include time window when resource has to be booked or geographical availability. Moreover, resource availability could be constrained by waiting times. HPC computers have a queue of activities waiting, which results in additional time before the activity can be executed.

4.2.2 Human designers

Companies could attain long-term benefits by assigning designers to perform certain activities, either specialising them or increasing their range of skills. However, allocation of designers should account for both project needs and designer's preferences since preference and motivation of designers towards a task will also influence their performance. Therefore they require a treatment that differs from other resources, where allocation only follows project needs and cost-availability.

In a preliminary design, the allocation of designers is done through work packages allocated to projects. Managers will negotiate how many designers they will need for each part of the process based on their experience and knowledge. Being able to quantify the effects of changing resource configuration in the process (e.g. request an expert, have more designers, amongst others), could allow them to present arguments to management to obtain a more cost effective allocation of resources. Hence the potential benefits of simulating the amount and type of resources to study the trade offs between cost and time to complete a project.

Besides the aforementioned attributes, human designers will also include a set of capabilities that differentiates each other. *'Designer capabilities'* distinguish an aerodynamicist from a structure engineer, and differences in competencies and knowledge can also separate an expert from a novice (Ahmed et al., 2007). The type and number of team members in a project changes frequently as it progresses. Teams must be selected according to their competences towards completing the design activities, thus understanding their attributes will be important to assign them to the right tasks. Other attributes include *'learning curves'*, '*likelihood of iteration'*, and *'time dedication'* to a task. Different designers could experience dissimilar learning curves. An example is having an expert and a novice work on the same task. The expert's learning curve would likely increase marginally, whereas a novice could increase steeply in the beginning before stabilising. Moreover, the learning period for a system engineer is probably different to an aerodynamicist. Depending on the type of task, engineers working on a mature activity will not experience the same learning than on an innovative task. Learning curves could potentially influence likelihood of iteration and attributes such as time to completion or quality output. Likelihood of iteration depends on the type of designer and task, and it comprises iterations due design exploration and risk of failure (Wynn et al., 2007). As concepts converge, rework on innovative task will require less time and decrease failing risk. A mature or homogenous task will be more prompt to be just repeated. Finally, time dedication of a designer to a task is another crucial factor, since many designers will be working in different activities or projects at the same time. Interviewees have stated that overloading designers could be very counterproductive.

4.2.3 Computational resources

The allocation of computational resources follows different channels depending on its type. Some computational resources are capable of independently performing design activities by receiving a series of inputs and producing results for the next task. They are normally computers of different capabilities performing design generation or analysis. In engineering companies, the effective management of these resources becomes essential. For instance, some tasks can only be completed using high computational power (e.g. HPC), which leads to tough resource competition and creation of bottlenecks. Due to the important capital investment in some of them, companies would aim for high utilisation. This trade-off adds to the complexity of managing them. Allocation of HPC could include long waiting times and depends on number and size of submitted jobs by each department. These variables will influence the job queue order: the bigger the size and number of jobs already submitted, the more waiting time for new job requests. Thus, some departments will plan the amount, size and time to submit jobs. It could become problematic, if in order to save time, submitted jobs do not request the recommended computational power trying to push faster into the queue. Thus, a more integrated system within the process that can aid planning and foresee tasks' needs for these resources could potentially parallelise waiting times with other activities.

Other computational resources will participate in the design process and deemed to be essential due to the bottleneck effect that their absence could produce (e.g. software). Examples are licences or software, which are allocated depending on the priority of given tasks.

Besides the discussed common attributes, computational resources posses *'computational capability'* of its software and hardware, *'compatibility with other resources'*, *'reliability'*, and potentially others. Computational capabilities will determine their suitability to complete specific tasks. Compatibility should indicate if they could be deployed and used with other computational resources to perform activities. Reliability of computational resources is the analogue to failure risk for designers. However, reliability not only accounts 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). Examples are if hard disk gets full or risk of unforeseen maintenance shutdowns. Whether computational resources have learning curves is unclear, and it could depend on the activity. Some activities will perform standardised operations; others may build upon previous iterations providing a sense of learning.

4.2.4 Prototyping resources

Prototyping resources are the ones necessary to produce a prototype or the prototype itself in the design stages just before testing. Their importance 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 the lack of planning into acquiring the necessary resources to develop the right prototype. Common mistakes during preparation include overlooking the required time, quality needed for specific testing, total cost of developing a prototype to the desired standards, number of prototypes needed in case of failure in testing, amongst others.

4.2.5 Testing resources

Testing resources include all the necessary resources for a specific testing activity, spanning from testing facilities, materials to specialists that could constrain the process if they are missing. In complex PD such as aerospace products, testing resources are usually some of the company's most expensive assets. Thus, their quantity is normally restrained to a level that aims for high utilisation. Consequently, important bottlenecks could be generated in the process when the utilisation is at capacity. The possible risks, if not planned appropriately, exults the significant importance of testing resources for the process. Sometimes the design process has to be scheduled around the availability of key testing resources. It was acknowledged by the company that some test beds were only available to use 2 months in a year due to weather conditions in specific geographical locations.

5 REQUIREMENTS TO DISTINGUISH ENGINEERING DESIGN RESOURCES

This section presents a discussion of requirements to distinguish engineering design resources based on literature and insights from interviews. At the highest level, companies have to acquire, develop, or have access to a set of resources that would enable them to produce successful products or services. In a wide sense, this set of resources can encompass financial, human, equipment, facilities, materials, legal, market information, amongst other resources. They are regarded as resources since they are indispensable or their level of availability can impact the performance of the company at different levels. For instance, the scarcity of money could limit the number of active projects in the company or even provoke bankruptcy. Facilities, equipment, materials and human resources are the core structural elements of a company, whereas legal resources protect the functioning of the company in the market. Finally, the lack of specific market information could position companies in competitive disadvantage.

The authors differentiate project resources from company resources by excluding the ones that are not directly involved in the development or accomplishment of the project. Money is necessary to run the different projects within the company, in which people will execute activities using equipment and materials in plants or facilities. Also information and legal resources can constrain the projects. In addition, if project resources can be further deconstructed, all the resources that are not involved directly in the project should be no accounted as such (e.g. general overhead, rent of offices, etc.).

Design resources are elements required to directly participate in design activities and comprises facilities, materials, equipment, people, and maybe informational and legal resources. It excludes financial resources that might be used to purchase design resources. Financial resources are generally allocated to whole projects, and could delay, improve or cancel it. Allocated money will be dedicated to hire designers, computers, amongst others resources to perform design activities; having a few *degrees of separation* between its allocation and the impact on process performance. For instance, if the same amount of money can be used to hire three novices or one expert, their output on the quality or time performing the activity will be different. In this context, money should be considered a project resource since it has direct impact on the project, but indirect impact on the immediate outcome of design activities depending on what the money is used for. It would be more useful to account it as a performance metric to measure cost of utilising different resources. Thus, it affects the project on a large scale but the design process indirectly. Informational resources and licenses could be considered a project resource since they normally affect a project globally, not just specific activities. In another words, they cannot run out or produce activity bottlenecks. However, in cases they produce these effects, they should be considered design resources. For example, an engineering company's license could be a company resource if it feeds globally to a whole company, a project resource if it is just constraining a project, or a design resource if it is creating bottlenecks for tasks within design process.

Resources that are participating in the design process such as designers have been object of extensive research. Correlating to interviews, most of the discussed resources had direct involvement or participation in the design process, taking part either actively on the execution of design activities (e.g. HPC) or passively as constraining elements (e.g. licences). Literature has also identified that availability and impact on performance are critical to the process. Firstly, since **availability of resources** can drive and set boundaries to the process performance, such a characteristic has been modelled and regarded as crucial to understand by many researchers. It correlates to the findings in the case study, where availability has been accounted in several fundamental attributes (quantity available, calendar availability, and window of time to book). Secondly, to derive significance from resources, they must somehow **impact the performance** of design processes. Impact on performance in terms of quality, total time to completion and cost have been accounted in fundamental attributes (capabilities, time needed to finish a task, and cost of utilisation), designer attributes (designer's capabilities, learning curves, likelihood of iteration, and time dedication to a task), and computational attributes (computational capability, compatibility, and reliability). Thus, at the authors' consideration, for an element to be considered a resource in engineering design, there is a top requirement of whether the resource is necessary to the design process and sub-requirements regarding its availability and impact:

- **Required to deliver the design:** They can be actively performing the activity such as a designer or a High Performance Computer (HPC), or they could be passively part of the activity such as the need a specific software tool or network. It is then required that:
  - **They have availability:** Availability of resources is fundamental to allow the process to advance. The absence of a required resource will be reflected as bottlenecks and delays, or

paralyse the project. Availability could also expose if a resource is limited or unlimited. As a result, the authors believe that 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 project resource.

- **Their effectiveness affect the process performance metrics:** Due to the various properties of different resource (quality, expertise, etc.), their effectiveness could produce different outcomes in performance when executing the same activity. For instance, an HPC could converge an analysis much faster than some stations or desktops, thus impacting on the time of the process. However, the higher cost of HPC could increase project cost.

6 BALANCING RESOURCES

There is an inherent complexity in deciding what resources should perform which tasks taking into account their effectiveness towards completing the task while adjusting to their availabilities. As explained, the right resources must be applied to the right tasks in the correct order. It becomes particularly apparent when taking into account the different attributes of each resource that could impact process performance. In terms of effectiveness, the time and quality output of a novice designer performing an activity will differ from an expert's. Thus, we argue that resources in a design project are *heterogeneous*. Distinctive resources executing the same task could impact the performance metrics differently and hence the behaviour of the process. In terms of availability, after a resource is allocated to a task, it could become unavailable for subsequent activities that might be strongly dependent on that specific resource, resulting in bottlenecks. At the planning stage, managers must be aware that some activities could display such behaviour (e.g. towards expert designers, HPC, etc.) due to the nature of the activity and the capabilities of the resource. Resource allocation should be prioritised for those tasks to avoid mismatches in calendar or paralysing the process for too long due to pre-allocating the resource to upstream tasks. For this to be feasible, other tasks might need certain degree of flexibility by having a larger number of resourcing options. If one of the options were allocated to a resource dependent task first, another could still perform the activity. Increasing the number of possible options to the tasks that are less sensible to resource changes enhances the ability of allocating resources to prioritised tasks first. However, the fact that a resource is an option to perform an activity does not imply that the performance output would be as optimal as the first choice. Having identified this, it is almost imperative that companies balance their resources in terms of availability and effectiveness in output performance since the perfect combination of resources is not always available. These complexities lead to key managerial questions, examples are: How can I predict and optimise future resource needs? Which resource should be allocated to a task if it would be unavailable for subsequent tasks? How can I plan my process around my key resources? Which activities are more sensible towards a change of designer performing it? What impact on the overall design process would have increasing/reducing computational resources? Do designers performing a certain activity had to perform specific upstream activities? A testing was scheduled in two months, something unexpected changed, should I dedicate all my resources to reach the testing slot?

The authors believe that assessing the impact of different resource configurations on the overall project could help answer the above questions, provide further insights on the process behaviour and help decision-making. Process modelling and simulation could help in this endeavour. However, as identified in section 2, very few can support different type of resources and its attributes. Nevertheless, simulations would allow managers to assess different resource allocations to tasks: add/subtract resources, change resource option, and other variations. Depending on the task, a resource change could have a ripple effect with significant impact on the whole process. Given the different characteristics of each resource option performing the same task, an increased flexibility will provide simulations the ability to explore a wider range of resourcing possibilities.

7 CONCLUSION AND FUTURE WORK

The paper has been motivated by current industrial needs to identify and classify engineering design resources derived from an empirical study in order to improve current resource management methods. As a result, it introduces resource attributes that managers should take into account due to their impact on availability of resources and their effectiveness on influencing design process performance. In addition, it proposes a set of requirements to distinguish design resources after analysing the literature and case study interviews. The paper has highlighted the importance of identifying and understanding the full range of design resources required in delivering a successful product, which not only includes human designers but also computational, prototyping and testing resources. It also advocates for flexibility in allocating and balancing resources in the process, reflecting on the need to support appropriate resource selection in process planning and execution. The authors believe that current approaches to explore resource configurations in terms of estimation, allocation and scheduling have shortcomings. Simulation methods that can model design resources along with their attributes to study the effect of different resource configurations on process performance could bring further insights, answer key managerial questions and aid decision-making. Future work will finish the investigation on design resources and develop new methods to analyse different resource configurations.

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