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CONCEPT COMPARISON: A FUNCTION INTEGRITY INDICATOR

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Abstract

Comparing the propensity for risk in concepts with little commonality, such as different working principles, different number of functions and components, is challenging to achieve in a systematic and traceable manner. This paper builds on the Function Integrity Diagnosis and Documentation method to introduce a Function Integrity indicator as a means to quantitatively compare dissimilar design concepts based on risk assessment. The proposed indicator is intended to support designers converge on a suitable design concept based on considerations of risk to concept functions.

Keywords: risk management, conceptual design, functional modelling

1. Introduction

Product adaptation can be motivated through internal and external sources with objectives such as fault removal, customisation or changing requirements (Jarratt et al., 2011). As technical products are becoming more versatile and being applied across domains, emerging requirements are likely to become increasingly multifaceted and complex. Many organisations do not have the resources or capability to develop solutions for an intended adaptation without risking being outpaced by competitors (Müller et al., 2018). The a-posteriori integration of externally purchased products is a strategy to manage the complexity of fulfilling challenging requirements beyond the capabilities of an organisation. It allows an organisation to integrate functionality that it itself cannot develop in a competitive time frame. As such, if an organisation does not develop the technical solution and seeks the capabilities or components externally, the challenge becomes to determine which available concept is worthwhile to pursue.

In (n)ew (p)roduct (d)evelopment (NPD), a design concept is an early design state defining an initial solution for a design problem (Pahl et al., 2007). Design concepts are often vague and lack concreteness (Buur and Andreasen, 1989), hence in product adaptation, concept design is treated differently because there is concrete information available from the preceding product generation. However, in this paper, a *design concept* is any design intended for adapting a product which include any novel entities such as functions, components, etc. While available information (often unknown in NPD) accelerates concept understanding, novel entities can have propagating effects (Clarkson et al., 2004) which are crucial to consider when comparing concepts and implementing changes.

Besides the inherent functionality, *risk* is a prevalent consideration of the decision making process in engineering design (Hazelrigg, 1998). According to ISO 31000 (2018), risk is any uncertain effect on function-fulfilment of a system. Therefore, to better understand the risks of a concept as it develops, risk management is being progressively integrated into cohesive design methods (Bassler et al., 2011).

A common, often mandatory, method to assess the risk of a technical system is applying the (F)ailure (M)ode and (E)ffect (A)nalysis (FMEA) (Maurer and Kesper, 2011; Roth et al., 2015). This method facilitates a systematic analysis of inductively associating functions and components with possible failure modes. A failure mode is any risk carrier that can jeopardise the functions of a system. The designer reviews all identified failure modes and gauges their effects using a (R)isk (P)riority (N)number (RPN). Calculating the RPN depends on the organisation or applied industrial standard; however, it is usually the product of three determined factors, severity (S), likelihood of occurrence (O) and likelihood of detection (D), as illustrated in Equation (1).
The convention is that a high RPN indicates high-risk, which allows designers to prioritise failure modes for risk mitigation against an empirically determined acceptance threshold (Pahl et al., 2007). While the effect of thresholding has statistical weaknesses and leads to the disregard of risk to the greater system (Bowles, 2015), it is a pragmatic approach when analysing a large inventory of failure modes. Additionally, an approach for understanding the greater implications on a system is through allocating risks to an overarching entity by summing the partial risks to a (T)otal (S)ystem (R)isk (TSR), calculated applying Equation (2) (Lie Arntsen, 2007; Pfitzer, 2015). The risks can be allocated to the focus of the comparison; for example, to an overall concept as TSR or to an overarching function, where risks are allocated to the individual functions of a concept in (R)isk (t)o (F)unction (RtF_i).

$$RPN = S \times O \times D \qquad S = (1-10),\ O = (1-10),\ D = (10-1) \tag{1}$$

$$TSR = \sum_{i=1}^{i=n} RPN_i \qquad n = \#\, of\, risks \tag{2}$$

RtF_i does describe a relationship between function and risk; however, summing partial risk is not immediately applicable in decisive comparison. Table 1 compares two hypothetical concepts, but the designer cannot select one concept over the other based on the average RPN and RtF_i. Such a concept comparison requires a more nuanced method to indicate the relationship between function and risk.

Table 1. Comparison of two Concepts

Design Concept 1	Design Concept 2
# of concept functions: 5	# of concept functions: 6
# of identified failure modes: 100	# of identified failure modes: 300
TSR: 4000	TSR: 8000
Average RPN: 40	Average RPN: 27
Average RtF: 800	Average RtF: 1333

There are diverse conclusions about the utility of the FMEA (Bowles, 2015); however, because of its relevance among various industries, the possibility to recycle known risk information and relative ease of use, there is motivation to improve on its effectiveness (Maurer and Kesper, 2011). We have identified opportunity to integrate features of the FMEA into the (F)unction (I)ntegrity (D)ocumentation and (D)iagnosis (FIDD) method to create an indicator expressing the relationship between function and technical risk. This paper will extend on the FIDD method to determine a (F)unction (I)ntegrity (i)ndicator (FI_i) as a means to compare alternative design concepts for product adaptation.
This research aims to support designers to reliably adapt their products by analysing how the functionality of a design concept is vulnerable to risk. The results of the FIDD method and proposed indicator, should provide insight into the integrity of a concept (as a consequence of its individual functions) and quantitative indicators for comparison. In reference to the generic engineering change process (see Figure 1, Jarratt et al., 2011), the proposed method is intended to support the *risk/impact assessment of solutions*. It offers a cohesive approach, taking input from *identification of possible solutions* and providing comprehensive insight for the *selection and approval of a solution*.
The paper is structured into five sections. Section 2 will explain the FIDD method and will outline a cohesive approach for how to assess risk to function. Section 3 will define how this insight can be translated into a function integrity indicator. The fourth section describes how the proposed method was tested by applying it on an aerospace subsystem, namely a (H)old-(D)own and (R)elease (M)echanism (HDRM). It will conclude with a discussion and outlook for further research.

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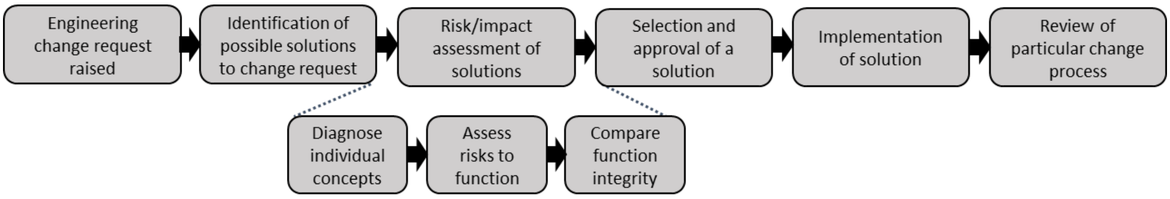

Figure 1. The FIDD method in reference to the generic engineering change process (adapted from Jarratt et al., 2011)

2. A concept analysis method for product adaptation

The earlier reliable decisions can be made in the process of converging from many alternatives to few, the more organisational resources can be constructively allocated (Andreasen and Hein, 2000). In product adaptation, having available information (often unknowns in NPD) leads designers to not adhere to systematic methods as they aim to expedite the process (Fricke et al., 2000). A disregard of method suggests that designers do not perceive value in applying a method (López Mesa and Bylund, 2011) and therefore design practice could benefit from additional methods dedicated toward design adaptation (Eisenbart and Kleinsmann, 2017).

2.1. Concept risk identification and assessment

A concept assessment method for product adaptation should balance pragmatism with detail to achieve high effectiveness with efficiency. To create a sufficient compromise, the FIDD method applies a system modelling approach for concept analysis (Wichmann et al., 2018). The (I)ntegrated (F)unction (M)odelling (IFM) framework was selected because it provides opportunity to integrate design concepts in an (I)ntegrated (F)unction (IF) model (Eisenbart et al., 2017). An IF model merges six design entities into matrix-based views, which supports interdisciplinary collaboration such as working across domains and organisations. Additionally, a matrix-based representation, such as the (D)esign (S)tructure (M)atrix (DSM), is common among engineering design to model system interaction (Eppinger and Browning, 2012) and is advantageous for continuous model refinement (Eisenbart et al., 2015).

Once an IF Model of the to-be adapted product or subsystem is created (see Gericke and Eisenbart, 2017) the FIDD method defines an approach in how to diagnose (identify) risks and their failure modes (see Figure 2). The seven step approach (see Wichmann et al., 2018) offers guidelines to analyse an IF model following a logical sequence that scrutinises the modelled entities.

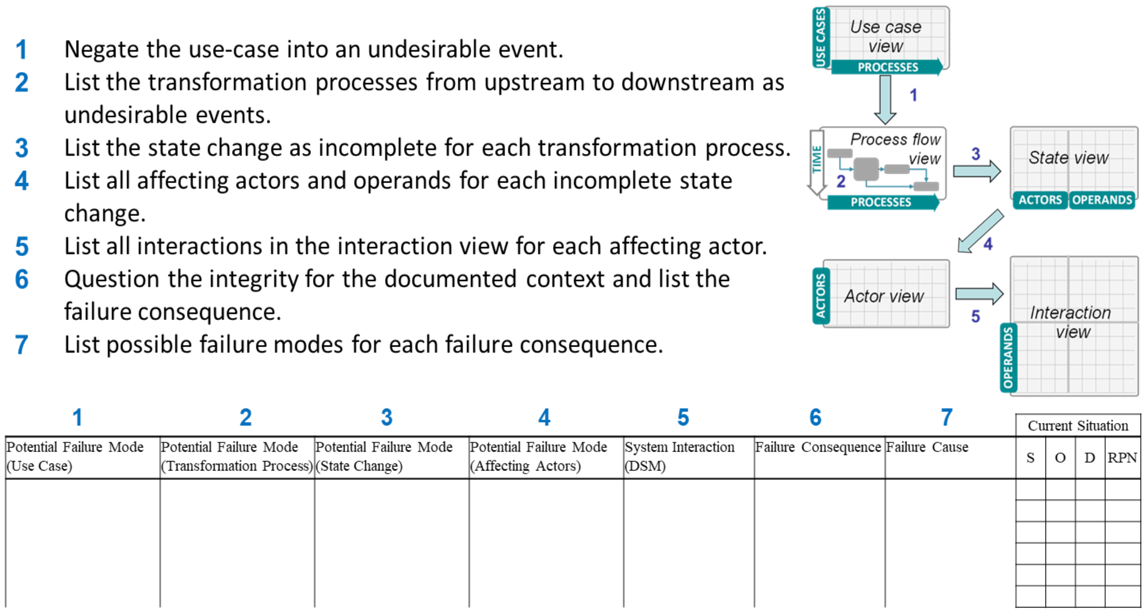

Figure 2. Risk identification applying the FIDD method (adapted from Wichmann et al., 2018)

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The identified failure modes can be documented in an extended template of a generic FMEA supporting the designer to track any failure mode to an overarching function and use-case. The RPN for each failure mode can then be calculated as defined by the applied standard of the organisation and it is then possible to calculate a RtF_i. As an RtF_i yields an indication to the accumulated risk jeopardising the fulfilment of a function, the individual function can be analysed to understand if the degree of risk to a function is acceptable.

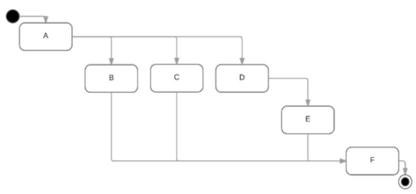
2.2. Assessing function contribution

In fulfilling an overarching function, not all sub-functions contribute equally (Pahl et al., 2007). Individual functions have different dependencies in their inputs and outputs, and it should not be assumed that the degree of transformation is evenly proportionate. (V)alue (S)tream (M)apping (VSM) is a method that lets engineering designers determine the individual contribution of a sub function to their respective overarching main function or overall system purpose (McManus, 2005).
Designers can rank the contribution of a function using intuition (similar to FMEA). The FIDD method provides means to calculate the individual (F)unction (C)ontribution (FC_i) quantitatively. FC_i is calculated by translating the IF model process view into a (F)unction (D)ependency (M)atrix (FDM). The designer then creates an initial ranking for the degree of transformation and process dependencies (similar to VSM). Finally, in applying an approach by Gries and Gericke (2009), FC_i can be calculated from ranked values. Equation (3) defines how to calculate the columns and Equation (4) the rows, a hypothetical example is illustrated in Figure 3.

$$a_{ii} = a_{ii} + \sum_{j=n;j\neq i}^{n} a_{ji} \quad (3)$$

$$a_{ij} = (a_{ij} * a_{ii})_{j=1,\dots,n;j\neq i} \quad (4)$$

In the illustrated example, a process model (Figure 3 left) with Functions A through F are listed in the FDM (Figure 3 middle). The functions are initially given an ordinal rating of contribution from low to high (1-10) and a rated dependency from minor to crucial (0-1). A new FC_i is calculated through considering the contribution of down stream functions and prospective dependencies (Figure 3 right). By ranking the function contribution and dependencies separately, determining a calculated contribution of a function becomes more traceable. Take for example FC_D of 12.50, which is raised from the initially ranked 4.0 because the dependent Function E cannot fulfil its function if Function D is unfulfilled. It is because of the contribution of the dependent function and degree of dependency that FC_D is raised.



	A	B	C	D	E	F
A	7.0					
B	0.5	4.0				
C	0.5		5.0			
D	0.7			4.0		
E				1.0	6.0	
F		0.2	0.3		0.5	5.0

	A	B	C	D	E	F
A	21.50					
B	2.50	5.00				
C	3.25		6.5			
D	8.75			12.50		
E				8.50	8.50	
F		1.00	1.50		2.50	5.00

Figure 3. Determining FC_i by translating the IF process model (left) into a ranked FDM (middle) to a calculated FDM (right)

With an indication of the risks to an individual function and the degree in which a function contributes to an overarching process, the designer can visualise this data using a fever chart with two axes comparing the Relative FC_i (see Equation (5)) and Relative RtF_i (see Equation (6)).

$$Relative\ FC_i\ (\%) = \frac{FC_i}{\sum_{i=1}^{i=n} Total\ FC} \quad (5)$$

$$Relative\ RtF_i\ (\%) = \frac{RtF_i}{TSR} \quad (6)$$

The resulting visual provides insight into how the functions of one concept contribute to the functionality of the concept and how those functions are vulnerable to identified risks. Figure 4 illustrates this relationship of nine functions. Take for example Function E of Figure 4, which

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contributes 17% to fulfilling the overarching process (FC_E=17%) and contributes 12% of the risk (RtF_E=12%) in this concept.

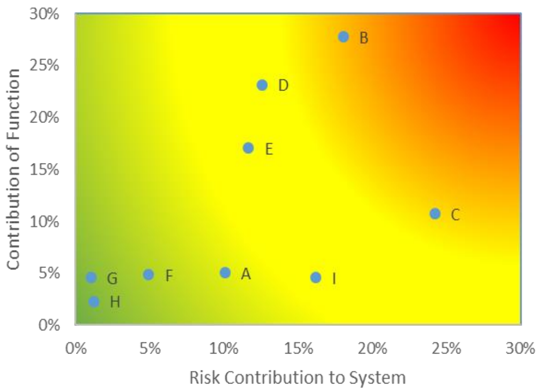

Figure 4. Relative function and risk contribution

2.3. Objective

Through performing the FIDD method, the designer acquires an understanding of the risks of a design concept for a to-be-adapted product. The method provides structure that supports designers to be thorough and systematic. While this assessment may provide insight for ostensive decision making, the determined data currently provides no traceable means for quantitative comparison with another concept. A designer cannot decisively compare two fever charts documenting the FC_i and RtF_i of a function (see Figure 4) of two different concepts because there is no common reference.
Here we intend to propose an indicator for function integrity to determine how one concept may be more suitable than another based on the performed assessment. As long as there is one overarching function (i.e. in an IF Model, a use-case), the indicator should be capable to compare:

- concepts applying different working principles;
- concepts with different number of functions and components;
- concepts with a different number of identified failure modes;
- concepts with varying degrees of novelty.

3. A proposal to quantify function integrity

ISO/IEC 15393 (2017) defines an indicator as a means to gauge the degree of some phenomenon and provide knowledge to the designer. Operatively, they must be repeatable, sufficiently sensitive and be able to be calibrated. Some indicators are impartial, where a desired trend is not self-evident such as a pH level in chemistry; others have an inherent objective no matter the context such as manufacturing process capability (C_{pk}). Function integrity is of the latter and has a desired trend of greater is better than less. The (F)unction (I)ntegrity (i)ndicator (FI_i) expresses the relationship between (F)unction (C)ontribution (FC_i) and (R)isk (t)o (F)unction (RtF_i) with the overall condition, *the higher the contribution of a function, the lower the degree of risk is acceptable*.

3.1. A common scale for risk to function

RtF_i is not an indicator appropriate for comparison because of its dependency on the number of identified failure modes, which are analogous to the number of components, see Table 1. A means to compare the RtF_i of different concepts is to normalise RtF_i on a scale of a possible maximum as an (A)djusted RtF_i ($ARtF_i$). The maximum RPN for one failure mode is 10x10x10=1000. Equation (7) determines how to calculate $ARtF_i$. Figure 5 illustrates the transition from $RtF_i$to $ARtF_i$. The perspective shifts from where the risk is relative to a concept, to where the risk is scaled against a possible maximum.

$$ARtF_i = \frac{RtF_i}{\#\ of\ identied\ Failure\ Modes \cdot 1000} \quad (7)$$

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With an $ARtF_i$ it is possible to understand how each function is vulnerable to risk and compare the functions of one concept with another. The next step is determining a comparable reference for both dimensions, FC_i and $ARtF_i$.

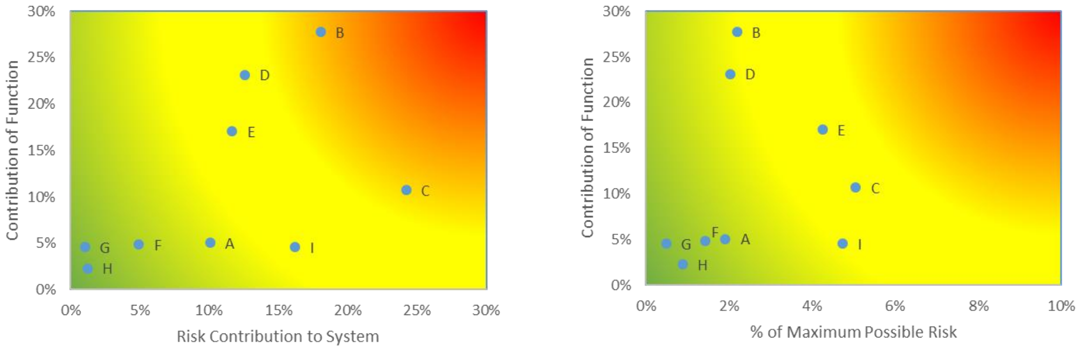

Figure 5. Relative risk contribution (left) with the possible maximum ARtF (right)

3.2. A curve of reference

The colour coding of the fever charts emphasises the condition of function integrity, in which it is undesirable that functions with high process contribution are vulnerable to much risk. This is analogous to a curve of exponential decay making it possible to examine the functions of different concepts to a common (R)eference (C)urve (RC). A natural curve that can be calibrated for different contexts and simple to model is the exponential function (Goldstein et al., 2005). The designer can determine a (R)isk (L)imit (RL) for the absolute maximum acceptable $ARtF_i$ and an (A)mplifying (F)actor (AF) for risk averse contexts. RC can be determined with Equation (8). An exponential factor (AF) can be determined empirically, or it can be calculated using Equation (9) in which the designer sets an FC_i and RtF_i relationship threshold. The same RC can be superimposed on the alternative design concepts which provides a traceable reference beyond a colour coding scheme, see Figure 6.

$$RC = RL \cdot e^{-AF \cdot FC_i} \tag{8}$$

$$AF = \frac{\ln RtF_i}{-FC_i} \tag{9}$$

Finally, the FI_i indicates how $ARtF_i$ compares to the determined RC, using Equation (10). If $ARtF_i < e^{-FC_i}$, either through a low FC_i or RtF_i, then the FI_i is positive. In case $ARtF_i > e^{-FC_i}$, then the FI_i is negative.

$$FI_i = (L \cdot e^{-AF \cdot FC_i}) - ARtF_i \tag{10}$$

When comparing multiple design concepts with the same RC, the higher the function integrity of the individual functions the more likely the concept is to be selected for implementation. Contrary to a high function integrity, a negative FI_i will reduce the possibility that a concept is selected. Figure 6 illustrates three functions of the design concept with a negative FI_i because these functions are vulnerable to more risk than is considered acceptable in reference to the determined RC.

4. Concept comparison

The FIDD method was tested by the authors on an aerospace subsystem called (H)old-(D)own and (R)elease (M)echanism (HDRM). This mechatronic system fulfils two main functions on a satellite; hold-down the solar panels during launch and subsequently release (deploy) the solar panels in orbit. There are a variety of commercially available remote actuators, using electromagnets, shape memory alloys or pyrotechnical concepts. Two alternative HDRM's were compared for function integrity and the FI_i, to simulate the applicability of the FIDD method. Figure 7 illustrates two concepts, one applying a shape memory alloy (C1, left) and the other a thermal cutter system (C2, right).

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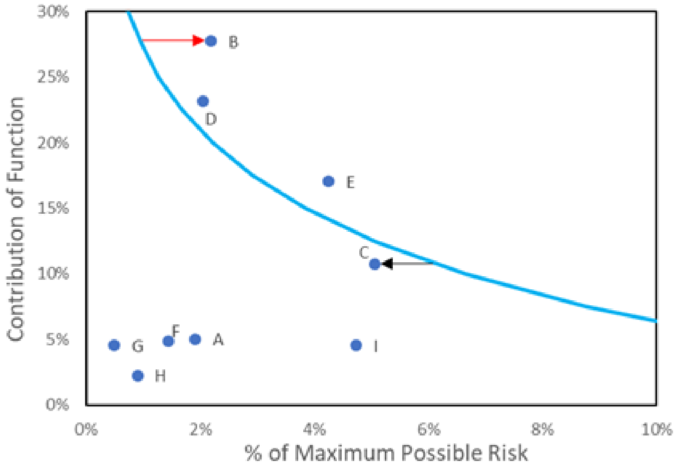

Figure 6. Concept functions compared to a common reference curve

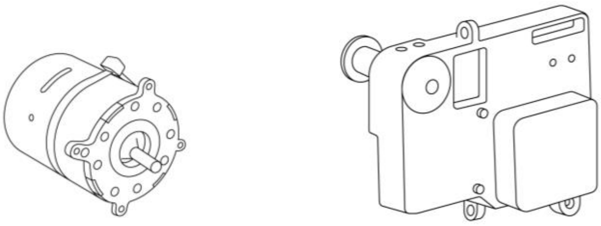

Figure 7. Hold down and release mechanism concepts, C_1 (left) and C_2 (right)

4.1. Comparison and results

This section will outline how two solution concepts for the HDRM were compared for the overarching function *release the solar wings*. An initial IF model of the satellite body was created. Next, the two design concepts were integrated into this model to become two separate IF models. These models were discussed among four researchers to clarify initial assumptions and to refine the model as more knowledge was gathered. C1 had 12 modelled functions and 60 modelled components, while C2 had 9 modelled functions and 48 modelled components. Based on the refined IF models, the FIDD method was applied to identify risks for each concept. The commercial vendors of these subsystems were not engaged to share their existing FMEA data.

Once the function contribution and relative risk were determined for each function and plotted in a chart, the AF was calculated by the involved researchers. Each researcher defined three FC_i and RtF_i relationships which they would consider the threshold of being unacceptable, i.e. for which FI_i should equal zero. These 12 relationships were normalised to the group and the exponential factor was calculated using Equation (9) to be AF = 7.6. The researchers collectively determined a maximum risk limit (RL = 0.3), meaning that it is unacceptable that a function with negligible contribution ($FC_i \approx$ 1%) can have a $ARtF_i$ of 30%. The smaller the defined RL, the more a concept is penalised if there are functions with high risk. A RC was then calculated using Equation (8) and Figure 8 illustrates the charts of C1 and C2 with the resulting RC.

With a determined RC enabling the comparison of both concepts, the FC_i for each function can be calculated. The results for C1 and C2 are listed in Table 2.

There are various statistical approaches to compare the resulting indicators. However, as the data was not relatively skewed, it was assumed that the averages and the medians (C1 = 0.0861; C2 = 0.0797) are acceptable as representative indicators. A sensitivity test was conducted by modifying the AF and the limit $ARtF_i$ however, this did not change the result. From the determined C1 FI_i and C2 FI_i, C1 has the higher function integrity and is the more suitable option to pursue in this context. All efforts can now be intensively focused to adapt C1 and the existing satellite for integration. Subsequent activities would be to gather more information about C1, such as engaging the vendor and addressing the individually identified risks.

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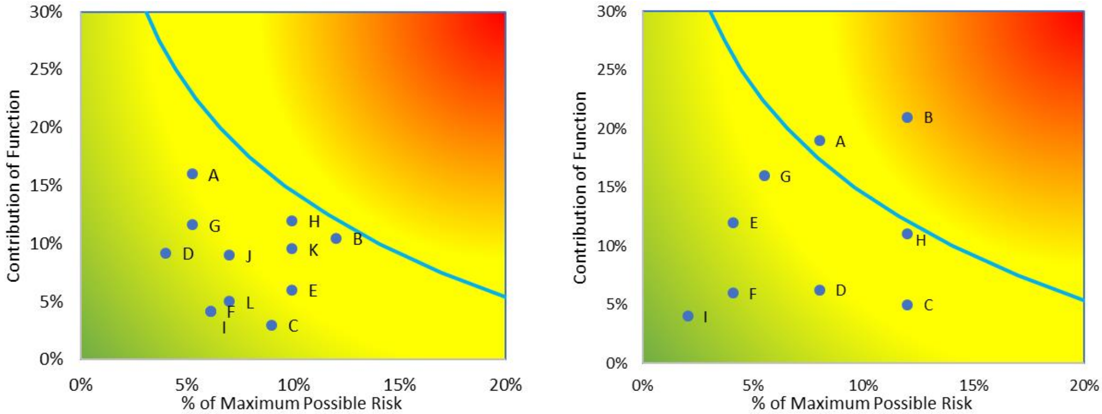

Figure 8. Concept comparison C1 (left) and C2 (right)

Table 2. Results of concept comparison

C1				C2			
Functions	12	Components	60	Functions	9	Components	48
Identified Failure Modes			308	Identified Failure Modes			204
TSR	23500			TSR	16238		
Function	FC_i	$ARtF_i$	FI_i	Function	FC_i	$ARtF_i$	FI_i
CF_A	0.16	0.05	0.04	CF_A	0.19	0.08	-0.01
CF_B	0.10	0.12	0.02	CF_B	0.21	0.12	-0.06
CF_C	0.03	0.09	0.15	CF_C	0.05	0.12	0.09
CF_D	0.09	0.04	0.11	CF_D	0.06	0.08	0.11
CF_E	0.06	0.10	0.09	CF_E	0.12	0.04	0.08
CF_F	0.04	0.06	0.16	CF_F	0.06	0.04	0.15
CF_G	0.12	0.05	0.07	CF_G	0.16	0.06	0.03
CF_H	0.12	0.10	0.02	CF_H	0.11	0.12	0.01
CF_I	0.04	0.06	0.16	CF_I	0.04	0.06	0.16
CF_J	0.09	0.07	0.08			C2 FI_i	**0.0620**
CF_K	0.10	0.10	0.05				
CF_L	0.05	0.07	0.14				
		C1 FI_i	**0.0892**				

4.2. Discussion

FIDD, as a means to facilitate concept selection, is intended to be applied in a risk averse context such as the aerospace industry or in any context where an additional degree of rigour is required to avoid a critical risk to function fulfilment. The FIDD method supports designers systematically converge on a design concept in a way that is thorough and ensures traceability. Applying the FIDD method should allow designers to expedite product adaptation if a reliable design concept – one with high function integrity – can be determined. However, this requires that designers have confidence that the method and the resulting FI_i are reliable in comparing diverse design concepts.

One challenge in comparing alternative design concepts is gathering sufficient insight for risk assessment with little concrete information. As designers must accommodate an uncertain availability of information and a varying degree of novelty, the FIDD method builds on analysing an IF model and its six design entities for risk identification. System modelling allows designers to gather a degree of insight about a design concept before analysing more detailed features of embodiment such as structural topology. In this project, a significant inventory of risks (failure modes) were identified before engaging the vendor of the subsystems.

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As many industries are obligated to apply a FMEA to analyse identified failure modes, the FIDD method builds on this rigour and allocates the determined RPN of each failure mode to an overarching function. Allocating risk to function allows designers to explicitly map from which failure modes and to what degree a function is vulnerable. Additionally, following a VSM process to calculate how a function contributes to an overarching function is more traceable and representative than an intuitive ranking. Understanding the contribution of function and risk to an overarching concept provides valuable insight that can subsequently focus risk mitigation activities. However, at this point the analysis is only relative to one concept and does not allow decisive concept comparison.

In this regard, the FIDD method defines how to create a reference with which to compare design concepts. Creating a reference remains contestable as a RC underlies the same statistical weaknesses as an acceptance threshold of the FMEA. The RC does not act as a threshold, however if modifying the RC can change the result of a comparison, then there needs to be a traceable way to calibrate the RC to the needs of an organisation. The current approach is to apply the collective insight of the researchers which is analogous to the empirical definition of industrial acceptance thresholds. In the case of this assessment, even an imperfect RC provided an indicator relevant for comparison as the final result did not change after modification. While the RC was deemed a pragmatic solution to compare dissimilar concepts, future research will investigate how to better calibrate the RC.

The resulting FI_i is considered applicable for relatively early concept analysis and comparison; however, it was determined that it would be less suitable for later stage assessments when concrete measurables are more available. The FI_i provides a more holistic indication, such as an RPN, and does not capture concrete component properties (dimensions, weight, aesthetics, etc.). The FI_i would not be applicable in detailed optimisation activities and there are currently no logical links to performing simulations.

The FIDD method has been applied for concept risk assessment but, there is currently no corroboration of confidence in the FI_i for the purpose of concept comparison. The newly proposed FI_i requires further testing on more complex systems and with more diverging design concepts to investigate if the application of the method can be reliably extended. Our outlook is to test the reliability of the FI_i in an empirical case-study to determine the level of perceived confidence of designers comparing alternative design concepts. Further research will seek to identify if the FI_i is a reliable indicator worthy to be adopted in concept selection methods.

5. Conclusion

In the process of product adaptation, selecting a design concept with limited risk to function fulfilment is a logical objective. However, converging on a suitable design concept from many alternatives is challenging to achieve in a systematic and traceable manner. Comparing concepts with little commonality, such as different working principles, different number of functions and components, does not offer much opportunity for quantitative comparison. This paper builds on the (F)unction (I)ntegrity (D)iagnosis and (D)ocumentation (FIDD) method to introduce the (F)unction (I)ntegrity indicator (FI_i) as a means to quantitatively compare dissimilar design concepts based on risk assessment.

The FI_i assumes its inputs from applying methods, analogous to a fault tree analysis, FMEA and VSM, all structured into a cohesive method. What differentiates the FIDD method from these established methods, is that with manageable sophistication a designer can compare alternative design concepts against a common quantifiable reference of function integrity. In applying the FIDD method, it is our hope that designers will be able to adapt their products by integrating reliable design concepts with high function integrity.

References

Andreasen, M.M. and Hein, L. (2000), *Integrated Product Development*, Institute for Product Development.

Bassler, D. et al. (2011), "A comparison of the integration of risk management principles in product development", *Proceedings of the 18th International Conference on Engineering Design (ICED11)*, Vol. 3 No. January 2016, pp. 306-316.

Bowles, J. (2015), "An Assessment of RPN Prioritization in a Failure Modes Effects and Criticality Analysis", *Journal of the IEST, IEEE*, Vol. 47 No. 1, pp. 51-56. https://doi.org/10.17764/jiet.47.1.y576m26127157313

https://doi.org/10.1017/dsd.2020.70 Published online by Cambridge University Press

Buur, J. and Andreasen, M.M. (1989), "Design models in mechatronic product development", *Design Studies*, Vol. 10 No. 3, pp. 155-162. https://doi.org/10.1016/0142-694X(89)90033-1

Clarkson, P.J., Simons, C. and Eckert, C. (2004), "Predicting Change Propagation in Complex Design", *Journal of Mechanical Design*, Vol. 126 No. 5, p. 788. https://doi.org/10.1115/1.1765117

Eisenbart, B. et al. (2017), "A DSM-based framework for integrated function modelling: concept, application and evaluation", *Research in Engineering Design*, Vol. 28 No. 1, pp. 25-51. https://doi.org/10.1007/s00163-016-0228-1

Eisenbart, B. and Kleinsmann, M. (2017), "Implementing shared function modelling in practice: experiences in six companies developing mechatronic products and PSS", *Journal of Engineering Design*, Vol. 28 No. 10–12, pp. 765-798. https://doi.org/10.1080/09544828.2017.1395395

Eisenbart, B. et al. (2015), "Integrated function modelling: Comparing the IFM framework with SYSML", *Proceedings of the International Conference on Engineering Design, ICED*, Vol. 5 No. DS 80-05, pp. 1-12.

Eppinger, S.D. and Browning, T.R. (2012), *Design Structure Matrix Methods and Applications*, MIT Press, Cambridge.

Fricke, E. et al. (2000), "Coping with changes: Causes, findings, and strategies", *Systems Engineering*, Vol. 3 No. 4, pp. 169-179. https://doi.org/10.1002/1520-6858(2000)3:4<169::AID-SYS1>3.0.CO;2-W

Gericke, K. and Eisenbart, B. (2017), "The integrated function modeling framework and its relation to function structures", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 31 No. 4, pp. 436-457. https://doi.org/10.1017/S089006041700049X

Goldstein, L.J. et al. (2005), *Brief Calculus and Its Applications*, 11th ed., Pearson Education.

Gries, B. and Gericke, K. (2009), "A method for identifying improvement potentials within product development processes", *Proceedings of the 17th International Conference on Engineering Design (ICED'09)*, Vol. 1 No. August, pp. 291-298.

Hazelrigg, G.A. (1998), "A Framework for Decision-Based Engineering Design", *Journal of Mechanical Design*, Vol. 120 No. 4, p. 653. https://doi.org/10.1115/1.2829328

ISO. (2017), ISO/IEC 15939 Systems and Software Engineering — Measurement Process, International Organization for Standardisation, Geneva, available at: https://www.iso.org/obp/ui/#iso:std:iso-iec-ieee:15939:ed-1:v1:en.

ISO. (2018), ISO 31000 Risk Management, International Organization for Standardisation, Geneva.

Jarratt, T.A.W. et al. (2011), "Engineering change: An overview and perspective on the literature", *Research in Engineering Design*, Vol. 22 No. 2, pp. 103-124. https://doi.org/10.1007/s00163-010-0097-y

Lie Arntsen, V. (2007), *Summation of Risk: Assessment of Total System Risk for Complex Systems*, Uppsala University.

López Mesa, B. and Bylund, N. (2011), "A study of the use of concept selection methods from inside a company", *Research in Engineering Design*, Vol. 22 No. 1, pp. 7-27. https://doi.org/10.1007/s00163-010-0093-2

Maurer, M. and Kesper, H. (2011), "eFMEA – Raising Efficiency of FMEA by Matrix-Based Function and Failure Networks", *Research into Design – Supporting Sustainable Product Development*, pp. 179-186.

McManus, H.L. (2005), "Product Development Value Stream Mapping", Lean Aerospace Initiative, No. September.

Müller, J.M., Buliga, O. and Voigt, K.I. (2018), "Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0", *Technological Forecasting and Social Change, Elsevier*, Vol. 132 No. December 2017, pp. 2-17. https://doi.org/10.1016/j.techfore.2017.12.019ss

Pahl, G. et al. (2007), *Engineering Design a Systematic Approach*, 3rd ed.

Pfitzer, T. (2015), *Risk Summation*, International System Safety Conference, San Diego.

Roth, M., Gehrlicher, S. and Lindemann, U. (2015), "Safety of individual products perspectives in the context of current practices and challenges", *Preceedings of the 20th International Conference on Engineering Design ICED*. No. July, pp. 113-122.

Wichmann, R.L. et al. (2018), "A method for Function Integrity Diagnosis and Documentation: FIDD", *DESIGN 2018 15th International Design Conference*, Dubrovnik, The Design Society, pp. 1429-1440. https://doi.org/10.21278/idc.2018.0211

https://doi.org/10.1017/dsd.2020.70 Published online by Cambridge University Press