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THE BENEFITS OF PREDICTING CHANGE IN COMPLEX PRODUCTS: APPLICATION AREAS OF A DSM-BASED PREDICTION TOOL

T. Jarratt, C. Eckert and P. J. Clarkson

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1. Introduction

Most designers struggle to fully understand a complex product. For example a designer may be an expert on the electrical systems within a device, but struggle with the mechanical aspects. This can hinder them significantly when they assess the potential impact of a proposed change to a design, which is a key phase in any engineering change process. Although the majority of alterations made to a product have little impact, a few can unexpectedly propagate, resulting in many other parts or systems being affected, some of which may not even be directly linked to the initially changed component. This knock-on effect has been referred to as an "avalanche" of change [Eckert *et al.*, in press; Fricke *et al.*, 2000] or the "snowball effect" [Terwiesch and Loch, 1999]. Such an event can have a major affect on budgets, schedules and organisations.

Throughout the entire life cycle of a product, engineers are frequently required to predict how a change could propagate: from alterations being made to a conceptual design to modifications to a product when it has been in service for a long period of time. Currently, few methods or tools are available to support this process; commercially available software to manage product data does not model information that would be useful for engineering change assessment [Riviere *et al.*, 2003]. This paper describes part of an ongoing research project, the aim of which is to support designers making engineering changes by (1) giving them a better understanding of the linkages between components and systems within their product and (2) helping them to assess the risk of a change propagating. A Design Structure Matrix (DSM) based method of modelling products by analysing the linkages between components and systems, has been created. This paper provides an overview of the method, discusses other potential applications of it within the design process and describes a developmental computer tool for visualising linkages and predicting change propagation.

2. Methods

The research is based on three detailed case studies. An initial case study in a UK aerospace company involved interviews with over twenty engineers and observations of meetings and design practice. This led to the creation of a theory of change propagation [Eckert *et al.*, in press] and the initial development of algorithms to predict the risk of change propagation occurring [Clarkson *et al.*, 2001]. A second empirical study was then carried out with a UK company in the automotive sector, where twenty engineers were interviewed and key meetings observed. The concept of component linkage models was developed in conjunction with this company. It was tested through protocol analysis experiments with four engineers, who filled in a DSM of component connectivity. The results of the experiments were used to develop a detailed model that was created during a team elicitation session.

Validation of the model with historic engineering change cases was favourable and the firm is now using it as a support for Failure Mode and Effect Analysis (FMEA) during the concept design phase of the next generation of product. The method was extended in a further case study with another UK aerospace business. A junior designer in the company took over the construction and population of the matrix after brief initial training by the authors.

3. The Change Prediction Method and Product Linkage Modelling

Only once a change is worked out in detail it is possible to know which other parts and sub-systems have been affected. Throughout the entire design process, engineers need to know the risk of a change propagating to other parts of the product: when they tender for a new design variant, when they think about how to implement a change, when they select between change options and when they plan the design process. While it is possible to work out fairly accurately how change will affect the product, this takes considerable effect. CAD system can analyse the immediate consequences of a change, but can not predict how the change will spread, because this is not a deterministic process. Therefore designers need a probabilistic understanding of change and a high level overview to decide how a change will affect the product as a whole. The Change prediction method (CPM) provides an indication of the risk of a change affecting other parts based upon the connectivity between individual parts (see Clarkson *et al.* [2001] for a full discussion). However, how a change will affect another component depends on the kind of change that is required and the linkage that exists between components. To reflect this the modelling element of the CPM was extended to include the linkages between components and sub-assemblies within the product (see Jarratt *et al.* [2004] for a full discussion); this has been termed Product Linkage Modelling (PLM). For any change it is easier to change some components then others. Ongoing research currently looks at the "logic" that designers apply to any change problem. Whether a change will pass to other designs depends on the tolerance margins of this component [Eckert *et al.*, in press], which will be the focus of a further extension.

3.1 The Change Prediction Method

At the core of the CPM tool is a combination of the representation and analysis methods used with Design Structure Matrices (DSM) (see Browning [2001] for a comprehensive review of these techniques), which are used to model the connectivity between the components and sub-systems that make up the product, with risk management techniques. The CPM uses a simple model of risk, where risk is defined as the product of likelihood and impact. Likelihood is defined as the *"average probability that a change in the design of one sub-system will lead to a design change in another by propagation across their common interface"*, whilst impact is the *"average proportion of the design work that will need to be redone if the change propagates"* [Clarkson *et al.*, 2001].
The method as illustrated in Figure 1, has 3 steps. Firstly a product model or breakdown must be created and put into DSM format. Once the interconnectivity between the sub-systems is represented, the change relationships can be shown. Matrices for likelihood and impact are generated with values between 0 and 1. The impact and likelihood matrices created are *direct* matrices in that they represent the risk of change propagating between directly linked sub-systems. *Indirect* change propagation requires the involvement of at least one intermediate sub-system and this forms a chain of change propagation. The combined impact of changing one component on another is the sum of the direct and indirect affects. Various algorithms are being evaluated for the calculation of the combined relationships; the initial method was based upon calculating all possible routes between the initiating component and the target component [Clarkson *et al.*, 2001]. In a second step the initiating component for a change is identified and diagram is drawn which indicates the risk, that this change will speed to other components. With this increased understanding the designers can embark in the required redesign.
The major issue at the start is the granularity of the product breakdown. Whilst a model that incorporates every single part of a product may have a certain completeness to it, there is a loss of focus to the technique along with the difficulty of handling and understanding such large arrays of information (for example a helicopter has over 10,000 parts). In most products simple, standard parts,

such as nuts and bolts can be ignored. Most products are too complex to be modelled on a component level, and therefore have to be modelled as sub-systems or assemblies.

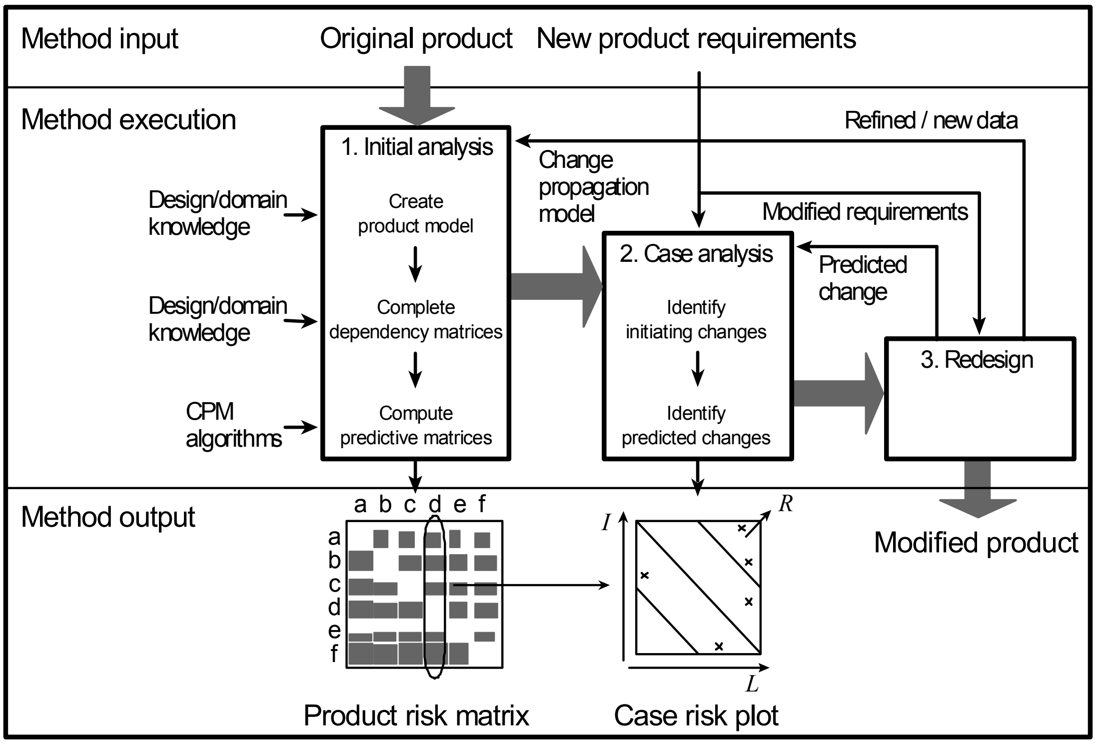
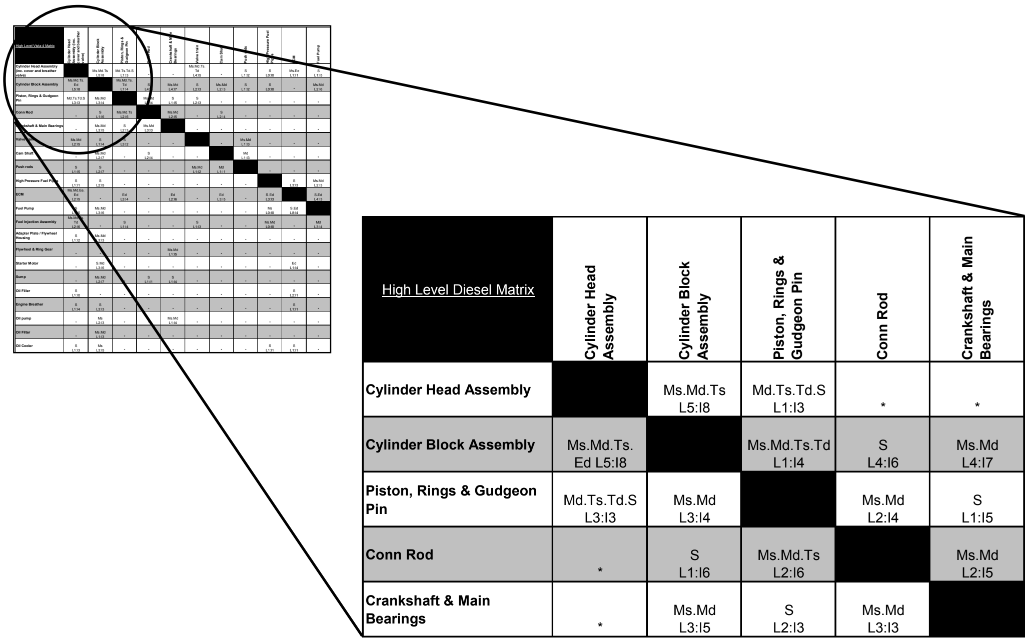


Figure 1. Schematic diagram of the Change prediction method [Clarkson et al., 2001]

3.2 Product Linkage Modelling

A component linkage is a direct relationship or connection that exists between two pieces of a product. Depending upon the level of granularity chosen, the pieces can be individual parts, sub-assemblies or modules. The linkage can represent any important relationship that would connect the two pieces, from a connection, which, if broken, causes the device to cease to operate (e.g. electrical flow) to an association, which, if violated, does not affect the product's primary performance (e.g. a vibration effect). Linkages can either be symmetrical (acts in both directions i.e. A → B and B → A, e.g. when two components are bolted together) or directional (there is a flow or transfer from one component to the other i.e. A → B only, e.g. a signal passing from or to a control unit). Obviously change can only spread from one component or sub-system to another if they are connected in some way. Even a simple product has a complex network of linkages between its parts. As the complexity of the product examined increases, the number of potential types of linkage rises to include issues such as heat, vibration, electricity, etc. An example of such a model (for a diesel engine) is shown in figure 2. Linkage modelling differs from functional modelling in a number of ways. Firstly, linkage modelling examines the connections between components and assemblies whereas functional modelling identifies the functionality of the individual components themselves. Added to this, linkage modelling looks at a product from a change perspective and as such has to fully embrace negative aspects (e.g. heat dissipation, electro-magnetic interference, vibration, etc.) and could include aesthetic/ form issues as well as the functional aspects.

The PLM approach has similarities to that of Pimmler and Eppinger [1994], who used static DSMs to reveal and examine alternative product architectures. The method investigated four different possible interactions between components/ assemblies: spatial, energy, information and material. These were related to the functional modelling concepts that were proposed by Pahl and Beitz [1996] and Suh [1990]. One key difference is that this work focuses upon making product models to assist the alteration of already established products (i.e. the architecture is already established), whereas the work of Pimmler and Eppinger focused upon the development of different architecture concepts.



High Level Diesel Matrix	Cylinder Head Assembly	Cylinder Block Assembly	Piston, Rings & Gudgeon Pin	Conn Rod	Crankshaft & Main Bearings
Cylinder Head Assembly		Ms.Md.Ts L5:I8	Md.Ts.Td.S L1:I3	*	*
Cylinder Block Assembly	Ms.Md.Ts. Ed L5:I8		Ms.Md.Ts.Td L1:I4	S L4:I6	Ms.Md L4:I7
Piston, Rings & Gudgeon Pin	Md.Ts.Td.S L3:I3	Ms.Md L3:I4		Ms.Md L2:I4	S L1:I5
Conn Rod	*	S L1:I6	Ms.Md.Ts L2:I6		Ms.Md L2:I5
Crankshaft & Main Bearings	*	Ms.Md L3:I5	S L2:I3	Ms.Md L3:I3	

Figure 2. Example of a Linkage Matrix (each different type of linkage has a letter code e.g. Ms = Mechanical Static linkages) and change propagation values (likelihood: impact)

4. A computer based change prediction and visualisation tool

While a DSM is a better representation then most to display complex product data [August *et al.*, in press], designers need a variety of different visualisations of the data to be guided to important data. A basic computer tool is under development that can switch between matrix and graphical representations of key product data; this is illustrated in figure 3.

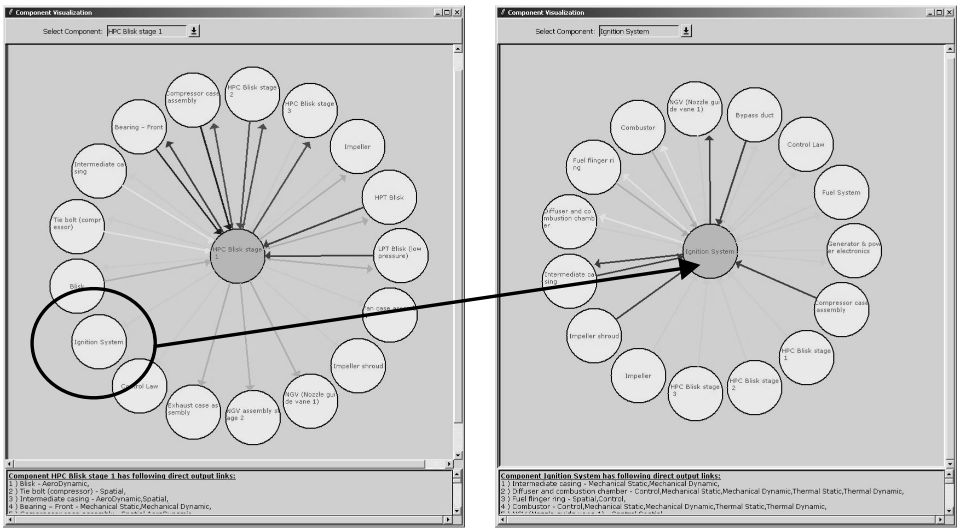


Figure 3. Screen shot from the matrix visualisation software showing part of a jet engine model. A circle represents each component; the different types of linkages are colour coded; arrows mark their direction. Clicking on a component causes the graphic to redraw with the selected component in the centre of the screen (illustrated above with the ignition system)

5. Results

Since the methods were developed the industrial partners and the research team suggested and examined other applications. These will be summarised in this section.

5.1 Change prediction

The method can be applied to **tendering** to assess the likely scope of the knock-on effects, either by providing a probabilistic aggregate value or by highlighting high risk areas, so that relevant people can be consulted to check whether their area or component will be affected. When **a new change is implemented or a variant is designed** the impact on other components can be assessed through the aggregate risk values of the CPM or a list of potentially affected areas can be drawn up using the PLM. This enables the designers to conduct a fast and focused evaluation of several solution alternatives. A similar evaluation can be undertaken for the **new product development** of an evolutionary product, where most companies want to carry over at least some of the existing components. As long as the high-level product architecture stays the same (as is the case with many established products), a linkage model of a previous product can still provide useful insights.

5.2 Knowledge Capture

The matrix method provides a formalising for capturing **past experience of changes**. In an elicitation exercise designers talk through connectivity in a very systematic way, which triggers their memory of past changes. In fact during the elicitation session engineers provided elaborate trails of changes from the past. This can be carried out as a systematic process, where designers are encouraged to describe cases of change propagation in the past to build up a picture of the parts of the design most susceptible to change in an intuitive and easily assessable way. The PLM records the **linkages in a product**. In complex products no one engineer can understand all these linkages completely. Using visualisation software this knowledge can be made accessible to everybody concerned with the product. When talking about linkages and propagation chains, designers frequently mention the **rationale** for the design decisions that led to the change or were taken in response to a change. The PLM method could potentially be linked to rationale capture tools, such as DREd [Bracewell and Wallace, 2003] and provide a very rich picture of a product.

5.3 Team support

The matrix elicitation is a useful **team building exercise** in its own right. It forces everybody to talk through their assumption in a very systematic way and provides team members with an understanding of which changes their colleagues have seen and been influenced by. New team members can listen to their more experienced colleagues and pick up the jargon as well as the experience of the their older colleagues. In our evaluations, all the team members enjoyed participating. In one company they learned about the way their colleagues thought about their design problems, which they had not appreciated despite of working together for up to 20 years. In another company a young engineer spearheaded the elicitation and commented that he become more confident about his product knowledge because of talking it through with his experienced colleagues. Communication about the product is eased by a common **product visualisation**, where the views and experiences of different team members are expressed in a commonly understood and neutral way. People usually can find out quite easily who is the owner of a part and can use the tool as **communication support** to find out whom to talk to, which is important in a geographically distant team or across the supply chain.

5.4 Process Management

The matrix enables everybody to see the "**big picture"** on some level by providing the same view of the product on a fairly high level of abstraction. This can be very useful in **planning tasks** and **putting together** meetings, because it focuses the attention to those parts of the product that are relevant. One of our collaborator companies has began to use the matrix in **design review meetings** as a check list to see whether all the possibilities of the change spreading have been considered. In a similar way the matrix could be used for **FMEA reviews** to find about what could go wrong in a design process. In contemporary design processes, **risk assessment** has become a very important issue. The linkage matrix can support design managers in making risk assessments, because it brings together information that would otherwise be difficult to collate; in addition the results from the CPM tool could also be useful for justifying design decisions to superiors.

6. Conclusions

The change prediction and visualisation methods presented in this paper are easy to understand and simple to use taking only a few hours to pick up and apply. The original aim of the CPM was to predict risk in tendering, while the PLM technique was developed to increase the overview that designers have over the product during the engineering change process. However, the methods have a far wider application throughout the entire design process, largely because they given designers an insight into their product that is otherwise hard to gain. Ongoing work is focused on the creation of a computer support tool based upon these techniques. Research is being carried out to develop the different uses described above, especially with regards to knowledge capture and communication.

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Timothy A W Jarratt
Engineering Design Centre, University of Cambridge
Trumpington Street, Cambridge, CB2 1PZ, UK
Telephone: +44 1223 766955, Telefax: +44 1223 766963
E-mail: tawj2@eng.cam.ac.uk