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USING EMBEDDED DESIGN STRUCTURES TO UNRAVEL A COMPLEX DECISION IN A PRODUCT DEVELOPMENT SYSTEM

1 INTRODUCTION

Advances in design computation are producing collections of design tools with the potential to deliver step improvements in the availability of information to product development teams. These tools promise to improve understanding of the product, thereby improving the quality of the design and product performance, and reducing downstream costs and time to market. However, people are still likely to need to be involved in the development process: making complex decisions that require human characteristics such as the ability to interpret results from multiple design tools, making trade-offs in the context of engineering uncertainty, and working with ambiguous and qualitative information. Indeed, introducing new technology without such consideration of human and organisational aspects is known to have a detrimental impact on productivity (Brynjolfsson & Hitt, 1998). This paper reports research that used rework as a negative proxy indicator for productivity in an industrial product development process. The aim was to explore the potential of embedded design structures to unravel complexity in engineering design decisions with a high impact on development process performance (by generating rework), and to identify factors that contribute to this complexity. The paper reviews literature in decision making and embedded structures before presenting the case study analysis.

2 BACKGROUND

It is widely accepted that engineering companies need to respond quickly to change that occurs during a product's lifecycle (Vianello & Ahmed-Kristensen, 2012). Becoming effective at requirements engineering and management is challenging for organisations designing and developing complex systems (Fernandes et al., 2014). A large number of requirements typically need to be managed at different levels of the product's physical and functional hierarchies (Weber & Weisbrod, 2002). Multiple internal and external stakeholders are involved with negotiation and decision making (Pohl, 2010) and engineers and designers performing the process must act and take decisions in an environment with technical uncertainty, ambiguity and imperfect communication (Tseng & Jiao, 1998). Consequently, understanding of decisions that lead to engineering change is crucial in planning product lifecycles, forecasting errors and reducing rework. Decision making plays a central role in product development and is a critical component of engineering design (Gero, 1990) with designers spending 9% of their time making decisions (Robinson, 2012). Human error, which according to (Reason, 2008) is commonplace, can have significant consequences and complex decisions need to be well informed with a good understanding of the reason for changes (Vianello & Ahmed-Kristensen, 2012). However, evidence of sub-optimal decision making is well documented within those contexts. For example, Hallihan et al. (2012) describe heuristics and biases common in design, including confirmation bias that limits the number of generated design ideas, and Viswanathan & Linsey (2011) describe design fixation and the 'sunk cost' fallacy which limit designers' ability to move on from a failing project.

Key decisions in product development systems, such as the selection of a baulking strategy (the key decision in the case study reported in this paper), are usually made collaboratively by groups. A number of psychological biases[1] influence decision making, of which confirmation bias is critical (Jonas et al., 2001). Confirmation bias can lead to over-confidence and complacency, but this can be countered by people considering why a proposed solution may be incorrect or sub-optimal (Koriat et al., 1980). Within engineering design, the phenomenon of "design fixation" is closely related to confirmation bias (Linsey, et al., 2010). In essence, confirmation bias reduces the amount of "cognitive work" needed for a decision and is a natural human characteristic explained by the observation that people are "cognitive misers" (Fiske, 1980; Gigerenzer & Gaissmaier, 2011). Within teams, such confirmation bias can lead to a further decision making bias known as "group polarization" (Myers & Lamm, 1976). Here, whatever the initial position of the group is, it will become more extreme after discussion within the group

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[1] A Codex diagram giving a full range of biases is available at https://cdn-images-1.medium.com/max/2000/1*71TzKnr7bzXU_l_pU6DCNA.jpeg

(Isenberg, 1986). The timeframes of decisions[2] mirror the two major decision-making processes that people use: System 1 and System 2 thinking (Kahneman, 2011). System 1 thinking is rapid, intuitive, and automatic (i.e., unconscious) whereas System 2 thinking is slower, analytical, and more deliberate (i.e., conscious), weighing up advantages and disadvantages slowly. As expertise increases, so too does the automaticity of thinking (i.e., System 1 thinking), and thus experts are more likely to make rapid, intuitive decisions than novices (Hodgkinson et al., 2008). In engineering design, experienced designers have been observed to make these faster decisions through pre-evaluating their decision, where novices require a more deliberate approach (Ahmed et al., 2003).

In most product development contexts, decisions have to be made in the absence of accurate or complete information (Kühberger, 1998). Here, no matter how good the decision making processes, decisions may still have a detrimental impact on the performance of the development process or the product because they are based on poor quality information. Thus, behaviours such as the seeking and processing of information are also integral components of decision making in real world environments (Oppenheimer & Kelso, 2015). This is particularly true in engineering environments, where 56% of engineers' time is engaged in information behaviours including 14% of time actively seeking information (Robinson, 2010). Finally, the outcome of some decisions is immediately apparent while for other decisions the outcome may not be known for a long time (months, or even years in some cases). In most cases, the more senior the person's role in the organization, the longer the time for the consequences of their decisions to become apparent (although there are notable exceptions). Essentially, the more distant the horizon at which a decision is aimed, the less predictable the scenario will be (Robinson et al., 2005), so decisions will be based on less accurate information.

3 METHODOLOGY

Embedding allows one instance of a mathematical construct to be superimposed on another (Stiny, 1991). Using the principles for the definition of design structures outlined in (McKay et al., 2015), it is possible to define individual design structures as lattices (Behera et al., 2017) which, being mathematical structures, can then be embedded on an underlying lattice that can accommodate all of the individual lattices. Although concrete applications of embedding do occur, e.g., in the shape computation literature (Stiny, 2006), methods to enable the robust implementation of embedding for use in real-world applications remains an open research issue (McKay et al., 2012). It is, however, feasible to implement embedding on paper, e.g., using acetate slides to overlay different design structures, defined using the method described in (McKay et al., 2015), onto a given design definition. This approach was used in this research.

A case study based on a major quality incident in an engineering company's development process was used as the focal point of the study. A case-study approach is a method adequate for empirical investigations intending to study contemporary phenomena in their real-life contexts, when the boundaries between phenomena and context are evident and when multiple sources of evidence are used (Yin, 1994). For investigations into "cause-effect" relationships and for explanatory types of research, a case-study method is suitable as it deals with 'how' and 'why' questions (Lindvall, 1997). The case study in question, which has been anonymised in this paper to maintain confidentiality, surrounded the design and testing of a product that failed during the testing phase of its lifecycle. Engineering design in this part of the industry can be regarded as variant design. The product is complex with a large number of components and interactions but the majority of designs are variants of previous designs. In this case, the incident had been attributed to a design decision that was made to innovate an aspect of the design. The development of the product involved multiple design teams from across the case study company and its suppliers. The case was selected because an internal investigation had concluded that design decisions were a root cause of the failure.

A preliminary analysis of documents related to the case study, including analysis of an internal incident report, was carried out. This enabled the identification of key design documents. Qualitative and quantitative document analyses were carried out on the design documentation. Twenty-seven documents were provided, including Product Introduction Lifecycle Management documents, Design Definition Reports and Problem Definition Reports. Three of the documents provided reported the

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[2] Some decisions have to be made rapidly (in seconds), while others can be made without immediate time pressures (in days, weeks or longer).

company's internal evaluation of the incident in question. The remaining documents were associated with system-level design, including Component Design Reviews, Design Review and Audit Meetings, Business Reviews, Interface Control Documents, Solution Issues Reports and risk analyses. These included details from before the fault occurred through to details of rework conducted afterwards. However, all of these documents were concerned with the System-Level Design & Testing and the Integration & Testing stages of the product's lifecycle (Vianello & Ahmed-Kristensen, 2012).

In addition to document analysis, six interviews were conducted to provide further qualitative data that was not present in the documents and to gain alternative perspectives from a range of stakeholders involved in the product development process. Interviews were semi-structured and conducted individually with each participant by two interviewers. Each interview lasted 60-90 minutes and they were conducted at the company's facilities. The case study (see next section) has been anonymised and the descriptions of the participants in this section refer to parts in the anonymised version that correspond to parts in the real case. Table 1 details the profiles of the interviewees including their roles in the development process at the time the incident occurred and their prior experience with the product. The documents and transcribed interviews were analysed using a range of lenses. In this paper, the use of design structures as an analysis tool is reported. The design structures used were embedded manually, by drawing them on acetate slides overlaid on design definitions.

Table 1. Profiles of the interview respondents

Role	**Product-related expertise**
Reviewer of the subsystem components and lead for the internal incident investigation	Extensive experience of this product family
Integrated project team leader of the nozzle and diffuser, and an assistant work package owner of the containing subsystem	Experience of the relevant subsystem for this product family
One of the designers working within the subsystem including the design and integration of the nozzle and diffuser	Limited experience of this product family
Work package owner for system components, responsible for overseeing the design of the whole system, including this subsystem.	Experience of the relevant subsystem for this product family
Lead designer working on the design of the casing, in an external organisation that also designed parts of the diffuser assembly	Involved in the initial design on the product and some structural component design of the relevant subsystem of the product
Design team leader for containing systems, responsible for design processes across all subsystem components. Owing to personnel changes, joined the design team after the development project had started	Extensive experience of this product family

Steps were taken to reduce bias during both data collection and data analysis because some bias is always inherent in a qualitative study such as this. When collecting data, the incident took place in 2010, the major quality incident investigation was completed in 2011 and interviews were conducted in 2016. The respondents were interviewed individually under conditions of anonymity. In addition, they no longer worked in the same teams as each other and the time difference between the internal investigation (2011) and the interviews (2016) meant that respondents were unlikely to have discussed the case prior to the interviews to arrive at common interpretations. In addition, one respondent worked for an external company at the time of the incident and was unfamiliar with the results of the internal investigation. Moreover, the internal investigation report does not overtly reference weak knowledge management practices as a cause of the incident; it only asserts, "[the] decision to deviate from standard baulking practice was not recorded". In the data analysis, reference to weak knowledge management practices appear 22 times across the responses of all the respondents. Conclusions were based on an analysis of the data that included coding and categorizing data, looking for common categories, themes and patterns, and comparing data within and between interviews. Constant comparative methodology, where data is compared within single and between multiple interviews, was used to analyse the data (Boeije, 2002; Strauss & Corbin, 1990). Comparisons increase internal validity of findings as the researcher looks to capture the range of the variation in the phenomenon under study by looking at similarities and differences in reasons, perspectives, attitudes, behaviours, sentiments, emotions and the like. Constant comparison method also increases external validity of findings and helps detect and minimise bias. Although, because of confidentiality issues, we cannot present a rich description of the case study, the solid methodology employed alleviates doubts about the study's internal validity and present its grounding in the minute details of a real life design incident.

4 RESULTS

A major quality investigation was instigated following the emergence of the fault during product testing. An anonymised summary of key findings from the investigation is provided in Table 2 and a block diagram representation of the anonymised design data is provided in Figure 1. It can be seen that a key issue lay in the baulking strategy used in the design process to avoid assembly of the nozzle in incorrect orientations. Two baulking strategies were considered. The first related to the (Pitch Circle Diameter) PCD of holes which, with one offset hole, physically prevents assembly in the incorrect orientation; this was the case in previous designs. The second, used in this case and a deviation from the traditional baulking strategy for this product family, was to design the nozzle and diffuser so that there was a physical clash if the nozzle was orientated incorrectly during the assembly process. In the final design, the issue was that, although the designs would clash, the clash was small enough for a fitter to overcome as part of the fitting process. If this is possible then the design is deemed to be at fault.

Table 2: Summary of findings from company investigation (Part names are from Figure 1)

Statement of Problem	Product failed on test due to an incorrectly fitted nozzle. The fitment was not error proofed, enabling it to be fitted in the incorrect orientation.
Previous models	Previous products in this family have an offset bolt to prevent incorrect fitting.
Root Cause	Inadequate mitigation and control of interfaces during design process.
Corrective Action	Nozzle checklist and good practice guides updated to improve baulking requirements and an improved baulking design to be introduced. Product manuals to be updated to reflect best practice for service.
Lessons Learnt	Generic themes and potential concerns from this incident were shared widely. Lessons were shared directly with Design, Development, Service, Regulatory Compliance and Quality teams.

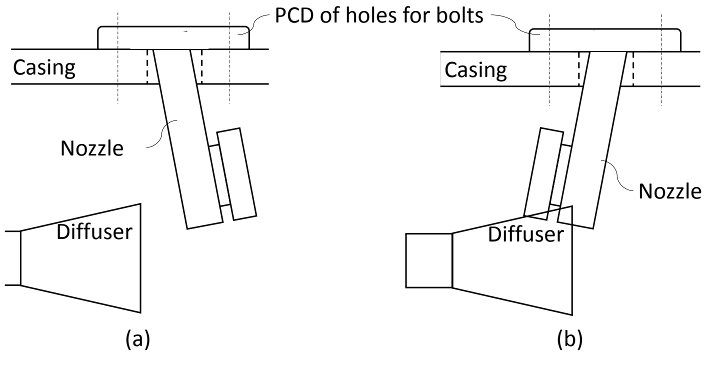

Figure 1: Possible arrangements of the nozzle: (a) Nozzle in correct orientation; (b) Nozzle in incorrect orientation which is prevented by baulking

The following reasons for failure were identified by the incident investigation team as being related to tolerance stack up that meant the resulting interference between the nozzle and diffuser was less than anticipated and small enough to be 'resolved' during the fitting process.

- Complex decision under time pressure: From the documents and interviews, the decision to use the new baulking strategy was related to time pressure in the development process and the tighter than usual space available for baulking.
- Baulking functionality shared between two components and two teams: In addition, the management of interfaces was highlighted, especially given that key parts of the subsystem were

designed across a network that included two organisations with one in two locations. An Interface Control Document with the diffuser design organisation existed but the diffuser's role in the baulking function was not specified.

- Requirements not documented: The minimum clash dimensions between the diffuser and nozzle were not specified in the Interface Control Document and clash estimator changes were not communicated; as a result, their significance was missed. In addition to these technical issues, the design of the nozzle was frozen 18 months before that of the diffuser.
- Reliance on informal knowledge: This impacted situational awareness and knowledge sharing within the design team. In addition, there was turnover of personnel throughout the development period, e.g., the design team leader for this particular subsystem changed.

Figure 2, based on the document analysis, shows the order of key design decisions that were made in the context of the product development process. The implications of each of these factors on design decisions, in terms of the complexity each creates for downstream design and development processes, can be established by embedding different kinds of structure on the design definition.

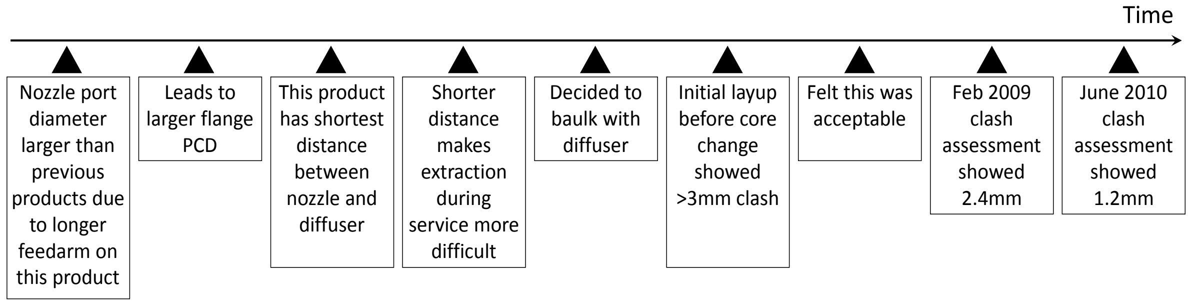

Figure 2: Key decisions in the design process

4.1 **Embedded design structures**

Embedding was used to superimpose different design structures onto the case study with a view to identifying whether design structures could provide insights on sources of complexity in design decisions. If this were possible then, in the future, embedding could be used as a design tool to identify sources of complexity, and so design risk, during product development processes.

4.1.1 Embedded product structure

Design information used in the decision making process that resulted in this deviation from traditional processes was investigated by embedding three types of design structure on case study data: a product structure (bill of materials) and a supply chain structure which included organisations involved and the design process. The product structure implications of the two baulking strategies are illustrated in Figure 3. Both baulking strategies related to features (shown in grey) on parts of the overall system but one, (a), was localised to mating parts in a single subsystem whereas the other, (b), was spread across two subsystems and related to parts that would not naturally be seen as mating parts. The other factor highlighted by embedding the product structure was the state of the product to which each strategy related. Strategy (a) related to a permanent state (as built) that exists in the design definition whereas Strategy (b) related to a non-permanent state (during the assembly process) that does not exist in the design definition. In summary, baulking via a clash between the diffuser and nozzle is, architecturally, the less simple option because it covers more elements and relationships in the product structure and its detection depends on an in-process condition that does not exist in the design definition. As a result, checking during the design phase would be difficult or impossible and the human ingenuity used by the fitter in the final assembly process is unlikely to be captured in simulations of the assembly process.

4.1.2 Embedded supply network structure

Embedding a supply chain structure highlighted further complexities in the selected baulking strategy. The implications of the two baulking strategies on the supply network are illustrated in Figure 4. This structure also highlights cross-network process-related issues. Key factors highlighted by embedding the supply network structure related to the extent to which the implementation of the strategy required design processes to be carried out across the network and whether the critical interface would be recognised as such by engineers working on the project. Strategy (a) would be implemented across two partners in the network but engineers in each would recognise a PCD of holes as being a product feature that would be expected to match a similar pattern of holes on a mating part. On the other hand, although Strategy (b) would also be implemented across two partners in the network and the interface requirement was documented in the Interface Control Document, engineers would be unlikely to recognise the need to confirm the interface was fit for purpose. This problem was exacerbated by a number of social and technical factors. Personnel changes and the 18 month time delay between the freezing of the nozzle design and the design of the diffuser made knowledge management through the process more difficult, in part because this lengthened the feedback time on decisions. Technically, for Strategy (a), the CAD model of the final assembly design represented the product in its as built state, making inconsistencies in design definitions easier to see. On the other hand, for Strategy (b), the CAD model, even of the assembled product, would not capture the assembly process and ingenuity of the fitter, both of which would be necessary information to detect the problem during the design process.

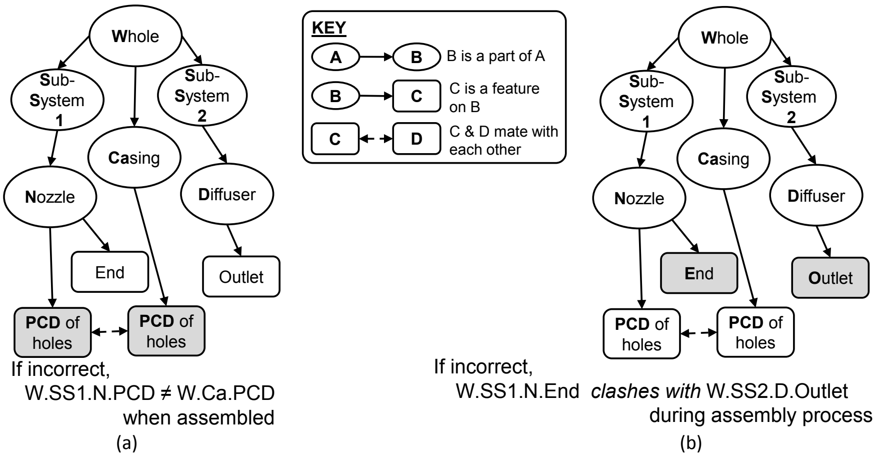

Figure 3: Baulking strategies and product structure: (a) offset bolt, (b) nozzle-diffuser clash

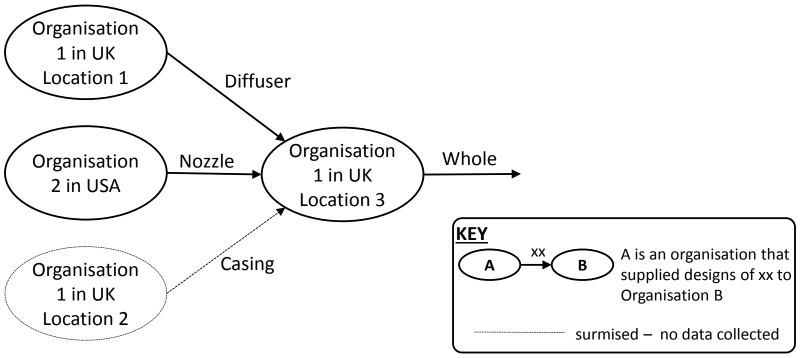

Figure 4: Supply network structure

5 DISCUSSION: FACTORS AFFECTING THE DESIGN PROCESS

An analysis of the case study data highlighted how design decisions relate to design knowledge (in the form of documents and the like) and its communication. Figure 5 summarises the results of this analysis. This section covers three factors: time pressures influencing the whole development process, communication (bottom layer of Figure 5) and knowledge management (top four layers of Figure 5).

5.1 Time Pressures

This was one of the major factors highlighted through the project. As determined during the document analysis, the baulking strategy for the nozzle differed from the design previously implemented with previous models. It was stated during the interviews that baulking the nozzle with the diffuser was a satisficing solution. Engineers are under pressure to find a solution quickly and reasoning and rationale are often not recorded comprehensively (Reason, 2008). Given that automaticity of thinking increases with expertise, it is important to note that the designer involved in making this decision was a relatively novice designer having recently joined the organisation and may not have been as well equipped to make

such rapid decisions as an experienced designer. However, this was not a decision that was made solely by the designer. A team reviewed this decision and although this was not well documented, discussions took place, despite time pressures, to determine the final decision.
In addition to time pressures, another temporal factor revealed during both the interview analysis and document analysis was that there was a significant period of time (18 months) between the designs of the diffuser and the nozzle. As a result, the nozzle was one of the first components to be integrated in the product space and the diffuser one of the last. Interviews highlighted that this delay may have negatively impacted the knowledge transfer and communication between the two design teams. Although not adding to the pressure in decision making, this factor may have had an impact on the quality of the decisions made and the ease at which knowledge was available. Indeed, here it was a decision made by a novice designer and the team reviewing the decision did not realise the consequences of the decision immediately.

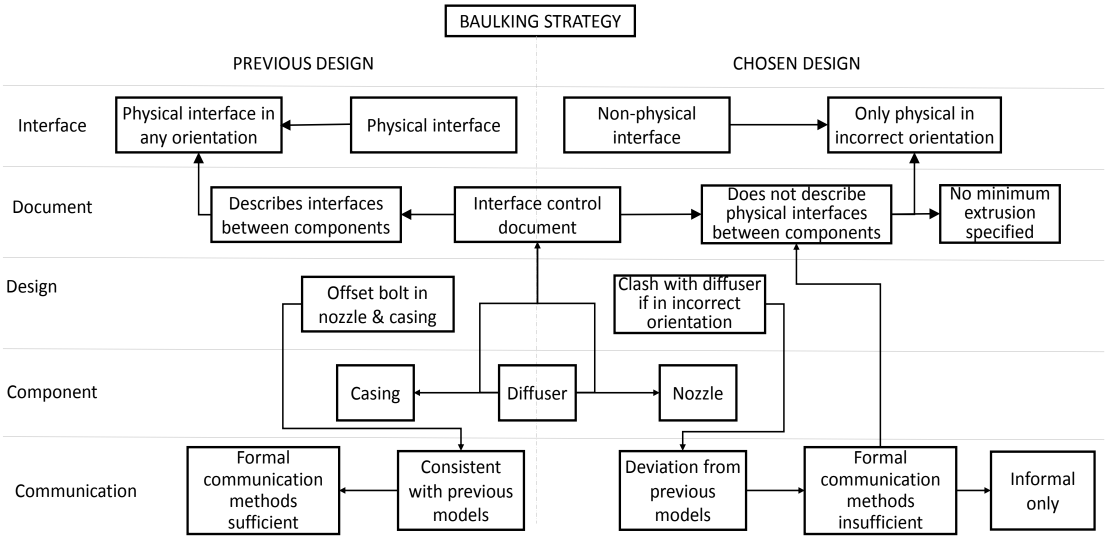

Figure 5: Factors Affecting the Design Process

5.2 Knowledge Management

The most common factor highlighted by the interview transcript analysis was a ‘Lack of Knowledge Management’. This refers to the transfer of knowledge through the product development system and the manner in which design information is provided to engineering designers, which are of significant importance for a successful design project (Womack et al., 1990). During the design of this system, the two major components involved were not designed concurrently and were designed by different teams, one of which was an external company hosted by the lead organisation and tasked with the design of the diffuser. This complicated the management of knowledge as certain restrictions were placed upon the access that the external design team had to the lead's documentation and design work. Despite hosting this design team at the lead's site, with the aim of improving knowledge management, it was clear from the interview data that more could have been done to effectively manage knowledge transfer. In particular, had the design structures been embedded earlier in the process, the importance of managing the interface, through the Interface Control Document, between the nozzle and the diffuser would have been recognised and could have been acted on to reduce the risk of the incident occurring. The results of the interviews suggest that a lack of knowledge management was not only an issue for the Interface Control Document; many design decisions and knowledge were not documented effectively.

5.3 Communication

In addition to Knowledge Management, another frequently occurring factor established during the interviews was ‘A Lack of Communication Management’. Similar principles can be observed as those discussed within the analysis of knowledge management as the presentation and accessibility of knowledge is usually due to communication factors. Ultimately the communication between the two fundamental design teams involved in this case-study was restricted. A fundamental causation factor identified from documents and interviews was a failure of the interface document presented to the diffuser design team. In essence, this document failed to communicate effectively the requirements for baulking the diffuser and rather focused on another major concern for the designers, interchangeability of the diffuser in service. Although this could be attributed to a design error, the fault could also be attributed to the design of the interface document itself where the baulking requirement was expressed negatively. The baulking design implemented only included a physical interface when the diffuser was fitted in an incorrect orientation. Since the Interface Control Document only required physical interfaces for components in their correct orientations, this can be regarded as a failure of the requirements definition process in that ‘hypothetical’ interfaces had previously not been included and including them was not common practice.

Ultimately the fact that this type of interface was unusual and a deviation from traditional processes should have been highlighted and structures should have been put in place to cope with the risks that this issue may have caused. Figure 5 has been developed to encompass the major issues. This figure highlights the differences between the baulking strategy implemented on previous designs and the strategy implemented in this case study. The model aims to capture the fact that the Interface Control Document was insufficient and the general system for implementing such an innovation, in terms of the baulking strategy, was ineffective. Therefore, employees resorted to informal communication methods which, in turn, are accompanied by their own issues.

6 CONCLUSIONS

This research investigated an industrial case from multiple perspectives to provide insights on complex decision making in a product development system. The embedding of design structures on the case study data highlighted areas of downstream risk that, if used as a design tool, could have informed management interventions and mitigated the risk. By embedding the supply chain structure (including process aspects) it could be seen that the design of the interface between the nozzle and the diffuser was carried out across organisational boundaries and that there was a significant time difference between the design processes for these two parts. These factors were known at the time when the product was being developed and may have been constrained by contractual arrangements. However, using embedding as a design tool could have highlighted such consequences as part of the early design process, and the information factored into decisions related to both the selection of the baulking strategy and the subsequent management of this part of the development process. Analysis of the embedded product structure shows that implementation of the proposed baulking strategy was architecturally more complicated than the previously used strategy, and related to an aspect of the design that was transient. Three important sources of product development risk can be drawn from this analysis. Firstly, because human designers are an integral part of the development process, psychological factors associated with how people make decisions need to be taken into account and managed, especially if novel approaches are selected. Secondly, high level information requirements for the Interface Control Document can be seen in the interface details highlighted in the embedded structure. And finally, being transient, the critical clash of parts needed for successful baulking was unlikely to exist in current design definitions; as such, even with advanced design computation tools, the required clash would have been difficult to see.

This research shows the benefit of a multidisciplinary perspective on engineering design cases, and has implications for supporting organisations to successfully implement design decisions that deviate from what has been done before, both in highlighting complexity in design descriptions and the socio-technical perspective. The potential value of embedding as an early design tool has been illustrated. Further work is needed to develop analysis methods for design structures that have the strong theoretical foundations needed to ensure reliable support for early design processes without creating significant additional workload that would be infeasible for adoption in product development processes where time and cost are critical drivers.

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