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FUNCTION DRIVEN ASSESSMENT OF MANUFACTURING RISKS IN CONCEPT GENERATION STAGES

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ABSTRACT

Decisions made in the concept generation phase have a significant effect on the product. While product-related risks typically can be considered in the early stages of design, risks such as supply chain and manufacturing methods are rarely easy to account for in early phases. This is because the currently available methods require mature data, which may not be available during concept generation. In this paper, we propose an approach to address this. First, the product and the non-product (manufacturing and/or supply chain) attributes are modelled using the enhanced function means (EF-M) modelling method. The EF-M method provides the opportunity to model alternative solutions-set for functions. Dependencies are then mapped within the product and the manufacturing models, and also in between them. An automatic combinatorial method of concept generation is employed where each generated instance is a design concept-manufacturing method pair. A risk propagation algorithm is then used to assess the risks of all the generated alternatives.

Keywords: Functional modelling, Risk management, Early design phases, Product architecture, Decision making

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1 INTRODUCTION

As the world is moving towards a cleaner and greener future (ACARE, 2020), technology-intensive companies such as in the aerospace industry, are having to radically rethink approaches for design and development. In order to achieve the desired sustainability goals (Seebode et al., 2012), significant and concentrated efforts have been put into projects such as the European Commission-funded program “Clean Sky” and its successor “Clean Sky 2” (Brouckaert et al., 2018). These initiatives are expected to be based on the integration of disruptive technologies on novel product architectures (Isaksson et al., 2021). However, before such novel product architectures are introduced, aerospace businesses must develop the capability to assess risks against the benefits in the early design stages. The aerospace industry, for instance, has updated their Strategic Research Agenda (SRA) to reflect the abrupt change of priorities that follow SARS-CoV-2 and climate developments and the urgency to develop more disruptive solutions has increased (Brouckaert et al., 2018). Assessing risks early, not only enables their consideration in the design process but also reduces downstream mitigation efforts and costs (Lough et al., 2009). Further, early assessment of risk enables the management of wider strategic and commercial expectations. While expanding the design space for a better exploration is a potential way forward, a larger number of resulting concepts makes decision-making tedious. For complex products such as aircrafts and their propulsive systems, such assessments may include impact analysis of critical downstream aspects such as manufacturing and supply chain (Aguila and ElMaraghy, 2018). Early design phases, however, often lack adequate information which makes this difficult. Further, since complex systems are usually highly multidisciplinary, any such assessment capability must also be multidisciplinary in nature, i.e., the ability to simultaneously evaluate a product on multiple metrics enabling trade-offs between different domains.

During the concept selection process, it is possible to explore multiple architectures (Müller et al., 2019). Individual architectures, however, may come with their unique manufacturing and supply chain-related requirements and constraints (Aguila and ElMaraghy, 2018). Choice of one architecture over others therefore must consider the associated risks before they are selected. In this paper, we propose a function-driven approach, which can be used to assess risks in concept selection based on supply chain or production-related risks, while simultaneously exploring various product architectures. While the individual methods used in this paper are well established, we contribute by proposing a new approach which is motivated by emerging manufacturing alternatives such as additive manufacturing (Patterson et al., 2021), especially in the pre-embodiment phases. The method application in an industrial case of a Turbine Rear Structure (Figure 1) is presented.

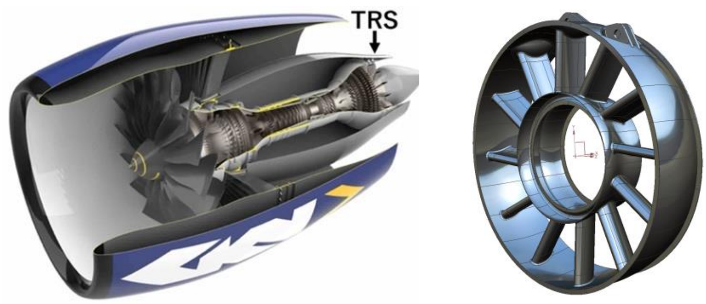

Figure 1. A typical turbine rear structure (TRS) and its location in an aero-engine. Reproduced from Panarotto et al. (2022)

2 BACKGROUND

In this section, we discuss some of the concepts relevant to this paper. First, we present a section exploring how functional models can be used to develop sets of alternative product-production architectures. Second, we discuss methods of risk analysis available in the literature including a brief background on the Change Prediction Method (CPM) of Clarkson et al. (2004), which is used as a risk analysis technique in this paper.

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2.1 Exploration of alternative architecture using functional modelling

Literature has highlighted the importance of exploring and assessing a large number of alternatives during the design stages. For example, models such as set-based concurrent engineering (SBCE) (Sobek II et al., 1999) argue that sets of feasible alternative design solutions should be maintained throughout the design process instead of selecting one design solution. However, this could be quite challenging as engineers often have to work with partial or incomplete information in the early design phases (Turrin et al., 2011). Researchers define these phases as “pre-embodiment” (Raudberget et al., 2015), or “architectural” (Ulrich, 1995) to reflect that the design is not yet embodied as CAD, or as refined drawings. The term product architecture is also used to describe how physical components, technologies and solutions accomplish desired functions. To support the definition of an architecture, function modelling is widely adopted in industry and its benefits are well recognised (Eisenbart et al., 2017). Popular techniques for functional modelling are the Function Block Diagram (FBD) or the Function Analysis System Technique (FAST). However, a limitation of these approaches is that they do not allow the representation of design solutions and functions in the same model. Also, these techniques do not allow for the representation of architectural innovations (Henderson and Clark, 1990), where the functions and the solutions remain the same, but where linkages are changed. These limitations have led to the development of novel approaches to function modelling. One such method called the enhanced function-means (EF-M) modelling (Müller et al., 2019) enables the representation of both functions, solutions and interactions in the same model. Further, the EF-M method also allows for the representation of a vast set of principally different architectures in a single model along with the export of design structure matrix (DSM) representations of each architectural variant. These DSMs can then be used for architectural analysis and/or to assess more articulated properties of a design such as risks.

2.2 Risk assessment in engineering design

Assessment of risks primarily aims at estimating the effects of uncertainties (Earl et al., 2005; Grebici et al., 2008) such as non-fixed requirements, unmodelled or misunderstood dependencies/interactions, improperly made assumptions etc. (De Weck et al., 2007). The uncertainties may not only be endogenous to the product (i.e. its design), they may also for instance come from an uncertain supply chain, manufacturing process reliability, user skill and so on (De Weck et al., 2007). It is therefore important to account for these uncertainties, and therefore the risks in early design phases (Tan et al., 2017).

Methods to assess risks were developed in the 1960s in the US, primarily in the civilian and military aerospace industry (Stamatelatos et al., 2011). Among early methods, Failure Mode and Effect Analysis (FMEA) for example, entails identifying potential faults (failure modes), assessing the risks associated with them and identifying possible mitigating options, prioritised based on the severity of the risk (Gilchrist, 1993). A modification of the FMEA approach is the Failure Mode Effect and Criticality Analysis (FMECA) approach, which focuses more on the criticality of the failure. These methods aim at identifying the possible causes to be the starting point moving towards the effects, following a “bottom-up” approach. Other methods, such as fault tree analysis (FTA) and probabilistic risk assessment (PRA), are instead “top-down approaches”, intended to determine how a failure mode can occur, i.e. starts with the effect and moves towards the causes (Mobey and Parker, 2002). In FTA for instance, a failure mode is considered and then boolean logic is used to determine what faults/combinations of faults lead to the undesired outcome (or failure mode) Vesely et al. (1981). Common to all these approaches is how the risks are assessed, commonly known as the “set of triplets”. Kaplan and Garrick (1981) suggest that the set of triplets which constitute risk analysis are three basic questions. The first question relates to what can go wrong (the failure mode), the second question relates to the likelihood of that happening and the third question answers what the impact of such a failure would be. A similar top-down approach is used by Clarkson et al. (2004), in their Change Prediction Method (CPM), which was developed in the context of changes propagating in a design. In the CPM, the initiated change is analogous to a fault occurring, likelihood is interpreted as the likelihood of a change propagating from one component to another and the impact is the effect a change has on one component. The impact and likelihood values are used to calculate the risk to a component from a given change. CPM, in addition, also considers the knock-on effect of change and therefore propagates the probability to other connected components. Since the CPM was first published by Clarkson et al. (2004), significant advances have been made in the approach, with many authors reporting improvements in it (Brahma and Wynn, 2022). However, a review of the literature does not reveal any work where CPM is used to assess the combined risk of a product and a manufacturing system architecture. The simultaneous modelling of product-manufacturing systems has been applied to the functional domain instead, for example using EF-M (Landahl et al., 2021). However, in such cases, the assessment is not dynamic using a top-down approach enabled for example by CPM. The method presented in this paper, therefore, addresses these limitations by combining two approaches. Firstly, an approach where product and manufacturing alternatives are modelled simultaneously, and secondly their combined risks are assessed using a propagation approach.

3 METHODOLOGY

The methodology is explained using a simplified case of a desk with two functional parts as shown in Figure 2.

3.1 Step 1: Create enhanced function means model of the product

The objective of this step is to create a EF-M model for the product. For our example, the desk overall has a function to hold objects at a certain height, as shown in the product EF-M on the left of Figure 2. This is decomposed into two sub-functions; "Provide flat surface" and "provide height". Each of these sub-functions can be solved by two alternative design solutions. Further, the interactions between these design solutions are shown as lines connecting them. A total of four unique combinations of design solutions are possible. For instance, a wooden desk top can be combined with hollow round legs or a glass desk top can be placed on hollow square legs.

3.2 Step 2: Create enhanced function means model for production/manufacturing method

In the next step, another EF-M is constructed for the production aspect required to be assessed (marked 2). For this example, we use a simplified manufacturing EF-M. In this EF-M, first, the main function of "Manufacture desk parts" is decomposed into sub-functions relating to the functions in the Product EF-M in Step 1. Similar decompositions can be constructed for other aspects, such as a supply-chain. In the simplified example, two manufacturing methods for each of the functional aspects of the product are shown. The 'iw' (interacts with) connections represent the dependencies/interactions within the manufacturing methods. For example, a desk-top manufacturing method may have an interaction with either of the leg manufacturing methods. These interactions are important as they are used to propagate risks in the later steps. For this example, four unique manufacturing method-design solution combinations are possible. Desk-top manufacturing method A combined with either leg manufacturing method A or B, or desk-top manufacturing method B combined with either leg manufacturing method A or B.

3.3 Step 3 & 4: Establish cross-domain dependencies and extract DSMs

In the third step (marked 3 in Figure 2), dependencies between the production EF-M and the product EF-M are established. These dependencies could be based on how manufacturing methods are allocated to design solutions (or for a supply chain, how a supplier is allocated to a part). For the example case of the desk, the EF-M shows four possible ways the selected manufacturing methods could work. Manufacturing method A could be used in making the wooden top, while the leg is produced using either manufacturing method A or B depending on whether the legs are made out of hollow square or hollow tube sections. Or, manufacturing method B is used for the top, with a choice of legs using manufacturing methods A or B, again depending on the choice of the cross-section. Here for simplicity, it is assumed that there is a 1:1 mapping between design solutions in the product EF-M and the manufacturing method in the production EF-M. This means that a method is unique to the type of design solution. If a manufacturing method can be used to make multiple design solutions, then this can also be shown as additional dependency lines between the two EF-Ms. These dependencies can be extracted as DSMs as shown in step 4. Similar to Steps 1 and 2, combinatorially, $4 \times 4 = 16$ unique possibilities exist with respect to product design and production (manufacturing method) alternatives.

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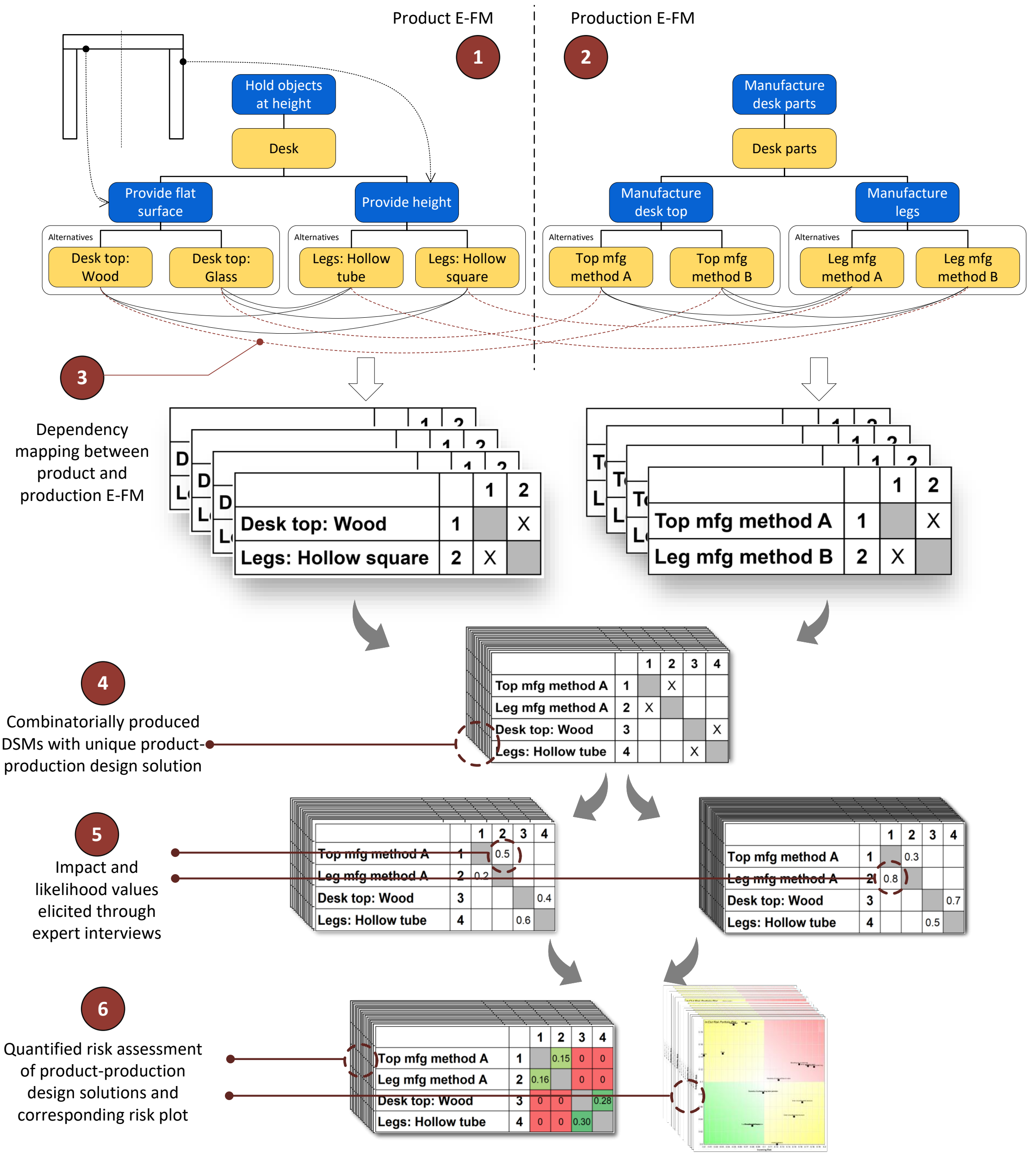

Figure 2. Simplified example of a table with two parts i.e., a table-top and a set of 4 legs. Two alternative solutions for each function are shown in the EF-M tree

3.4 Step 5: Assign impact likelihood values for dependencies

In the next step (marked 5 in Figure 2), we use the concept of the set of triplets, as discussed in Section 2.2 and assign likelihood and impact values to each of the interactions. The definition of likelihood and impact depends on the objective of the analysis. For instance, if the objective is to assess risks to the lead time of the product, the likelihood values may mean which manufacturing method is more likely to fail to deliver the product in time. Impact may mean how much impact a manufacturing method's failure to deliver a part on time has on the lead time. Similarly, for the assessment of quality-related risks, likelihood may mean how likely a part is expected to have defects in it. Impact may in that case mean how a defect impacts the quality of a product.

3.5 Step 6: Run CPM algorithm for risk assessment

In the last step 6, quantified risk is calculated based on the CPM algorithm (Clarkson et al., 2004). The motivation behind using CPM as the risk assessment method is its capability to propagate the probabilities through the dependencies. The importance of this step is to recognise the significance of

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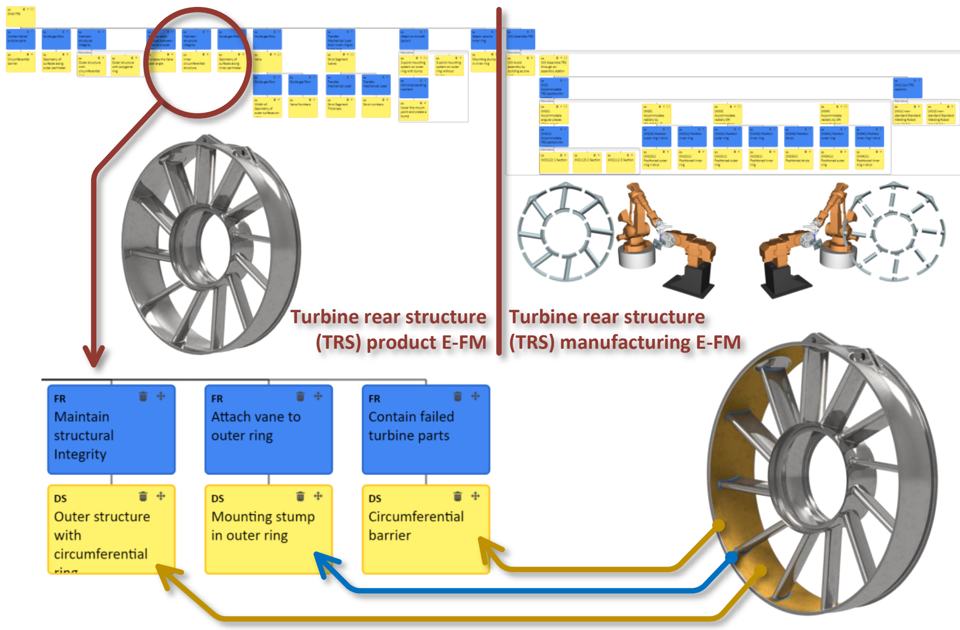

Figure 3. Model on the top shows both product (Left) and manufacturing (right) EF-M. Note that the iw connections in the EF-M are not shown for clarity

higher-order risks which may not be apparent normally. For instance, in the case of the desk, the top has a direct relation with the top manufacturing methods A and B. Any risks in these two manufacturing methods will therefore directly affect the desktop. However, there is an interaction between the top and the legs. So in an indirect 2nd order risk propagation, the risks to the manufacturing method of the top should also propagate to the legs. The risks can then be plotted as individual risk plots or parallel coordinate plots to facilitate trade-off studies between different design solutions, vis-à-vis the manufacturing method. Similar to Step 4, the number of such individual risk plots corresponds to the number of combinatorially produced alternative solution-manufacturing method combinations, as shown in the call-outs in Figure 2.

4 INDUSTRIAL CASE

As a part of the DIAS project, the methodology described in Section 3 was applied to an industrial case. The case involves a turbine rear structure (TRS) as shown in Figure 3. The TRS has a range of functional criteria which involves being able to withstand high thermal and structural loads. Further, since they are a part of an aero-engine, they must also be optimised to save weight thereby aiding fuel efficiency gains. Unlike classically modular products which are functionally decomposed based on modules or chunks (Ulrich and Eppinger, 2012), a TRS is a monolithic component and is highly integrated (Raja et al., 2019). The EF-M technique is therefore used to identify the elements of the product which satisfy the product's functions. As shown in Figure 3, top left, a total of 10 top-level functions were identified for the product. In terms of architecture exploration, two of the functions in the product DSM have alternative design solutions built into them. Figure 4 shows the two functions which could be solved by alternative design solutions. On the left, the function "maintain structural integrity" could be solved either by a circumferential ring or a polygonal ring. On the right of Figure 4, the function which enables the attachment of the component to the aircraft is shown. The function is solved by a 3-point mounting system. The two options are either to have a "bump" or not.

On the manufacturing side, one top-level function of "manufacture TRS" can be solved by either building the TRS as one unit (by casting) or by assembling and welding various parts in an assembly station, using welding robots. The method of manufacturing the TRS using an assembly station is decomposed further into two sub-functions which correspond to various manufacturing scenarios. These scenarios correspond to the way the components can be arranged and the types of robots which can be used in the welding operation. Once the manufacturing EF-M is completed, dependencies are established

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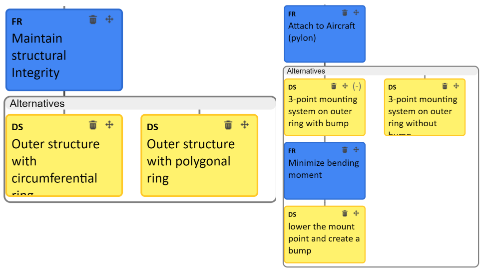
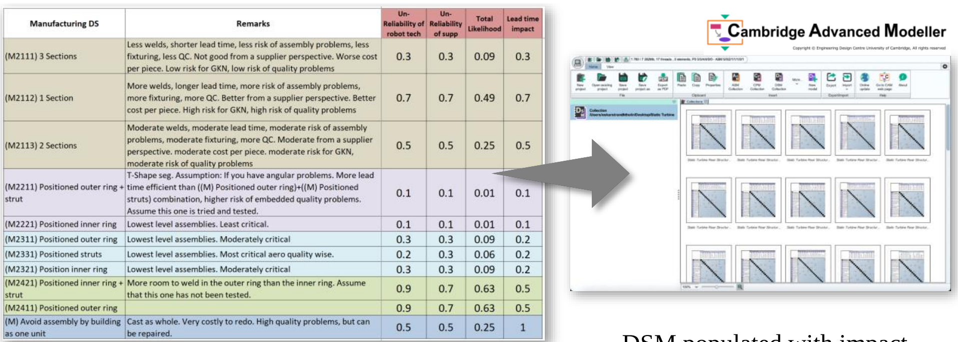


Figure 4. Example of two functions which are solved by alternate design solutions

from the manufacturing EF-M to the product EF-M. For example, when the TRS is manufactured as one unit by casting, the stumps (which are there for weld alignment) will not be required and therefore are not connected. Similarly, for all other manufacturing methods, appropriate parts in the product EF-M are carefully connected. Once the connections are complete, DSMs are extracted in bulk. The in-house online tool used to create the EF-M also provides a utility to instantiate design alternatives. With the alternative design solution combinations modelled in the EF-M tree, 52 unique design solution-manufacturing option combinations could be instantiated. The tool also provides an opportunity to extract these instances and the dependencies in them as DSMs. The details of the tool and the DSM extraction method can be found in Panarotto et al. (2022).
Once the DSMs are available, they are populated by a set of impact and likelihood values. In this case, impact-likelihood values were elicited from experts at the company, GKN aerospace. As previously mentioned, since risk in manufacturing methods was the focus of this analysis, the definition of impact and likelihood relates to the same. Likelihood for instance constitutes two parts. (Un)Reliability of robot technology and (un)reliability of the supplier. The total likelihood is the product of these two probabilities. The definition of impact on the other hand relates to how the lead time would be affected by the given unreliability of the technology and the supplier. The DSMs populated with impact-likelihood values are then imported into the Cambridge Advanced Modeller (CAM) (Wynn et al., 2010). CPM analysis is run on all 52 instances with 3 propagation steps. The manufacturing design solution was considered as the "risk initiator" which then is propagated through the DSM to the engineering DSM.

4.1 Results

In Figure 6 results from three out of the fifty-two cases are presented. In the first plot on the left, the option where the entire product is cast, without having to use any welding is considered. The likelihood considered is the product of the two unreliabilities. Both unreliabilities of the tech and the unreliability of the supplier considered is 0.5, which gives a total unreliability of 0.25. On the other hand, the impact on lead time is considered to be 1. Since the TRS is built as one unit, any issues with the manufacturing



Manufacturing DS	Remarks	Un-Reliability of robot tech	Un-Reliability of supp	Total Likelihood	Lead time impact
(M2111) 3 Sections	Less welds, shorter lead time, less risk of assembly problems, less fixturing, less QC. Not good from a supplier perspective. Worse cost per piece. Low risk for GKN, low risk of quality problems	0.3	0.3	0.09	0.3
(M2112) 1 Section	More welds, longer lead time, more risk of assembly problems, more fixturing, more QC. Better from a supplier perspective. Better cost per piece. High risk for GKN, high risk of quality problems	0.7	0.7	0.49	0.7
(M2113) 2 Sections	Moderate welds, moderate lead time, moderate risk of assembly problems, moderate fixturing, more QC. Moderate from a supplier perspective. moderate cost per piece. moderate risk for GKN, moderate risk of quality problems	0.5	0.5	0.25	0.5
(M2211) Positioned outer ring + strut	T-Shape seg. Assumption: If you have angular problems. More lead time efficient than ((M) Positioned outer ring)+((M) Positioned struts) combination, higher risk of embedded quality problems. Assume this one is tried and tested.	0.1	0.1	0.01	0.1
(M2221) Positioned inner ring	Lowest level assemblies. Least critical.	0.1	0.1	0.01	0.1
(M2311) Positioned outer ring	Lowest level assemblies. Moderately critical	0.3	0.3	0.09	0.2
(M2331) Positioned struts	Lowest level assemblies. Most critical aero quality wise.	0.2	0.3	0.06	0.2
(M2321) Position inner ring	Lowest level assemblies. Moderately critical	0.3	0.3	0.09	0.2
(M2421) Positioned inner ring + strut	More room to weld in the outer ring than the inner ring. Assume that this one has not been tested.	0.9	0.7	0.63	0.5
(M2411) Positioned outer ring		0.9	0.7	0.63	0.5
(M) Avoid assembly by building as one unit	Cast as whole. Very costly to redo. High quality problems, but can be repaired.	0.5	0.5	0.25	1

Impact likelihood values elicited from expert opinion

DSM populated with impact-likelihood values and imported into CAM

Figure 5. Likelihood and impact values relating to the manufacturing methods are used to populate the DSMs extracted from the EF-M instances, which are imported in Cambridge Advanced Modeller (CAM) for CPM analysis

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will lead to a delay to the entire product, which justifies the high value for impact. The propagated risks show that while most design solutions in the EF-M have mid incoming and outgoing risks, “lower the mount point and create a bump” is a risk propagation absorber while “Geometry of surfaces along the outer and inner perimeters” & “increase in vane lean angles and strut numbers” are highly susceptible to the risks. On the other hand, the case shown in the middle of Figure 6, shows the alternative relating to the welding robot supplier X and TRS built in three sections. In this alternative, “Supplier X” is a conventional supplier which means their unreliability was adjudged to be fairly low at 0.04, whereas the impact was high. This shows up in the risk plot in the top left corner, with the supplier option marked as a propagation absorber. For the third case on the right, a new welding robot “Supplier Y” is considered. Consequently, the total likelihood considered was 0.5, whereas the impact was 0.7. In the risk plot, this is reflected by the welding robot having a high incoming and outgoing risk, with the risk propagating to other components of the product EF-M such as the outer structure with a polygonal ring, the geometry on the outer perimeter and so on.

5 DISCUSSION

The method presented in this paper provides the opportunity to consider manufacturing alternatives in the early stages of design. The brief results from the industrial case study show interpretable results which may help managers with the required decision support. The method can also be expanded to analyse other aspects which are indirectly related to the manufacturing method individually, such as quality, cost etc. Combined effects can be elicited, for example, by performing sensitivity analysis leading to a potential way to select a method/supplier based on a company’s risk tolerance. A sensitivity analysis may also help mitigate the other limitation of this method such as the EF-M modelling needing expert knowledge of the product which is subjective. Like many other functional modelling methods, how an EF-M tree is built for a product depends both on the variations to be studied, and the modeller’s choice of organising the alternatives. This is somewhat mitigated by the possibility to instantiate multiple design options with the pre-defined design solution alternatives in the modelling. Further, such modelling may be cumbersome for products with a large number of functions and a large number of interactions. A related issue is regarding the combinatorial way of generating design alternatives which often leads to an extremely high number of instances generated with a small number of design solutions. Further, with every addition of design alternatives for individual functions, the resulting increase in the total number of instances can be exponential. As a part of the future scope of work, this will be mitigated by developing a ranking methodology to generate sets of low-risk solutions, eligible for further detailed analyses. The ranking metric could be based on, for instance, an aggregate value of risk for each of the concept-manufacturing method pairs. Another planned extension of this method is to capture and enable parametric variation of the design solutions. This will arguably enable a more direct link with aspects such as weld TRS, geometry assurance etc. The elicitation of likelihood and impact values depends on expert judgement, which also has its limitations. This problem is however very well recognised in the research community and a significant amount of work is available to address it (e.g. Hamraz et al. (2013), in the context of CPM). Experience from using CPM for comparison has resulted

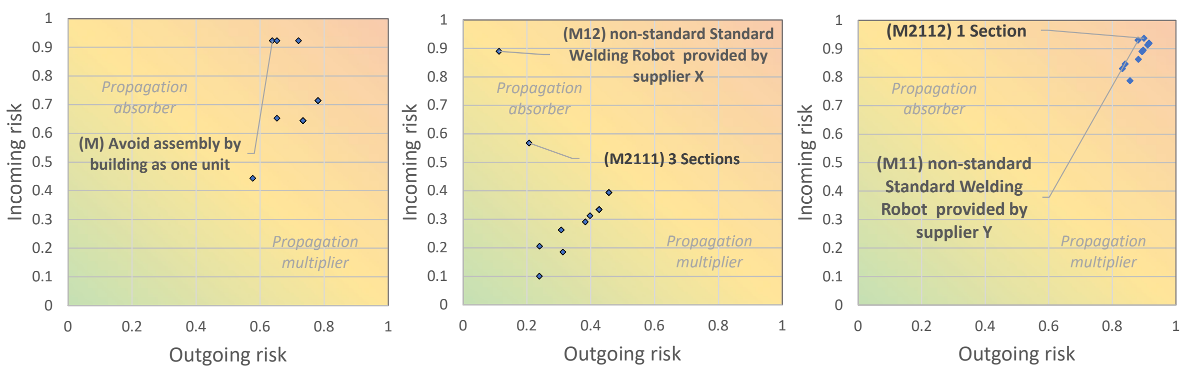

Figure 6. Risk plots of three of the 52 instances. The leftmost risk plot relates to the case of casting. The risk plot in the middle relates to the instance which uses welding robot manufacturer X with assembly in 3 sections. The risk plot on the right relates to the instance which uses welding robot manufacturer Y with assembly in 1 section. Label markers removed for better readability

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that relative orders of magnitude, e.g. "Low (0.2), Medium (0.5) and High (0.8)" give sufficient understanding to reveal trends and relative behaviours. Another limitation is the aggregating nature of the method. For instance, the averaging of the probabilities relating to the unreliability of technology and unreliability of the supplier in Section 4, may lead to a loss of information when it comes to analysing the results. Further, socio-technical aspects are currently not considered systematically. These may include dynamics of geo-political situations which may lead to the likelihood values, for instance, of a supply chain reliability, changing drastically during the course of the product development. Although only manufacturing-related risks are discussed in the case study, a similar approach can also help assess the supply-chain, quality and other aspects of the design life-cycle. Further, the manufacturing workflow can be taken into account. Aspects include risks associated with resource availability and scheduling, along with considerations on iterations in design (e.g. Wynn et al. (2014)). In the future, we intend to work on all the aforementioned limitations to make the method holistic and robust.

6 CONCLUSION

This paper reports the methodology developed for quantitative risk assessment in early design, which includes the effects of downstream manufacturing and supply chain uncertainties for the DIAS project. The methodology involves modelling the product and the manufacturing options in question using an enhanced function means modelling method. The modelling is used to combinatorially produce possible design options along with manufacturing options. The result is a set of product-manufacturing method DSMs which are then populated with likelihood and impact values for risk assessment. The results presented in this paper are the first results of its character that comes out of a currently ongoing EU project whose validation activities are still in progress. We also present the limitations of the method which will be addressed in future work.

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