2 CHANGE PROPAGATION MODELLING TO SUPPORT THE SELECTION OF SOLUTIONS IN INCREMENTAL CHANGE

Edwin C. Y. Koh*, **Rene Keller, Claudia M. Eckert and P. John Clarkson**

Engineering Design Centre, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom. Tel: +44-(0)12-23766955, Fax: +44-(0)12-23766963.
**E-mail: cyek2@cam.ac.uk*

It is common for companies to generate new products through modification of existing ones. This is known as incremental change. During this process, designers are usually faced with more than one solution alternatives at key decision points. These solution alternatives are then evaluated and selected during concept selection. However, it is well documented that changes required for the new solutions can propagate undesirably to the rest of the product. The objective of this paper is to identify the limitations of current concept selection tools in considering change propagation, and to describe how research in engineering change modelling can be incorporated to enhance current tools.

Keywords: Incremental Change, Selection of Solutions, Change Modelling.

1. INTRODUCTION

The term *incremental change* has been used to describe the design of new products through modification of previous products.[1] Some literature refers this as product *redesign* (for example see Ref. 2). The drivers for incremental change can be market competitions, new customers' requirements, or new legislation. In order to meet these new demands, new product features have to be implemented. In addition, the introduction of these new product features should cause minimum changes to the existing products so as to leverage the current product lines. Usually, multiple solution alternatives (concepts) can be generated to meet the new demands. A filtering process is therefore required to select the most viable solution. This is commonly known as concept selection. Typically, concept selection takes place at the end of conceptual design (refer to standard process models such as Pahl and Beitz[3] or Ulrich and Eppinger[4]), and also later in the design process as new requirements or problems emerge that need to be resolved.

Concept selection is a juncture in the design process where one or a few ideas are selected for further development.[4] In an ideal case, the changes brought about by the new solutions can be implemented with no repercussion to the rest of the product. However, this is often not the case. The implementation of new features can result in undesirable changes propagation.[5,6] In addition, it is possible for changes that were initially thought to be simple to propagate uncontrollably,[7] resulting in suboptimal last-minute solutions[8] and additional development cost.[9] This leads to the following questions — Why would solutions which were evaluated and deem viable result in change propagation? Are current concept selection tools insufficient in analysing the full effect of a new design? If so, how can we improve them? These questions provide the motivation for this research.

In an attempt to address these concerns, this paper provides a review of design literatures that describe how a product is modified during incremental change. The outcome is used to examine whether current concept selection tools are sufficient in capturing and evaluating the full effect of a new design. Lastly, this paper explores the work done on engineering change modelling and examines how research in this area can supplement current concept selection tools.

2. A PERCEPTION OF CHANGE

This section attempts to review the key descriptions that are used to conceptualise a design artefact. The aim is to identify which design descriptions have changed before and after an incremental change so as to understand the full effect of change propagation. The outcome is subsequently used in Section 3 to examine if current tools are sufficient in evaluating new designs.

The terms Function, Behaviour, and Structure (FBS) are commonly used in the engineering community to describe a design artefact (for example Refs. Refs. 10-13). However, various authors have adopted slightly different meanings for each term.[14] In this paper, we refer to the FBS definition as described by Gero,[10] where he uses Function variables to describe what a design object is for; Structure variables to describe the components and their relationship; and Behaviour variables to describe the attributes derived or expected to be derived from the Structure variables.

Alternative design descriptions also exist in other literature. Ullman[15] states that products (artefacts) are traditionally described in terms of Form (Structure), Fit, and Function. These descriptions should meet the requirements of the new product. While Ullman's definition of Function is similar to that of Gero's, he explains that the Form description accounts for the architecture and the shape of parts (and assemblies), and the Fit description represents how different components accommodate connecting components to be assembled together. This set of descriptions is slightly different from the FBS framework as it explicitly highlights the Fit description.

In another paper, McMahon[1] uses Explicit Attributes and Implicit Attributes to describe an artefact where the designers know how the device works and what the customary features are. He went on to describe explicit attributes as input parameters to define and construct the artefact (e.g. dimensional parameters) and implicit attributes as behaviour of the artefact subjected to the external effect (e.g. durability). In his paper, there were also mentions of another commonly-used term in design: Features.

The term feature has been used in various contexts to mean different things. In general, features can be broadly classified into marketing features[16] and technical features.[17] Marketing features refer to the selling points or attributes of a product (e.g. 'light-weight' bicycle) while technical features describe the engineering significance and physical details of a product or component (e.g. '29-inch' wheel). Nonetheless, some desirable technical features can also be used for marketing purposes. To avoid confusion, the term feature refers to only technical feature in the remaining of this paper.

In summary, the purpose and primary function of the new product is usually kept unchanged during incremental change. A good example is the incremental change of cars. In most cases, the goal is to achieve a new product with better attributes. As mentioned, product attributes can be seen as design targets and requirements (expected attributes) or derived behaviours (actual attributes). They cannot be directly modified unless changes are made to the product. This can be carried out by changing some of the product components. The detail of the changes can subsequently be broken down and described by a set of distinctive features. Therefore, features can be seen as the enablers to achieve certain product attributes. On the other hand, undesirable product attributes are also a result of certain features.

In an ideal situation, the introduction of a new design feature will attain the required attribute performance with no changes to other product attributes. However, this is not always the case. For example, an 'increased wheel diameter' feature for a bicycle can be seen as an enabler to meet the required attribute of 'high maximum speed'. Nevertheless, this feature can also affect other attributes such as the bicycle 'weight'.

It should be noted that most design features, such as 'increased wheel diameter', do not stand alone and cannot be carried out without changes to other features. For instance, when the bicycle wheel diameter is increased, it is likely that the 'spokes length' and the 'wheel thickness' features will be affected as well. Since these features are part of the 'wheel' component, this phenomenon can be described as within-component change propagation. If no further changes are required, it can be said that the component has *absorbed* the changes (see Figure 1).

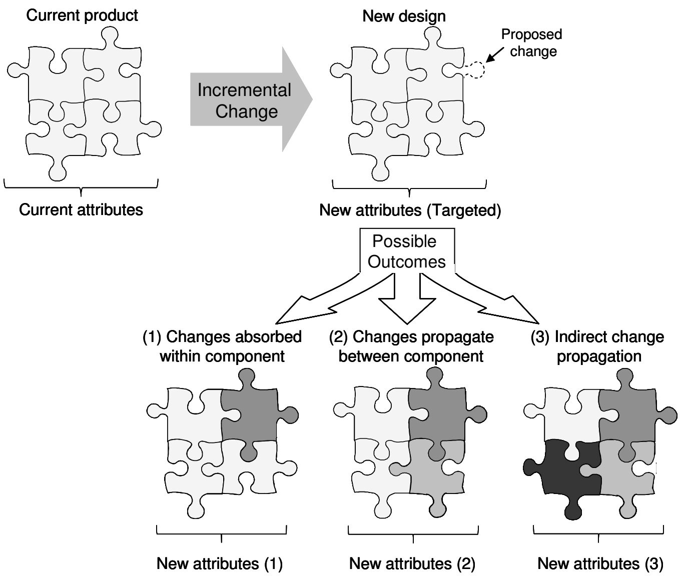


Figure 1. Classification and effects of engineering change propagation.

However, changes to a feature can also propagate between components. If the wheel component cannot fully absorb the changes, other components can be affected. For instance, once the wheel diameter exceeds a certain design margin, the 'fork' component must be redesigned. As a result, the 'fork length', 'fork thickness', and 'fork curvature' features can all be affected. This phenomenon can be described as between-component change propagation. The complexity of the problem increases when components which are not directly connected to the initiating component are affected. For instance, the 'suspension' component is not directly connected to the 'wheel' component. Nonetheless, since the 'suspension' is connected to the 'fork' component, changes to the 'fork length', 'fork thickness', or 'fork curvature' features can subsequently cause a change in the 'suspension'. This can be referred as indirect component change propagation. See Figure 1 for illustration.

It can be seen that a proposed minor change can potentially propagate to the rest of the product and, as a whole, affect the overall product attributes. Whether change propagation results in an improvement or deterioration of the product attributes depends on the intent of the design. Nevertheless, the existence of engineering change propagation highlights the need to investigate the full effects of a product change during the selection of solution alternatives.

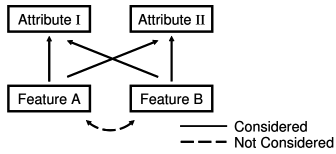
3. CONCEPT SELECTION AND CHANGE PROPAGATION MODELLING

In general, concepts at different level of abstraction can be evaluated during concept selection. For instance, at the earlier stages of the design process, concepts are usually generated and evaluated at the product level. These product concepts describe the solution principles of the new product and are often abstract. Towards the later stages of the design process, as designers generate alternative ways to materialise the product, detailed component concepts which focus more on the embodiment will be evaluated. Depending on the design context, the emphasis during concept selection can be different. In the context of incremental change, new products are usually required to perform the same function as the previous version, but with new (improved) product attributes. Therefore, the product concept is usually kept the same. The generation and selection of concepts in incremental change is thus associated with a more detailed level of concept descriptions, usually at the component level.

As design changes can occur throughout the entire design process,[7] new concepts will be generated to meet these emergent demands. The evaluation and selection of concepts is thus required whenever

Pugh Chart (Bicycle)	Concepts (Features)			
Attributes	Large Wheels (1)	More Gears (2)	Small Frame (3)	Titanium Frame (4)
High Maximum Speed	s	+	+	+
Low Weight	s	s	+	+
Fast Braking Rate	s	s	+	+
Low Cost	s	-	+	-
High Strength	s	s	-	s
Low Deflection	s	+	+	-

(a)



(b)

Figure 2. (a) Example of a Pugh Chart. (b) Evaluation of concepts using a Pugh Chart.

there is more than one solution alternative. There are currently a number of established methods available to rank and evaluate design concepts. For instance, the Pugh Chart, also known as the Pugh concept selection method, uses a minimal evaluation scale of worse (−), same (s), and better (+) to rank concepts with respect to a reference concept and can be seen as the basic concept scoring interface for conceptual selection.[18] Figure 2a shows an example of the Pugh Chart in selecting concepts for a *high-speed* bicycle design. Traditionally, each concept will be depicted by a sketch of the possible design. These concepts will be rated systematically against a list of (required) product attributes. Usually, one of these concepts will be assigned as a datum to benchmark against other concepts (concept 1 in Figure 2a). Over the years, researchers have tried to improve this selection method by introducing different scoring scales, weighted ratings, and multiple screening stages. For example, a two-stage concept selection methodology was suggested by Ulrich and Eppinger[4] to structure the selection process into the concept screening stage and the concept scoring stage. Nevertheless, the overall structure of the concept selection interface remains.

During incremental change, each concept can be a solution alternative for the new requirements. It is thus possible to adopt more than one solution in the new product. However, it should be noted that the Pugh chart considers the relationship between the product attributes and the proposed concepts (features) but does not assess how the new features will fit together with the rest of the product. For instance, the Pugh chart cannot directly assess the combined consequences of having a 'small frame' and 'more gears' in a bicycle design as the correlation between these features are not captured. The outright assumption that each concept (feature) is independent implies that the Pugh chart might not be sufficient in assessing and selecting new design concepts during incremental change. See Figure 2b for illustration.

The House of Quality (HoQ) can also be used for concept selection to analyse the tradeoffs between design solutions.[19] The HoQ is the primary tool of the management approach known as Quality Function Deployment (QFD) and is commonly used to translate customer requirements into product attributes.[20] Figure 3 shows the four HoQs which link customer's voices through to manufacturing. In the first HoQ, designers can assess the influence of different product attributes with respect to meeting customer's requirements. Whereas in the second HoQ, designers can assess a list of design concepts with respect to the important product attributes identified in the first HoQ. The third HoQ looks at the relationships between design concepts and the manufacturing processes, and lastly, the fourth HoQ investigates the production requirements necessary to fulfil the manufacturing processes.

To some extent, the second HoQ is similar to the Pugh concept selection method. The main difference is the inclusion of a 'roof' matrix which assesses the interaction between different concepts. By doing so, the dependencies between each concept can be explicitly assessed. Figure 4a shows the basic structure of a simplified second HoQ.

At first glance, the HoQ appears to cover the different design descriptions and dependencies mentioned previously (see Figure 4b). However, the 'roof' matrix in the HoQ can only facilitate the analysis of direct change propagation between conflicting concepts (features). The relationships between these

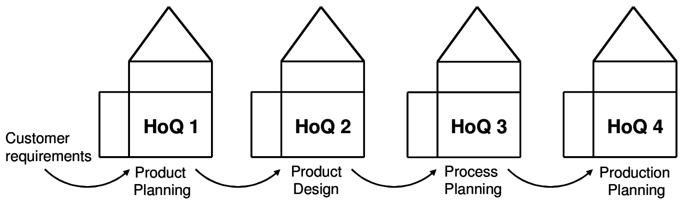
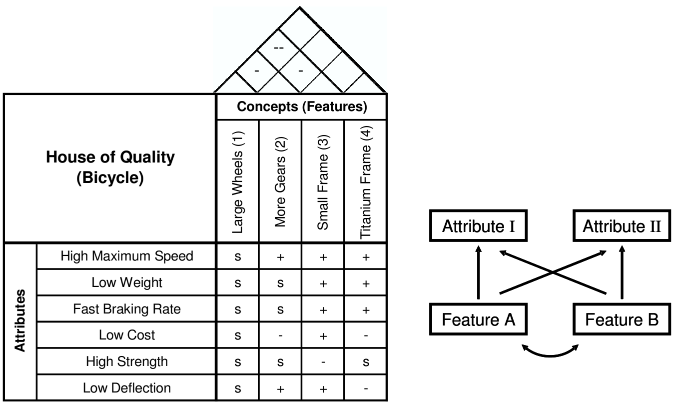


Figure 3. Quality Function Deployment (Adapted from Ref. 19).



(a) (b)

Figure 4. (a) Example of a simplified second HoQ. (b) Evaluation of concepts using second HoQ.

design features and the rest of the product is not explicitly examined. A more systematic and comprehensive evaluation approach is therefore required. This can be achieved by incorporating change propagation modelling during the selection of solution alternatives.

A few change management tools available have been discussed in the academic literature. Ollinger and Stahovich[21] developed the RedesignIT tool to assess probable behavioural side effects during a design change; Weber *et al.*[22] and Conrad *et al.*[23] described 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.*[24] introduced a methodology called Change Favourable Representation (C-FAR) to capture possible change consequences using existing product data information; Clarkson *et al.*[6] developed the Change Prediction Method (CPM) which aims to identify the likelihood, impact, and risk of change propagation between components. The CPM can be considered as an enhancement to the traditional Dependency Structure Matrix (DSM) analysis as it examines not just the direct component linkages, but also the indirect component linkages (Refer to Ref. 25 for an overview of DSM). Computer-Aided Design (CAD) tools can also be used for change propagation analysis. For instance, CAD solid modelling tools can identify geometrical interferences between components when a new component design is introduced.

In general, these tools can be broadly classified as shown in Figure 5. The tools listed in the left column address the dependencies between product attributes and their components, while the tools listed in the right column take into account the interdependencies between components. Each of these tools emphasizes on different aspects of change propagation and uses different level of detail for analysis. It can be seen from Figure 5 that while each tool has its own merits, they do not cover the entire change propagation spectrum as discussed in Section 2.

There are a number of attempts to model the entire spectrum of change propagation by extending the analysis to cover different concerns. For instance, Ariyo *et al.*[26] attempted to relate the connection

Classification of Change Analysis	
Attributes ⟺ Components	Components ⟺ Components
RedesignIT [21]	Dependency Structure Matrix [25]
Characteristics-Properties Modelling & Property-Driven Development [23]	Change Prediction Method [6]
Change Favourable Representation [24]	Computer-Aided Design (CAD) (e.g. Solid Modelling)
Computer Aided Design (CAD) (e.g. Finite Element Analysis)	

Figure 5. Classification of change analysis tools.

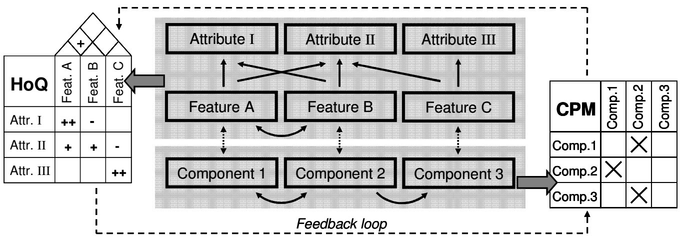


Figure 6. Concept selection with change prediction capability.

between Functions, Behaviours, and Structure during a design change; Flanagan *et al.*[27] introduced a mapping system to link component change propagation to their associated functions; Keller *et al.*[28] discussed the combined used of the Contact and Channel Model (C&CM)[29] for product functional analysis and the Change Prediction Method (CPM)[6] for component change propagation analysis. More specifically, a recent attempt to consider the full effects of change propagation during concept selection has been described by Koh *et al.*[5] This method uses the House of Quality (HoQ)[19] and the Change Prediction Method (CPM)[6] to break down the change propagation problem into two (see Figure 6).

The HoQ is used to relate how product attributes can be affected due to changes in the product, while the CPM is used to foretell which part of the product can be affected when a change is introduced. Although this approach appears to address the issue of change propagation during the selection of solution alternatives, some modelling challenges remain. These challenges will be discussed in Section 4.

4. BRIDGING THE GAP

Despite previous attempts to model the full effects of incremental change, some fundamental modelling challenges still persist. For instance, it is difficult to model how change propagation can affect attributes like noise or vibration as they are contributed by every part of the product. The assessment of the cumulative change propagation effects of multiple changes can also be difficult if there are overlaps in the propagation paths. Furthermore, the nature of change propagation for a platform or frozen component remains unclear. In addition, deciding the right level of detail for analysis can be challenging especially for complex product with multiple components. The overall management of such a modelling system in terms of adaptability to different design cases, ease of model generation, and maintenance can be a huge challenge as well.

Arguably, the most influential factor that affects the practicability and usefulness of a change propagation modelling tool in concept selection lies in the level of detail used for the analysis. This is due to the fact that the level of detail used in change propagation analysis directly influences other factors such as ease of model generation and maintenance (effort), adaptability to different design cases (flexibility), and reliability of the analysis (accuracy). Figure 7 shows the relationship between the level of analysis detail with flexibility, accuracy, and effort. On one hand, the amount of effort required to

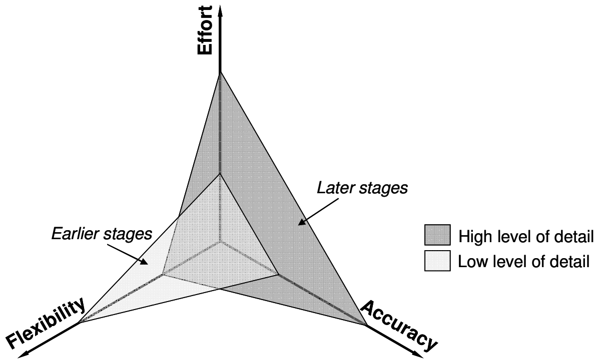


Figure 7. Relationship between the level of analysis detail with flexibility, accuracy, and effort.

capture, model, and maintain information at high level of detail is more demanding compared to those of low level of detail. However, using high level of detail in the analysis can yield more accurate results compared to the use of abstract ones. This is due to the nature of the inputs. When analysis is made at a detailed level, the effect of change propagation can be modelled at high resolution, thus resulting in a more deterministic model. On the other hand, as information are aggregated to an abstract level, the modelling of change propagation shifts towards a more probabilistic model.

The flexibility to adapt to different design cases is also related to the level of analysis detail. For instance, the introduction of a snap-fit attachment design for a mobile phone casing can render a list of detailed features such as ‘screw thread length’ and ‘hole diameter’ irrelevant. While an abstract model can aggregate the detailed changes as a change in the ‘casing’ component, such a design change can be difficult to simulate using a model at high level of detail. It is therefore beneficial to have a model that can switch between levels of abstraction (for example, through hierarchical decomposition) to match the design requirements of each project. This concern can be avoided if a new change propagation model is created for every new design.

It should also be noted that as the number of solution alternatives is greater at the earlier stages of the design process, the amount of analysis effort required can be huge if each concept are analysed at a high level of detail. In additional, information at high level of detail might not always be available as solutions can be vague at the earlier stages of the design process. Thus, change propagation analysis at a low level of detail is more feasible at the earlier stages of the design process, while analysis at a high level of detail is more suitable towards the later stages to avoid nasty surprises. More research is required to understand the appropriate transition point between the levels of detail used for the analysis.

5. CONCLUSION

This paper describes the limitations of current concept selection tools in evaluating the consequences of change propagation associated with each concept. It also discusses the need to model change propagation for the selection of solution alternatives during incremental change and highlights the challenges in doing so. The level of detail used in change propagation analysis is identified as an important factor that affects the practicability and usefulness of such modelling tools. More research is required to bridge the gap between change propagation modelling and the selection of solution alternatives.

REFERENCES

[1] McMahon, C. A. (1994). Observations on modes of incremental change in design. *Journal of Engineering Design* 5(3):195–209.

[2] Otto, K. and Wood, K. (2001). Product Design, Techniques in reverse engineering and new product development. Prentice-Hall.

[3] Pahl, G. and Beitz, W. (1996). Engineering Design-A Systematic Approach. Springer.
[4] Ulrich, K. T. and Eppinger, S. D. (1995). Product Design and Development. McGraw-Hill.
[5] Koh, E. C. Y., Keller, R., Eckert, C. M. and Clarkson, P. J. (2008). Influence of feature change propagation on product attributes in concept selection. *International Design Conference (DESIGN 2008)*, 1:157–167.
[6] Clarkson, P. J., Simons, C. and Eckert, C. M. (2004). Predicting change propagation in complex design. *ASME Journal of Mechanical Design*, **126**(5):765–797.
[7] Eckert, C. M., Clarkson, P. J. and Zanker, W. (2004). Change and customisation in complex engineering domains. *Research in Engineering Design*, 15(1):1–21.
[8] Eckert, C. M., Keller, R. and Clarkson, P. J. (2007). Avoiding emergency innovation: Change prediction in innovative products. *European Research in Innovation and Management Alliance (EIRMA'07).*
[9] Rios, J., Roy, R. and Lopez, A. (2007). Design requirements change and cost impact analysis in airplane structures. *International Journal of Production Economics*, 109(1-2):65–80.
[10] Gero, J. S. (1990). Design Prototypes: A knowledge representation schema for design. *AI Magazine*, 11(4):26–36.
[11] Gero, J. S. and Kannengiesser, U. (2004). The situated function-behaviour-structure framework. *Design Studies*, 25(4):373–391.
[12] Sembugamoorthy, V. and Chandrasekaran, B. (1986). Functional representation of devices and compilation of diagnostic problem-solving systems. *Experience, Memory, and Reasoning (Kolodner, J. L. and Riesbeck, C. K. (Eds.)*, pp. 47–73, Hillsdale.
[13] Chandrasekaran, B. and Josephson, J. R. (2000). Function in device representation. *Engineering with Computers*, 16:162–177.
[14] Chandrasekaran, B. (2005). Representing function: Relating functional representation and functional modelling research streams. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 19(2):65–74.
[15] Ullman, D. G. (2002). Toward the ideal mechanical engineering design support system. *Research in Engineering Design*, 13(2):55–64.
[16] Rust, R. T., Thompson, D. V. and Hamilton, R. W. (2006). Defeating feature fatigue. *Harvard Business Review*, 84(2):98–107.
[17] Shah, J. J. and Mantyla, M. (1995). Parametric and feature-based CAD/CAM: Concepts, techniques, and applications. Wiley.
[18] Pugh, S. (1990). Total Design: Integrated methods for successful product engineering. Addison Wesley.
[19] Hauser, J. R. and Clausing, D. (1988). The House of Quality. *Harvard Business Review*, 66(3):63–73.
[20] Akao, Y. and Mazur, G. H. (2003). The leading edge in QFD: Past, present and future. *International Journal of Quality & Reliability Management*, 20(1):20–35.
[21] Ollinger, G. A. and Stahovich, T. F. (2004). RedesignIT-A model-based tool for managing design changes. *Journal of Mechanical Design*, 126(2):208–216.
[22] Weber, C., Werner, H. and Deubel, T. (2003). A different view on product data management/product life-cycle management and its future potentials. *Journal of Engineering Design*, 14(4):447–464.
[23] Conrad, J., Deubel, T., Kohler, C., Wanke, S. and Weber, C. (2007). Change impact and risk analysis (CIRA) — Combining the CPM/PDD theory and FMEA methodology for an improved engineering change management. *International Conference on Engineering Design (ICED'07).*
[24] Cohen, T., Navathe, S. B. and Fulton, R. E. (2000). C-FAR, change favourable representation. *Computer-Aided Design*, 32(5):321–338.
[25] Browning, T. R. (2001). Applying the Design Structure Matrix to system decomposition and integration problems: A Review and New Directions. *IEEE Transactions on Engineering Management*, 48(3):292–306.
[26] Ariyo, O. O., Eckert, C. M. and Clarkson, P. J. (2006). On the use of functions, behaviour and structural relations as cues for engineering change prediction. *International Design Conference (DESIGN 2006).*
[27] Flanagan, T., Eckert, C. M., Eger, T., Smith, J. and Clarkson, P. J. (2003). A functional analysis of change propagation. *International Conference on Engineering Design (ICED'03).*
[28] Keller, R., Alink, T., Pfeifer, C., Eckert, C. M., Clarkson, P. J. and Albers, A. (2007). Product models in design: A combined use of two models to assess change risks. *International Conference on Engineering Design (ICED'07).*
[29] Matthiesen, S. (2002). A contribution to the basis of the element model 'Working Surface Pairs and Channel and Support Structures' on the correlation between layout and function of technical systems. Ph.D. Thesis, Institute for Product Development, Technical University Karlsruhe.