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A MODELLING METHOD TO MANAGE CHANGE PROPAGATION

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ABSTRACT

Many new products are developed through modifications of existing ones. However, the engineering changes required to implement such modifications can sometimes propagate, requiring further changes to the design. The propagation of change is therefore a significant influence on resource allocation when designing new products. This paper presents a modelling method that aims to manage the effects of change propagation and is applied to the design of a jet engine fan. The method uses a matrix-based approach to model the dependencies between the solution alternatives, the potential change propagation brought about by the solutions, the affected product attributes, and the resources needed to carry out the change work. It allows engineers to trace critical change propagation paths and manage them. The findings suggest that this modelling method is suitable for assessing solution alternatives during preliminary design and can help support engineers to explore the design space in the right direction.

Keywords: engineering change, change propagation, change management

1 INTRODUCTION

Engineering changes have always been fundamental to the development of new products [1]. Instead of designing new products from scratch, it can be more efficient to carry out engineering changes to existing products. Engineering changes facilitate the reuse of tested components in new products and cause less disruption to the supply chain. However, changes to a product can sometimes lead to undesired change propagation [2]. This is particularly true for complex technical systems (for instance [3]). In addition, it is possible for changes that were initially thought as simple to propagate uncontrollably, resulting in change *Avalanches* [4]. Although companies may have a choice to drop further changes and settle with sub-optimal products, they are sometimes bound by legislation to deliver new products that must meet certain product performance. For instance, new engines must satisfy emission legislation before they can be sold. It is thus important to model and predict how engineering changes can propagate in order to better manage the design process. Such sentiment is common among companies. For instance, during the *Engineering Change* workshop held by the Cambridge-MIT Institute in 2008, various companies expressed their recognition of the need to effectively manage engineering changes. In a follow-up interview, a staff from an aerospace company highlighted that "… the propagation of change is a concern. That is clear. And it does give us problems as well by not anticipating everything…" It was also added that having a system that can model the impact on the organisation (company), and not just the product, can be useful in providing insights.

To address this concern, this paper presents a modelling method that analyses the effects of change propagation on both the product and the organisation. The method allows engineers to trace change propagation paths from design requirements to affected product components and design personnel, and focuses on the design of complex product during preliminary design. The main objective of the method is to manage undesired change propagation and support resource planning during the early stages of the design process. The design of a jet engine fan is used throughout this paper as an example to illustrate how change propagation can affect the design process and demonstrate how the modelling method can be applied to provide insights.

The rest of the paper is organised as follows: Section 2 introduces the case study example on which later sections draw. Section 3 reviews previous work on change propagation modelling and resource planning, and identifies how current methods fall short in addressing the issues stated in Section 2. Section 4 draws on this analysis to present a modelling method that attempts to manage change propagation and support resource planning. Section 5 demonstrates how the modelling method can be applied to the design of a jet engine fan. The advantages and limitations of the method are discussed in Section 6. Lastly, Section 7 summarises the work and proposes future research directions.

2 AN EXAMPLE OF CHANGE PROPAGATION

This section describes the design of a jet engine fan and discusses how engineering changes can propagate in an industrial context. Figure 1 shows a picture of a jet engine fan. Two main components of a jet engine fan are the fan blades and the fan disc. These components are connected together and rotate as a unit during operation.

Terms	Example
product attribute	weight
required attribute	*low* weight
product component	fan blade
feature	fan blade height
design-feature	*reduced* fan blade height

Figure 1: Jet engine fan (courtesy of Rolls-Royce)

In an effort to produce a light-weight jet engine fan, engineers can explore different solution alternatives that can reduce the overall fan weight. These solution alternatives are differentiated by their distinctive design-features which describe how the new requirement can be met. For instance, engineers can reduce the fan blade height (design-feature), which involves modifying the fan blades (component), to reduce the overall weight (product attribute). However, it should be noted that a ‘reduced fan blade height’ design-feature can also influence other product attributes, such as the noise level, and consequently affect the overall performance of the product.

The complexity of the problem increases when changes propagate across to other components. For instance, during the design process, there might be an emerging need to increase the fan disc diameter to accommodate the ‘reduced fan blade height’ design-feature. As the ‘fan disc diameter’ is a feature that can also affect the weight of the jet engine fan (increasing the fan disc diameter can cause an increment in weight), the net effect of these changes might result in a jet engine fan that does not meet the new weight requirement. This can subsequently set off a series of last-minute changes to reduce the weight of the jet engine fan.

It should also be noted that changes (planned or unplanned) can only be implemented when resources are available. For large complex products, each component or module might be handled by different teams. Each team can subsequently be further classified into different specialisations (e.g. mechanical, electrical, etc.). The propagation of changes across different components can therefore affect various teams that were not initially planned for the project. For instance, if it was found during the design process that the only way to implement the ‘reduced fan blade height’ design-feature is to increase the fan disc diameter, additional resources related to the fan disc must be drawn into the project to complete the changes. Unavailability of these additional resources within the pre-determined project schedule can in turn result in project delays. Hence, change propagation is an issue that affects both the product and the organisation.

3 PREVIOUS WORK

There are various papers in the literature that discusses the effects of engineering changes. For instance, in an attempt to improve the changeability of products, Fricke and Schulz [5] propose the principles of Design for Changeability (DfC) and highlighted the four main aspects as Robustness, Flexibility, Agility, and Adaptation. Other literature suggests ways to model how the product attributes can be affected when parts of the product are changed. For instance, Ollinger and Stahovich [6] introduce the RedesignIT tool to assess probable behavioural side effects during a design change. Weber et al. [7] and Conrad et al. [8] describe a Property-Driven Development approach to assess the effects of changes by analysing the relationship between product behaviour and component characteristics given a set of internal dependencies and external conditions. Cohen et al. [9] propose a methodology called Change Favourable Representation (C-FAR) to capture possible change consequences using existing product data information. Hauser and Clausing [10] describe the use of the House of Quality (HoQ) 'roof' matrix to examine the interactions between design-features if changes do propagate. Clarkson et al. [2] introduce the Change Prediction Method (CPM) which predicts potential component change propagation through the modelling of component dependencies. Koh et al. [11] subsequently extended the CPM application to consider the 'knock-on' effects on the product attributes. These approaches, nevertheless, do not analyse the consequences of change propagation on the organization.

Change propagation can affect various aspects of the organisation. For instance, the impact on company documentation resulting from engineering changes was discussed by Pikosz and Malmqvist [12]. Cost analysis can also be affected as described by Rios et al. [13]. In addition, the emergence of unplanned change propagation can result in project delays and disruptions in design resources. Although there has been previous research on generating robust resource plans, for example [14], such methods model the flow of information and tasks rather than the flow of engineering change propagation.

In this paper, we extend the work described by Koh et al. [11] to examine the change propagation effects on both the product and the organisation. More specifically, we present a method that models the dependencies between the solution alternatives, the potential change propagation brought about by the solutions, the affected product attributes, and the resources needed to carry out the change work. This method can be used to support the assessment of solution alternatives in an engineering change process (Stage 3 in Figure 1). Such assessment is similar to the concept selection phase as described by Ulrich and Eppinger [15] except the evaluation criteria are much broader, considering the overall change impact on both the product and the organization.

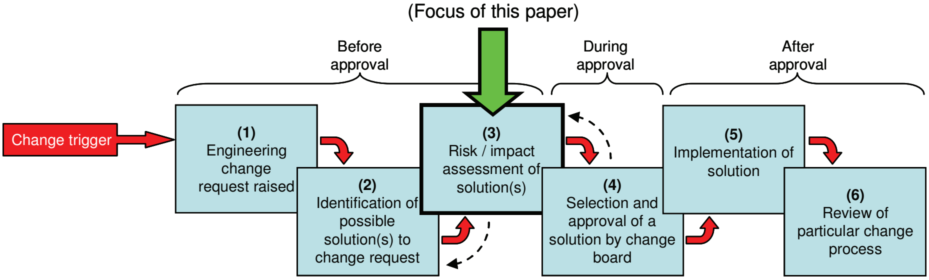


Figure 2: Generic engineering change process (adapted from [1])

4 PROPOSED METHOD

One of the main challenges in change propagation modelling is to decide on the right level of detail for analysis. The level of detail used in change propagation analysis directly influences factors such as ease of model generation and maintenance (effort), adaptability to different design cases (flexibility), and reliability of the analysis (accuracy) [16]. In addition, the 'right' level of detail for analysis can vary over time as the quality of the design details, the number of solution alternatives, and the purpose of the analysis change during the design process.

During preliminary design, different solution alternatives are usually generated to meet the new requirements. Each solution alternative is differentiated by its distinctive design-feature and outlines the required (planned) changes. Even though the design-features might be of detailed description, information on how these features will blend with the rest of the product is generally unavailable as the bill of materials is usually vague at such an early stage. Consequently, the analysis of change propagation at a low level of detail is more feasible during preliminary design. However, in order to make pragmatic use of the analysis results, the level of detail used must also suit the purpose of the analysis. A staff from an aerospace company described that as "(to be able to) target the right analyses on the right parts of the right options". This shapes the framework behind our modelling approach (see Figure 3).

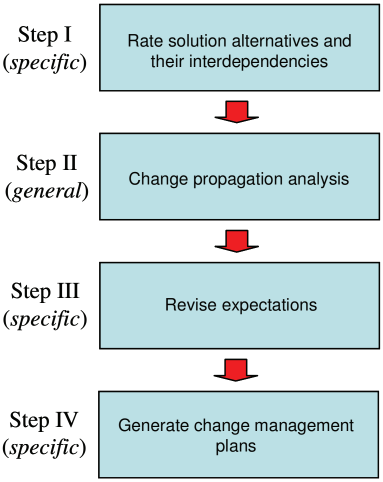


Figure 3: Framework of the change propagation modelling approach

In Step I, the solution alternatives are rated with respect to required product attributes. For example, the 'reduced fan blade height' design-feature in Section 2 will be rated with respect to the 'weight' attribute. In addition, the interactions between design-features such as 'reduced fan blade height' and 'reduce fan disc diameter' are also captured in this step. These ratings can be acquired either through discussions or design databases. The analysis in this step models the influence of specific design changes and is thus regarded as *specific*. Subsequently, in Step II, these design-features are linked to relevant product components. For instance, the 'reduced fan blade height' design-feature will be linked to the 'fan blade' component. This brings the analysis to a more *general* and abstract level. The purpose is to facilitate change propagation analysis at a lower level of detail (component level) as detailed description of the product might not be available at this stage. Once the analysis has been made, the next step (Step III) is to relate the change propagation information of each product component back to the relevant design-features and subsequently revise the ratings for each solution alternative. The expected resources required to carry out the changes can also be revised (or generated) by taking the possible change propagation into account. This brings the analysis back to the more *specific* and detailed level. These revised ratings and resource plans can then be used to support the assessment of solution alternatives and the generation of change management plans in Step IV.

As this modelling method involves the mapping of information between several matrices of different domains, a Multiple Domain Matrix (MDM) as shown in Figure 4 is used in this paper to illustrate the flow of information (refer to [17] on mapping between domains). A step-by-step description of the entire approach is presented in the following subsections.

4.1 Step I: Rate solution alternatives and their interdependencies

Step I involves Field A and Field B of the Multiple Domain Matrix (MDM) as shown in Figure 4. This part of the MDM acts as a second phase House of Quality (HoQ) to rate the solution alternatives with respect to the product attributes (See [10] on phases of HoQ). For instance, in Field A, the 'reduced fan blade height' design-feature is rated with respect to *required* product attributes such as '*low* weight'. A positive performance rating (*PI*) will be assigned to the appropriate cell if reducing the fan blade height can significantly reduce the weight of the jet engine fan. This is similar to a Pugh concept scoring chart [18]. Subsequently, the interactions between the design-features are accounted for in Field B which acts as the 'roof' of the House of Quality (HoQ). This field captures the implicit design constraints and describes how the design-features will be affected if changes do propagate. For instance, if the implementation of the 'reduced fan blade height' design-feature conflicts with the 'reduced fan disc diameter' design-feature, a negative interaction rating (*DI*) will be assigned accordingly in Field B.

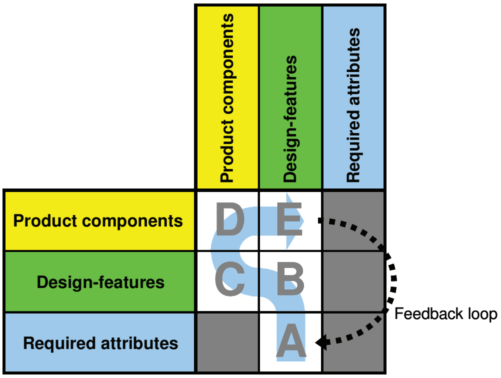


Figure 4: The modelling method illustrated in a Multiple Domain Matrix

In this paper, the Design Structure Matrix (DSM) is used instead of the conventional triangular 'roof' matrix to model asymmetrical interactions between design-features (see [19] on DSM). For example, reducing the fan blade height does not affect the fan disc thickness but a reduction in the fan disc thickness can affect the fan blade height. This is similar to the use of an asymmetrical roof as described by Lee and Kusiak [20].

4.2 Step II: Change propagation analysis

This step describes how the design-features are linked to a more general description (i.e. components) for change propagation analysis. It involves Field C and Field D of the Multiple Domain Matrix (MDM) in Figure 4. In Field C, the design-features are mapped to appropriate product components. For instance, the 'reduced fan blade height' design-feature will be linked to the 'fan blade' component. Subsequently, these components are mapped into Field D for change propagation analysis. The analysis technique used is the Change Prediction Method (CPM) as described by Clarkson et al. [2]. The CPM predicts the likelihood of change propagation between components by modelling the direct and indirect dependencies between them (see Figure 5). Similar to Field B, the connections between components are captured in a Design Structure Matrix (DSM) to account for asymmetrical dependencies. By using the CPM algorithm, the combined change propagation likelihood (*L*), which considers both direct and indirect change propagation, can be computed and updated in Field D.

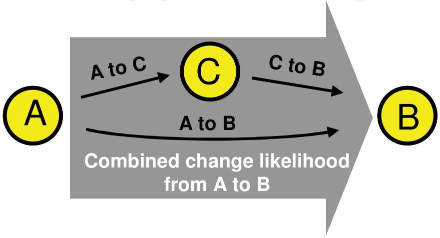


Figure 5: Modelling of direct and indirect change propagation

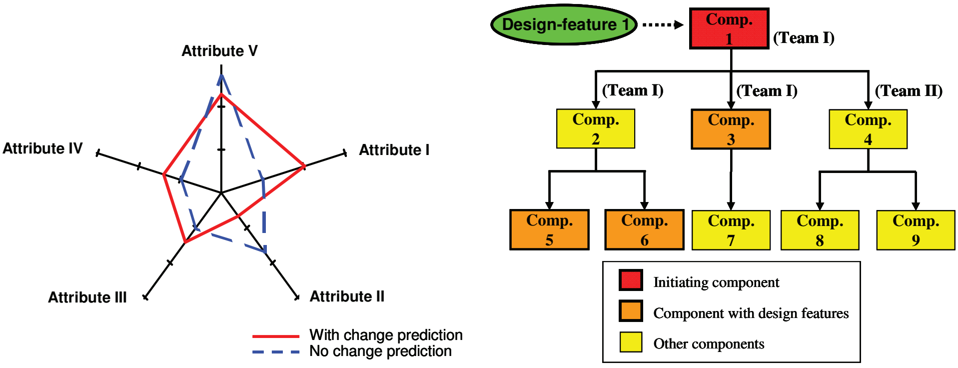
4.3 Step III: Revise expectations

Step III brings the analysis back to the more *specific* and detailed level by mapping the combined change propagation likelihood (*L*) of affected components back to relevant design-features in Field E. For instance, implementing the 'reduced fan blade height' design-feature involves changing the 'fan blade' component. If changing the 'fan blade' component is likely to cause a change in the 'fan disc' component (as determined in Field D), it implies that design-features related to the 'fan disc' component are also likely to be affected. Equation 1 shows how the performance ratings (*PI*) for each design-feature can subsequently be revised.

$$impr_{k,i} = PI_{k,i} + \sum_{j=1}^{n} [L_{j,i} \quad DI_{j,i} \quad PI_{k,j}] \tag{1}$$

Where $\boldsymbol{impr_{k,i}}$ represents the revised performance rating of design-feature $\boldsymbol{i}$ on attribute $\boldsymbol{k}$; $\boldsymbol{PI_{k,i}}$ and $\boldsymbol{PI_{k,j}}$ represent the initial performance ratings of design-feature $\boldsymbol{i}$ and design-feature $\boldsymbol{j}$ on attribute $\boldsymbol{k}$, respectively; $\boldsymbol{L_{j,i}}$ represents the combined component change propagation likelihood from design-feature $\boldsymbol{i}$ to $\boldsymbol{j}$; $\boldsymbol{DI_{j,i}}$ represents the design interaction rating from design-feature $\boldsymbol{i}$ to $\boldsymbol{j}$; and $\boldsymbol{n}$ represents the total number of design-features analysed.

The first part of Equation 1 (right-hand side) describes the initial performance rating of a design-feature while the second part indicates the amount of revision due to potential change propagation. The amount of revision computed in the second part of the equation can either build on or cancel out the initial performance rating in the first part of the equation depending on the change propagation likelihood (*L*), the interactions between design-features (*DI*), and the influence on the product attributes contributed by the affected design-features (*PI*). Figure 6a shows an example of a chart that contrasts the performance ratings of a design-feature when change propagation is considered. It allows engineers to revise their expectation and plan for improvement before more resources are invested.



(a) *(b)*

Figure 6: (a) Performance rating chart (b) Change propagation tree of a design-feature

The design resources required to implement each design-feature can also be determined (or revised) from the change propagation prediction. For instance, the naive estimation of resources required to implement the 'reduced fan blade height' design-feature is equivalent to those of modifying the 'fan blade' component. By examining how changes can propagate between components (see Figure 6b), resource plans can be revised accordingly to account for potential change propagation. For ease of illustration, the affected components along each propagation path are dissimilar in Figure 6b.

4.4 Step IV: Generate change management plans

Despite of the potential benefits that change propagation might bring (refer to Attribute I in Figure 6a), unplanned change propagation can be risky and detrimental to the success of a design project. In Step IV, we describe how change propagation should be managed based on the modelling results. The two factors considered in this step are (1) the overall product performance with change propagation consideration and (2) the design resources required to carry out the change work. The insights gathered from this step can be used to support the assessment of solution alternatives.

4.4.1 Change management based on product performance

Assuming that Design-feature 1 in Figure 6b is shortlisted as a promising candidate for further development, engineers can focus their discussion on preventing change propagation from reaching other design-features which can in turn affect the overall product performance. For instance, engineers can try to *freeze* Components 2 and 3, and try to redirect any change propagation towards Component 4 (see [21] on design freeze). This is due to the fact that Component 3 carries a design-feature that can influence the product attribute(s), and Component 2 is the gateway for change propagation to Components 5 and 6 (Components 5 and 6 carry design-features). If this is not possible due to technical reasons, the engineers can subsequently loosen the criteria and allow changes to propagate to ‘favourable’ design-features. For instance, if the propagation of changes to the design-feature(s) linked to Component 3 can improve the overall product attributes based on the analysis results, engineers can keep this option open and allow change propagation to Component 3 when required. Alternatively, the engineers can also consider implementing these design-feature(s) right from the start. The objective of this exercise is to warn engineers of critical spots and prevent last minute ‘fire-fighting’ down the wrong route.

4.4.2 Change management based on design resources

Changes can only be carried out when there are available resources. It is therefore crucial to plan for resources before any design project. The key idea of resource-based change management is to determine the amount of resources available for a design project and subsequently contain the changes within the available resources. The goal is to help create a robust schedule and resource plan by making sure that no activities are delayed due to conflict in resource demands. Depending on the outcome of this analysis, companies can either allocate more resources in anticipation of possible change propagation or postpone the design project to a more suitable time.

With reference to Figure 6b, if personnel in Team II are not available during the course of the design project due to other commitments, representatives from Team II should be involved at the early stages of the design process to assess the feasibility of freezing Component 4 and try to direct any change propagation towards Components 2 and 3. Similar to performance-based change management, such approach might not always be possible due to technical reasons. In such a case, the project schedule should be modified to take into account the probable change propagation work on Component 4, and subsequently, Components 8 and 9. Failure to do so can in turn affect other aspects of the company, such as the rollout plan.

5 CASE STUDY: JET ENGINE FAN DESIGN

A case study was carried out in an aerospace company to investigate the feasibility of the method described in Section 4. The method was used to evaluate solution alternatives for the design of a *light-weight* jet engine fan. The following sections describe the data preparation process (Steps I, II & III) and the recommendations made (Step IV) in greater details.

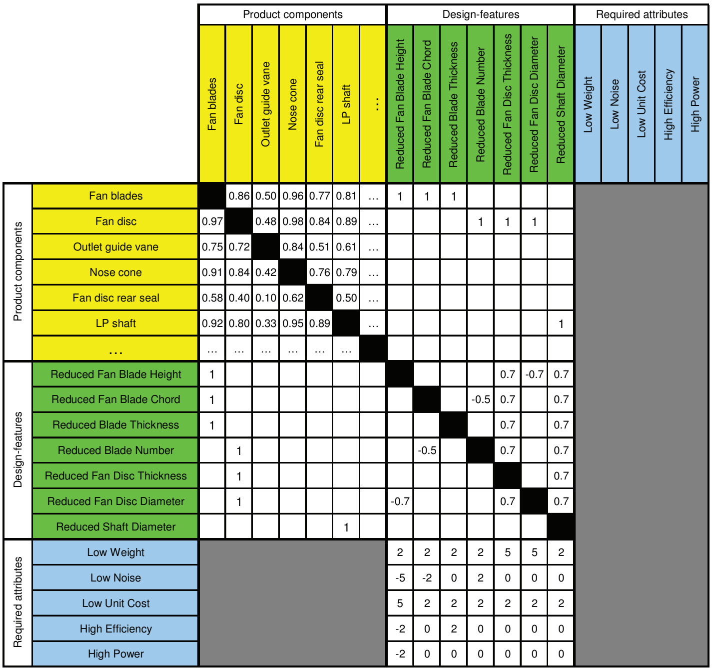
5.1 Data preparation

Figure 7 shows an excerpt of the data gathered from the company in a Multiple Domain Matrix (MDM). Field A indicates the performance ratings of different design-features with respect to product attributes. The scale used was from ‘-5’ (adverse effect) to ‘5’ (positive effect). In this paper, each product attribute is assumed to have equal importance and the ratings are not scaled by weightings. Field B shows the interaction ratings between design-features with the scale from ‘-1’ (affect in a conflicting way) to ‘1’ (affect in a complementary way). In order to map these design-features to relevant product components (Field C), the jet engine fan was divided into 13 components as shown in Figure 8 (shown with 6 components). The linkages in Figure 8 were elicited from engineers and subsequently converted into change propagation likelihood using the conversion table as illustrated. By using the Change Prediction Method (CPM), the combined (direct and indirect) change propagation likelihood can be computed as shown in Field D of Figure 7. The number of change propagation steps analysed for each component was 4. By mapping the combined change propagation likelihood of affected components back to relevant design-features in Field E, the performance ratings in Field A can be revised accordingly using Equation 1. Figure 9 shows the revised results along with the initial ratings.

5.2 Analysis and recommendations

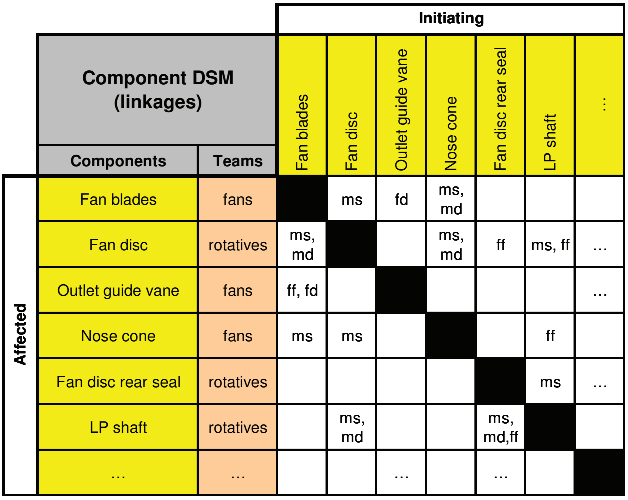
Based on the modelling results, engineers can better assess each design-feature by examining the performance rating charts as shown in Figure 10. For instance, the weight and unit cost of the jet engine fan is predicted to be affected in a favourable way when change propagation is considered for the ‘reduced shaft diameter’ design-feature. On the other hand, the power and noise attribute of the jet engine fan is predicted to be affected in a negative way.

The change propagation tree associated with the ‘reduced shaft diameter’ design-feature can also be generated as shown in Figure 11. As mentioned in Section 4.4, the general guide is to avoid change propagation to components with design-features even if it can lead to favourable outcome. Engineers should therefore try to direct change propagation towards the ‘fan disc rear seal’ or the ‘safety shaft’ as they do not carry any design-feature. A focused discussion should be held as well to ensure changes do not propagate to the ‘fan disc’ as it carries three design-features. Change propagation to the ‘nose cone’ is also undesirable as it is connected to the ‘fan disc’ and the ‘fan blades’ (both components carry design-features).



		Product components							Design-features							Required attributes				
		Fan blades	Fan disc	Outlet guide vane	Nose cone	Fan disc rear seal	LP shaft	…	Reduced Fan Blade Height	Reduced Fan Blade Chord	Reduced Blade Thickness	Reduced Blade Number	Reduced Fan Disc Thickness	Reduced Fan Disc Diameter	Reduced Shaft Diameter	Low Weight	Low Noise	Low Unit Cost	High Efficiency	High Power
Product components	Fan blades	■	0.86	0.50	0.96	0.77	0.81	…	1	1	1									
	Fan disc	0.97	■	0.48	0.98	0.84	0.89	…				1	1	1						
	Outlet guide vane	0.75	0.72	■	0.84	0.51	0.61	…												
	Nose cone	0.91	0.84	0.42	■	0.76	0.79	…												
	Fan disc rear seal	0.58	0.40	0.10	0.62	■	0.50	…												
	LP shaft	0.92	0.80	0.33	0.95	0.89	■	…							1					
	…	…	…	…	…	…	…	■												
Design-features	Reduced Fan Blade Height	1							■				0.7	-0.7	0.7					
	Reduced Fan Blade Chord	1								■		-0.5	0.7		0.7					
	Reduced Blade Thickness	1									■		0.7		0.7					
	Reduced Blade Number		1							-0.5		■	0.7		0.7					
	Reduced Fan Disc Thickness		1										■		0.7					
	Reduced Fan Disc Diameter		1						-0.7				0.7	■	0.7					
	Reduced Shaft Diameter						1								■					
Required attributes	Low Weight								2	2	2	2	5	5	2					
	Low Noise								-5	-2	0	2	0	0	0					
	Low Unit Cost								5	2	2	2	2	2	2					
	High Efficiency								-2	0	2	0	0	0	0					
	High Power								-2	0	0	0	0	0	0					

Figure 7: Excerpt of the case study data captured in a Multiple Domain Matrix



	Component DSM (linkages)		Initiating						
	Components	**Teams**	Fan blades	Fan disc	Outlet guide vane	Nose cone	Fan disc rear seal	LP shaft	…
Affected	Fan blades	fans	■	ms	fd	ms, md			
	Fan disc	rotatives	ms, md	■		ms, md	ff	ms, ff	…
	Outlet guide vane	fans	ff, fd		■				…
	Nose cone	fans	ms	ms		■		ff	
	Fan disc rear seal	rotatives					■	ms	…
	LP shaft	rotatives		ms, md			ms, md,ff	■	
	…	…			…		…		■

Likelihood Conversion

(ms) mechanical static → 0.5
(md) mechanical dynamic → 0.5
(sp) spatial → 0.3
(ff) fluid flow → 0.3
(fd) fluid flow dynamic → 0.3

(Multiple links)
With mech. Links → 0.8
Without mech. Links → 0.6

Figure 8: Excerpt of the list of components and their linkages

		Design-features						
	Performance ratings (initial ratings in [ ])	Reduced Fan Blade Height	Reduced Fan Blade Chord	Reduced Blade Thickness	Reduced Blade Number	Reduced Fan Disc Thickness	Reduced Fan Disc Diameter	Reduced Shaft Diameter
Required product attributes	Low Weight	-1.4 [2]	1.0 [2]	2.0 [2]	1.1 [2]	13.5 [5]	3.8 [5]	12.9 [2]
	Low Noise	-5.0 [-5]	-3.0 [-2]	0.0 [0]	2.9 [2]	-2.9 [0]	3.0 [0]	-2.7 [0]
	Low Unit Cost	3.6 [5]	1.0 [2]	2.0 [2]	1.1 [2]	10.2 [2]	-1.0 [2]	10.8 [2]
	High Efficiency	-2.0 [-2]	0.0 [0]	2.0 [2]	0.0 [0]	0.0 [0]	1.2 [0]	0.0 [0]
	High Power	-2.0 [-2]	0.0 [0]	0.0 [0]	0.0 [0]	-1.2 [0]	1.2 [0]	-1.1 [0]

Figure 9: Comparison between initial and revised ratings

If change propagation cannot be contained as recommended due to technical reasons, a more detailed analysis can subsequently be made. For instance, a reduction in the fan blade height (design-feature 1) might be required to accommodate the implementation of a reduced shaft diameter (design-feature 7). However, as a reduction in the fan blade height can adversely affect the ‘noise’ attribute, change propagation towards the ‘fan blade’ component is extremely undesirable. On the other hand, if a reduction in the blade number (design-feature 4) is required to accommodate design-feature 7, the noise level can be affected positively. Thus, from a ‘noise’ level perspective, change propagation towards the ‘fan disc’ is considered as more tolerable in contrast to the ‘fan blade’. This analysis can be repeated for all other product attributes and requirements.

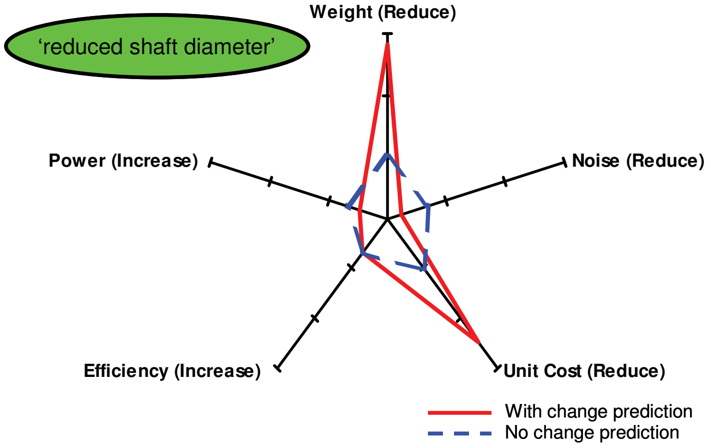


Figure 10: Performance rating chart for ‘reduced shaft diameter’

Change management plans based on resource allocation can also be generated using Figure 11. For instance, if the ‘fans’ team is expected to be unavailable during the course of the design project, change propagation from the ‘shaft’ to the ‘nose cone’ should be avoided at all cost. The engineers in charge of fluid-flow (ff) should be involved early in the process to ensure that the likelihood of change propagation between these two components is reduced to a minimum. The same can be applied to ensure that changes are unlikely to propagate from the ‘fan disc’ to the ‘fan blade’, ‘annulus fillers’, and ‘nose cone’ by analysing the mechanical static (ms) links between these components. Eventually, if undesirable change propagation associated with a design-feature is predicted as inevitable, engineers can explore other solution alternatives before more resources are invested.

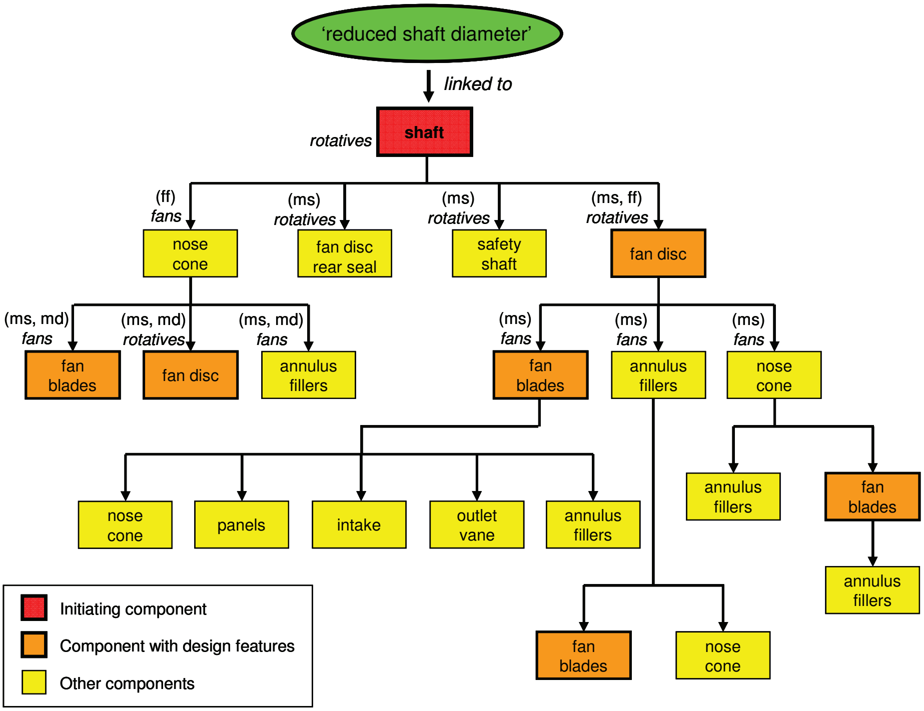


Figure 11: Change propagation tree for 'reduced shaft diameter' (links with change likelihood > 0.2)

6 DISCUSSION

The result of the change propagation analysis was reviewed by the aerospace company to assess the feasibility of the modelling method. The three main review criteria are – (1) ease of modelling, (2) flexibility to adapt to different design cases/projects, and (3) accuracy of the analysis results. In addition, the method was also rated in terms of its traceability (ability to map design requirements to specific changes). Table 1 shows the review results based on an independent questionnaire survey. The rating scale used was from '1' (bad) to '5' (good). Note that Staff 5 rated the case study results instead of the method.

Table 1: Review results

		Staff interviewed					
		Staff 1	**Staff 2**	**Staff 3**	**Staff 4**	**Staff 5**	**Average***
Review Criteria	**Ease of modelling**	3	3.5	2	2	3	2.6
	Flexibility	3.5	3.5	4	3	4	3.5
	Accuracy	2.5	2.5	3	4	2	3.0
	Traceability	4	3.5	4	5	1.5	4.1

*Ratings from Staff 5 is not considered in the average score

It can be seen from Table 1 that the modelling method was rated below average in terms of modelling effort. It was later explained in an interview that engineers find matrix-filling an unpleasant task. In addition, matrix-filling is also not regarded as an engineering assignment. On the other hand, the modelling flexibility which describes the ability to reuse the model for different design cases was rated above average. This implies that much of the effort invested in producing the initial matrices can be reused for future design work, thereby reducing the modelling effort in subsequent analyses. It was also commented in the interview that having a system that can automatically capture the modelling data from routine engineering activities can help to improve the usability of this method.

The modelling accuracy was rated as average when compared to Computed-Aided Design (CAD) modelling and engineers' intuition. However, it should be emphasised that the main goal of this method is not to provide a set of revised ratings for assessing solution alternatives. Instead, it aims to highlight the effects of change propagation and facilitate discussion among engineering staffs. For instance, during the interview session, Staff 5 indicates that the 'life' attribute is an important factor and must be included in the analysis. Such discussion can help to draw out design concerns and improve the understanding of the product.

Lastly, the traceability of this modelling method was rated highly. Traceability can be described as the ability to map design requirements to specific changes. Such information allows engineers to track changes and can act as useful references to support future design works.

In general, the company staffs indicated that the method is suitable for assessing solution alternatives during preliminary design and can support engineers to "... explore the design space in the right way".

7 CLOSING REMARKS

This paper presents a change propagation modelling method that aims to manage undesired change propagation and support resource planning during the early stages of the design process. The method can be used to support the assessment of solution alternatives in an engineering change. It focuses on the preliminary design of complex products and allows engineers to trace change propagation paths from design requirements to affected product components and design personnel. The method was applied to the design of a jet engine fan to assess the feasibility of using such a modelling approach in industry. Subsequently, the method was rated by the case study company in terms of modelling effort, flexibility, accuracy, and traceability. The findings suggest that this modelling method is suitable for assessing solution alternatives during preliminary design and can help support engineers to explore the design space in the right direction. Future work in this area includes the consideration of change propagation on other aspects of the organisation such as the supply chain.

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