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TOLERANCE MARGINS AS CONSTRAINING FACTORS OF CHANGES IN COMPLEX PRODUCTS

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1 Introduction

Engineering changes to a product are important for it to reach and maintain market competitiveness. The nature of today's market has seen the development time for many products reduced considerably. Companies strive to accelerate their development process while trying to maintain a high quality. Performing engineering changes is not a simple task, as small changes can cause severe disruptions to manufacturing and scheduling processes. Another potential major impact of engineering changes, perhaps more common in complex systems, is the effect it may have within the product itself. Changes to one component could necessitate further changes to other components of the design [CLA-01]. Change propagation in design causes forms of disruptive effects such as high amounts of rework and delayed schedules.

Engineers need support with evaluation of the effects of proposed changes. This paper looks at the different mechanism through which change can propagate within a system with the aim of applying this understanding to developing a method for evaluating the effects of proposed changes to a design. The method is based on the understanding that the components in a product are built to within certain tolerances and that change will only propagate if these tolerances are violated. These change margins are not the same as manufacturing margins.

The rest of this paper begins with a background discussion on existing research into factors responsible for change propagation in products and the techniques adopted to reduce its effects (section 2). The definition for "tolerance margins" and explanations of the relationships between these margins and change propagation are highlighted in section 3. A tolerance-based method for evaluating changes is discussed in section 4. The evaluation was carried out using a technique developed at the Cambridge University Engineering Design Centre known as the Change Prediction Method (CPM). This paper concludes with a brief summary of the usefulness of the method and highlights areas for further development.

2 Background

Complex products are products that have a relatively high number of interdependencies between components and parameters. They are often characterised by a lack of transparency in the relationships between its inputs and outputs. Changes are more likely to propagate within a product as the levels of interdependencies between its parameters increases. A high degree of novelty in the design also increases the possibility of change propagation due to increased uncertainty in possible outcomes. This is often as a result of lack of clarity in the relationships between the different design parameters.

Some of the factors responsible for change propagation include [JAR-04]:

- Lack of system knowledge or inexperience
- Communication breakdown between designers
- Emergent properties of complex systems that had not been known prior to that incidence.
- Basic human error, such as forgetfulness

Other factors responsible for change propagation in products are *design considerations*, such as safety, aesthetics and reliability. The impact of engineering changes on the process depends on factors such as, the timing of the change, the total number of changes and the number of tools affected by such changes [TER-99]. It is also dependent on the way the engineering changes are managed and carried out.

The key to minimising the impact of engineering changes lies in the way in which the engineering change process is managed [DIP-82]. Effective and efficient change management processes help reduce the amounts of rework, scrap costs and production delays associated with a making a change. Configuration Management and Quality Management standards such as ISO 10007 and ISO 9001 provide guidelines for effective and efficient engineering change management procedures. Perhaps the most important phase during the implementation of the engineering change management procedure is the evaluation phase, since up to 85% of costs is committed at this stage [NIC-90].

A number of management strategies that can be employed to reduce the risk of changes propagating include [FRI-00]:

- Carrying out less changes and giving priority to important changes.
- Probing the design early by applying techniques such as Failure Mode Effects Analysis (FMEA), to identify possible emergent changes early in the process.
- Adopting an efficient and effective change process.
- Learning from previous changes to improve the current change process.

2.1 Engineering Changes and the Product

There are different classifications for engineering changes, such as timing [REI-91], or the urgency of the change [DIP-92]. At a basic level, there are two classes of engineering changes [ECK-01]:

- Initiated change: These are changes often in response to demands from an outside source such as customer requests, certification bodies or product upgrade from the manufacturer. It is done to match products to new requirements.

- Emergent changes: These are the problems that arise anytime during the design phase or the product life cycle that leads to changes in the design.

3 The Concept of Tolerances and Changes Propagation

The introduction of change into a system, emergent or initiated, re-introduces a new level of uncertainty and/or technical ambiguity into the system. The effects of changes made are noticed in the design interfaces and/or in the performances of the system itself. The ability of the system to cope with the changes is dependent on its tolerance to the changes made.

Irrespective of whether a change is initiated or emergent, the resulting effects that are not contained within the component or system are transferred onto other components and systems within the product. The response of these systems to the changes characterises the system behaviour to change. These change behaviours are divided roughly into three categories [ECK-01] as illustrated in Figure 1:

- Absorbers: These are systems that absorb more changes than they cause. They can be broken down further into partial and total absorbers.

- Carriers: These are systems or components that pass on as many changes as they receive.

- Multipliers: Change multipliers expand the change problem; they generate more changes than they receive.

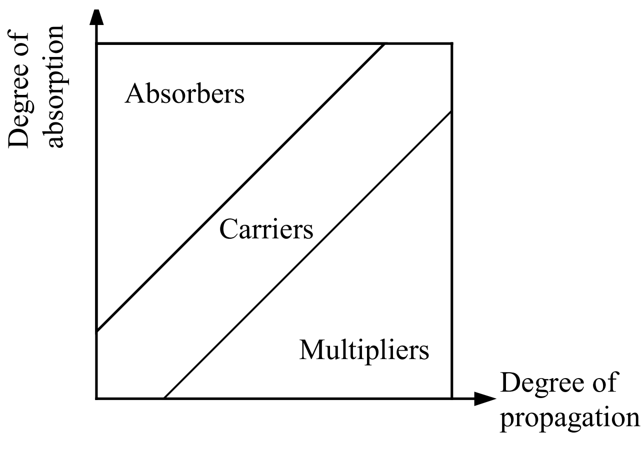

Figure 1. : Change propagation behaviour of parts and systems [ECK-01]

These change behaviours in components are not static. Changes that are too large to absorb could result in the component itself becoming a change multiplier [ECK-01]. This tendency to become a multiplier is increased when there are several changes being carried out simultaneously.

3.1 Tolerance in design

The tolerance of a component is defined as the permissible deviation from a specified value. Traditionally, in engineering, the term tolerance is used to describe structural dimensions. Low or tight tolerances are difficult to achieve and can increase costs. Therefore, they are used when it is important for the functionality of the system. However, in practice, many other design parameters such as pressure, force and temperature have tolerances. Often, reasonable variations in design parameters, within these tolerances, will not impinge on the component performance. The range for these design parameter variations serves as a constraint on changes that can be made to the system, otherwise known as *change margins* or *tolerance margins*. Tolerance margin is defined as the total variance allowed in a design parameter, excluding the necessary safety factor, without affecting operation capability or structural integrity of the component.

3.2 Change propagation paths

A component's ability to absorb changes is dependent on its initial specification and the change margin included in the system [ECK-01]. In practice, the tendency for a component to absorb or multiply a change is dependent on the type of change made to it. One component can exhibit all the three types of change behaviours. An example of such behaviour is witnessed in automobile design, where there are increasing electrical and electronics inputs, to meet new performance requirements. A situation may arise where an existing model requires a slightly larger alternator to cope with the new electrical demands, to prevent overloading the electrical system. Although the new alternator is an absorber of electrical changes to the system, it is also a carrier of geometric changes and a multiplier of vibration problems since the existing support structure has to be modified to cope with the larger alternator.

Each component of a complex product has a number of measurable factors, both within it and acting upon it, which describe its state in relation to other components. This may include vibrations, forces, heat energy or even colour. The interactions with other components occur at interfaces. This can be in a number of ways, for example spatially, as well as through transfer of energy. Similar factors can be grouped into domains governed by their respective domain rules. For example, the spatial domain addresses issues such as dimensions, alignment and orientation, while the heat domain covers thermal energy transfer, such as by conduction and convection. The term *tolerance domain* is used to refer to each of the different types of tolerance margins within a component, in other words, the components tolerance margin within a certain domain. Tolerance domains are effectively a way of grouping relevant design parameters, and as such, they are not independent, rather, they are interdependent.

Changes propagate within a product directly or indirectly through paths if the change margins for the relevant tolerance domains are exceeded. The path through which these changes propagate is dependent on the product's architecture, since the changes can only propagate from one component to another if there is some form of linkage between them [JAR-04]. The degree to which change propagates through the product depends on the complexity of the product itself [CLA-01]. Regardless of the cause of the change, the mechanisms through which changes propagate in a system are consistent. Based on a component's tolerance to change, the change propagation mechanisms can be classified into three. These are *margin erosion*, *chained dependencies* and *cliff-edge effects*.

Margin erosion

These are intra-domain change propagations. Change margins such as load tolerances are gradually eroded as the system absorbs more changes. This continues until the limits of the margins are reached and change propagates to other systems. For example, a continuous increase in the chassis load may require a change to the chassis support structure. The change propagates as a result of exceeding tolerance margins within one tolerance domain.

Chained dependencies

These are inter-domanial change propagations. Changes to one tolerance domain, may increase or reduce the effective change margins in another domain. This type of propagation mechanism is common in complex products. It occurs as a result of the high interdependencies between components. For example, one could increase the loading on a chassis such that the total load remains within the load tolerance margins of the chassis support structure, but the resulting vibrations may exceed the existing vibration tolerance limits of the chassis support structure. The system fails in one tolerance domain as a result of changes to another tolerance domain.

Cliff-edge effects

This is a combination of both intra and inter-domanial change propagation. It is common in complex systems, especially when tolerance margins are tight. Changes to one component causes intra-domanial margins to erode or affects other tolerance domains, instigating a process through which changes propagate through the system. Cliff-edge effects often occur as a result of changes to more than one component. Neither the intra nor inter-domanial margin reduction is in itself enough to cause changes to propagate.

4 Evaluating changes based on tolerance margins

This section describes a tolerance-based method of evaluating changes in design. Although there are different methods to model the product, this technique has been applied using the Change Prediction Method (CPM) technique.

4.1 The Change Prediction Method

The CPM tool is being developed at the Cambridge University Engineering Design Centre [CLA-01]. It is aimed at assisting in understanding how changes spread in a system. The CPM tool is based on a combination of risk management techniques with the representation and analysis method used with Design Structure Matrices (DSM)

[CLA-01]. The DSM is a square matrix with identical rows and columns [BRO-01] as illustrated in Figure 2. The CPM tool uses the component-based DSM to model the connectivity between components and sub-systems that make up the product.

Hair-drier	a	b	c	d	e	f
a power supply	-	x	x			
b motor	x	-		x	x	x
c heating unit	x		-	x	x	x
d fan	x	x	x	-		x
e control system			x	x	-	x
f casing	x	x	x	x	x	-

Figure 2. : Component-based DSM of a hair drier

On the binary form of the component-based DSM, such as the one in Figure 2, linkages between two components are highlighted with an "x" mark. In the CPM tool, these marks are replaced with numerical estimates of likelihood and impacts of change propagation. The risk of change propagation is defined as the product of the change likelihood and change impact. The CPM tool adds up the direct risks and indirect risks (i.e. the risk of changes spreading via intermediate parts) of change propagating to calculate the combined risk, from which it works out the combined impact of the change propagating.

4.2 The Tolerance-based method

The tolerance-based method is used to analyse the effects of a proposed change to one or more components on the rest of the product, in order to prevent changes from propagating. This method assumes that not every component in the design of a complex product is started from scratch, and as such, changes and/or modifications are only made to existing designs. In other words, there has to be an existing design for changes to propagate.

When applying the tolerance-based method of evaluating changes, the product is modelled on the DSM and the interfaces are marked accordingly. The key design parameters at each interface that affects the functionality of each component are noted. Although a component **a** may be symmetric to component **b** as shown in Figure 2, the key parameters from **a** to **b** may not be the same as that from **b** to **a**. Therefore, it is important to consider each interface separately. An evaluation of the possibilities of curtailing the change to within the change margins of the neighbouring components is carried out based solely on the technical skills and experience of the design engineers. Other independent factors that influence the design, such as safety and reliability are also to be considered during the evaluation. The opportunity to stop a change from propagating further only arises when the new parameters of the components, after all modifications have been made, fall within the constraints, set by the tolerances of other components.

Companies do not always have control over how much change they intend to carry out due to high interdependencies between components. However, once achievable interfaces have been identified, alternative methods of carrying out a change must be considered along with the necessary processes involved in making the change. These must also be considered in conjunction with the other processes going on in the organization. Changes should be directed towards components or systems where the tolerances are sufficient to absorb the change.

5 Discussion

This report gives a perspective on the way in which change propagates by capturing the necessary mechanisms involved and applying the understanding to the process of evaluating changes. This approach serves as a decision support for design teams as they can assess the volume of changes they intend to carry out and compare it with the available resources. It also offers a method for evaluating effects of changes to products with long lead-time components. Changes to the other parts of the design can be assessed based on change margins to prevent further rework later in the development process. The model in itself helps give design teams an appreciation of how their components fit into the whole product structure. This method also allows a reduction in the chances of change propagation as a result of communication breakdown between design teams. Considering every design parameter at the interfaces also helps reduce possibilities of any oversight or forgetfulness that may occur when implementing a change.

6 Summary and Further work

The objective of this paper is to improve the understanding on ways through which changes propagate within complex products. The paper explains that there are margins that allow for variations to a design without affecting product's performance. Constraining changes to within these margins can prevent changes from propagating to other components. The information in this paper is a step towards generating methods through which the effects of proposed changes to a design can be thoroughly analysed early in the design process. The tolerance-based method will soon be applied to a jet engine in a real life design environment.

Further work is required on ways to assess design interfaces for spatial, energy and materials transfer, in order to be able to analyse them against corresponding tolerances in other components. If the design parameters that instigate changes for the different components can be identified, larger change margins can be included early in the design process to make the systems more robust to change. Finally, the tolerance-based methodology will be incorporated into the change prediction tool [CLA-01] described earlier in section 4.1.

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