INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITÉ DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

PRODUCT MODELS IN DESIGN: A COMBINED USE OF TWO MODELS TO ASSESS CHANGE RISKS

René Keller[1], Thomas Alink[2], Christian Pfeifer[2], Claudia M. Eckert[1], P. John Clarkson[1] and Albert Albers[2]
[1]Engineering Design Centre (EDC), University of Cambridge
[2]Institute of Product Development (IPEK), University of Karlsruhe (TH)

ABSTRACT
When designing complex products such as robots or jet engines, companies face the problem that designers lack the necessary tools to predict the behaviour of the product in the case of component change, and to assess the risks associated with decisions. Product models allow companies and individual designers to reason about product properties. The information in the model can be used to analyse the properties of a product before decisions are taken about potential modifications. To meet time and budget constraints it is vital to have the ability to predict the risks of knock-on effects before a change is implemented and select alternative changes accordingly. This paper introduces a comparison of two product models used in the Change Prediction Method (CPM) and the Contact & Channel Model (C&CM). It analyses ways where both approaches can benefit and complement each other in analysing and predicting product change.

Keywords: Product modelling, change prediction, Change Prediction Method, Contact & Channel Model

1 INTRODUCTION
Changing existing designs due to new customer requests or to fix errors in the design is common throughout the entire product life-cycle [1, 2]. However, in complex design implementing changes can make alterations in other parts of the product necessary. Such knock-on changes can be costly and lead to overrunning time and budget constraints. Predicting the effects of changes before they happen can help designers select the best way to carry out a change, thus preventing them from implementing potential harmful changes or misallocating resources.
Recent research into the prediction of engineering changes has resulted in several methods which use models of the product. De Weck *et al.* [3] tried to identify components in a product family (platform components) that need to be designed flexibility in order to be able to cope with changes by using a "propagation network." Design for Changeability (DfC) [4] also incorporates change considerations early into the design. However, each of these approaches is limited in its focus as they are aimed at very early stages of the design to prevent change propagation. The research presented in this paper describes the use of two product models for change prediction in existing designs, the CPM method developed at the Engineering Design Centre in Cambridge and the Karlsruhe C&CM model. The design of the ARMAR III humanoid robot is used to illustrate how both models can be used individually and in a combined strategy to increase industries' ability to assess the impact of changes before they are implemented.
This paper is organised as follows: Section 2 reviews methods for predicting change propagation. Section 3 introduces the case study that is the basis for this research. Then, in Section 4 and Section 5, the analysis of changes to the *Lower Arm* of the ARMAR-III robot is discussed using both, the CPM and the C&CM method. Section 6 discusses the combined strategy for the prediction of change propagation using both methods in parallel and shows limitations of each of the methods.

2 PREDICTING CHANGE

Change is a key driver in new product development. In fact, many "new" products are based on modifications of existing designs. Nichols [1] reported that in the 1980s approximately 80% of all parts of American cars were carried over from previous designs and the basic design of a car engine has not changed fundamentally over the last 100 years. Innovation has occurred because of lighter and stronger materials or better engine management systems. There also exists economic pressure to maximise the reuse of existing components. Reuse affords economy of scale in production, reduced design time compared to new development and known risks over the life cycle. Customers are concerned about the reliability of the products they purchase, and therefore don't want to be confronted with too many elements in a design that have not been proven in real-world settings.

On the other hand, managing changes is also a problem in industry. Being unable to properly assess the consequences of changes can jeopardise entire projects. Nevertheless, decisions made at early stages of the design process have huge impacts on cost, reliability and performance of the product. Thus, the design team has to explore a variety of options, which should allow them to achieve the new requirements, whilst keeping other factors as constant as possible. Whether components and systems can be kept is not just a question of whether they should or should not be replaced with new and improved ones, but also whether they are resistant to the knock-on effects of other changes. In the selection of solution alternatives the issue of knock-on effects onto other components plays a very important role.

A study by the AberdeenGroup [5] showed that the majority of changes – although necessary for innovation – cause "*scrap, wasted inventory, and disruption to supply and manufacturing*". Nevertheless, the report also shows that companies do not properly assess the consequences of changes. Only 11% of all companies were able to *"provide a precise list of items affected by a change"* in the development of a single product, while only 12% were able to assess the consequences of changes on the life cycle of the product. On the other hand, the majority (82%) of companies interviewed also stated that they put a lot of emphasis on increasing the product revenue, which leads to innovation and in turn to the introduction of changes to the product.

A survey of 50 German manufacturing companies [6] supports these findings. It is pointed out that managing engineering change is an important issue in manufacturing industry. 56% of all changes made to a design happen after the initial design phase and of these, 39% are said to be avoidable. All this work suggests that industry needs a method that predicts changes caused by preceding changes in the design process because the later a change is implemented, the more costly it is. Clark and Fujimoto [7] suggested a "rule of 10" meaning the cost of a design change grows by the factor of ten with each passing design phase and Fricke *et al.* [8] summarised five strategies to cope with changes: Less, earlier, effective, efficient, better.

2.1 Decision Support Tools for Change Management

The general, an engineering change process is usually a straightforward sequence of a number of activities. Maull *et al*. [9], for example, describe a 5 stage process consisting of: 1) filtration of change request, 2) development of solution; 3) assessment of solution; 4) authorisation of change; and 5) implementation. Decision support tools for change management focus on the early stages of the change process where the change and potential solutions are analysed and the impact on the product is determined.

"RedesignIT" [10] is a tool that provides qualitative guidance for engineers based on models of the key components and attributes of a product. The software presents the user all possible solutions to a change request. Then by analysing all possible side effects of these solutions supports the designer in deciding on the best solution. This tool was used to model the changes made to a diesel engine that should be changed in order to have a larger output torque.

C-FAR (Change FAvourable Representation [11]) also aims at identifying the effects of changes. However, the underlying data structure, which tries to capture all relevant aspects of the design artefact, limits its use to simple and small products.

These concerns with change have not been limited to mechanical engineering, in software engineering, Schach and Tomer [12], presented a tool that helps highlighting change effects in software development. In a similar view Hassan and Holt [13] described an algorithm for predicting change effects in software systems that result from change propagation.

2.2 Change Prediction Method

Clarkson *et al.* [14] introduced CPM, as a technique for predicting change propagation. It is based on product connectivity models which are represented in a Design Structure Matrix (DSM). As a decision support tool it aims to identify the risks of emergent changes that result from the knock-on effects of preceding changes before changes are implemented.

The underlying data structure of this method is a product connectivity model that can be seen as a graph that stores information about components and dependencies between components. The basic idea is that, if one component is changed, this can affect directly connected components. These changes can, in turn, again affect other directly connected components (knock-on effects). A link between two components (nodes in a graph) means, in the terminology of graph theory, a change to the tail (change initiator) affects the head (change recipient) in a directed graph. Each link includes a direct change likelihood value that captures the probability of a change propagating from the tail of the node to the head. Secondly, impact values on a link specify how much of the head component has to be changed when a change propagates through this component connection. Storing likelihood *and* impact values allows the computation of risk, using the product of likelihood of impact. The main result of the CPM method is a matrix-based representation that allows visual identification of high risks in the component architecture. This supports managers and designers in making decisions about whether changes can be implemented or not.

2.3 Contact & Channel Model

The core of the C&CM method [15] developed at University of Karlsruhe (TH) consists of a systematic function-component mapping. The key idea of this approach is an orderly assignment of the functions of a product on their shape, which enables designers to break up with rigid, pre-fixating representations of products. C&CM product models by means of Working Surface Pairs (WSP) and Channel and Support Structures (CSS) force users to think about products in a more abstract way. Thereby, designers are provided with a means to jump easily between different model representations, which is a characteristic of successful problem solving processes [15]. WSPs and CSSs can be found in any product description, be it a functional structure, a sketch or a CAD model. In particular, WSPs are elements of the functional description of a product and their Working Surfaces (WS) link the functional description directly to the concrete physical description.

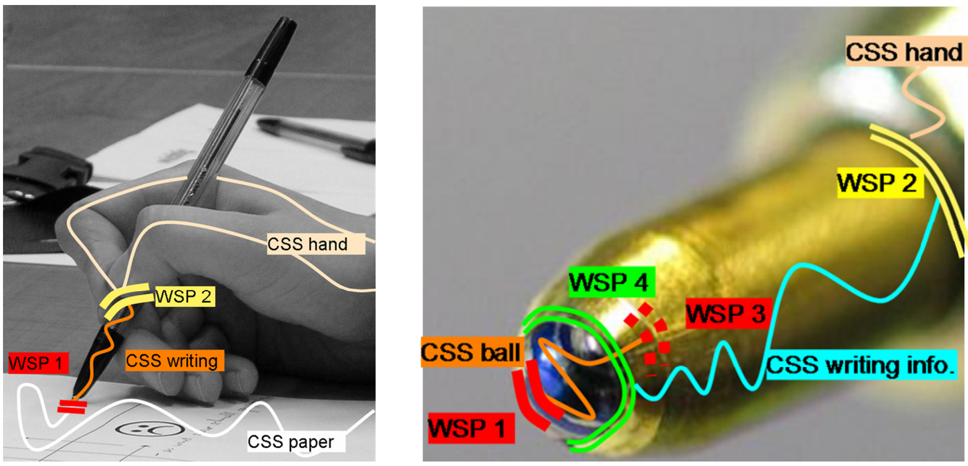


Figure 1: Abstraction and detailing of a ball-pen by means of C&CM

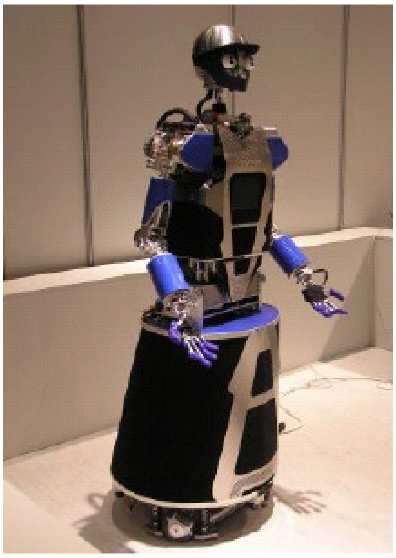
Basis for the work with the C&CM is the understanding that an effect can only be obtained if a WS of the system in focus is in contact with a WS of an adjacent system, which makes a WSP and that for a function in any technical context at least two WSPs and a structure (CSS) that connects both WSPs are required for the completion of the function. The ball pen shown in Figure 1 can only then obtain its function when a WSP between hand and pen, between pen and paper is established correctly. Writing on glass is not possible, as the WSP pen-glass prevents the transfer of ink. The right picture of Figure 1 shows that a C&CM product model can be build representing different levels of detail.

The use of C&CM product models supports the designing with focus on typical human behaviour in design [16] like e.g. a ongoing switching between task clarification and search for solutions. The elicitation of a C&CM product model is geared to a problem solving processes like e.g. SPALTEN [17]. Problem solving processes generally start with a system analysis and problem containment before the founded search for solutions is started. The target of these steps is to generate an understanding of the situation and make sure that the found solutions are grounded in the core of the defined problem.

3 CASE STUDY

The research presented here is based on a case study of the design process of the ARMAR III humanoid robot developed in the Collaborative Research Centre 588 at the University of Karlsruhe (see [18] and Figure 2-left). The goal of the project is to create a humanoid robot that is able to support humans in a variety of different tasks independently or in cooperation with humans. A very ambitious set of requirements has led to a design which is highly spatially and functionally integrated. The complex interactions between system elements pose further challenges in terms of predicting and handling knock-on changes. In order to predict modifications required to develop a new version, the two different product models (a CPM model and a C&CM model) of the lower arm (see Figure 2-right) of the robot were created.

The multidisciplinary development of the highly complex system and the fact that the robot design started from a blank piece of paper causes the development process to run through numerous iteration loops.



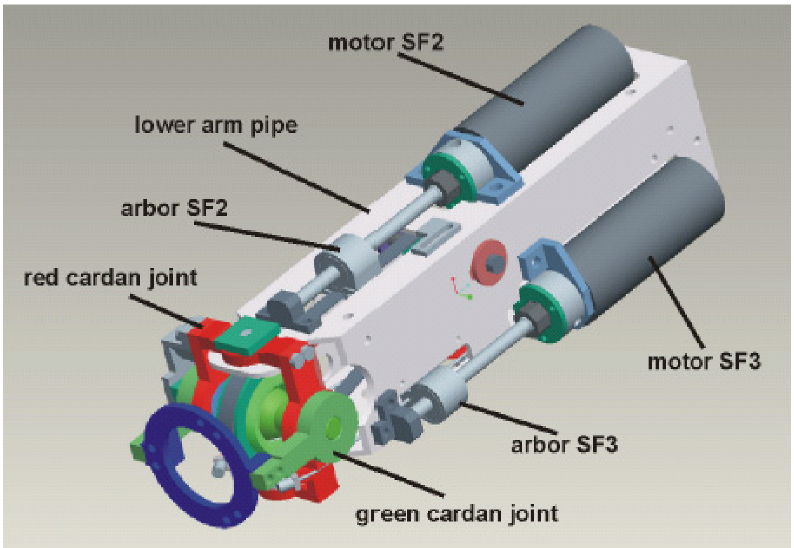


Figure 2: Left: ARMAR III robot. Right: CAD sketch of the lower arm

The mechanical design of the ARMAR III robot is generated by a team of 5 engineers with 2 to 5 years of experience in designing the ARMAR III and its predecessors. They are supported by several research students who generate CAD drawings and undertake Finite Elements Analysis, Multi Body Simulation and Optimization tools. The majority of components are manufactured at the IPEK factory. The case study included observations of designers carrying out development tasks and 3 semi structured interviews of in total 9 hours. Within the duration of the study three changes were carried out. Two of those, exchanging the *Ball Screw Spindle* and changing the *Power Train* location are being discussed in more detail in this paper.

4 MODELLING WITH THE CHANGE PREDICTION METHOD

Building a CPM model involves domain experts judging component connections and the likelihood and impact that a change of one component affects another component for all component pairs. This qualitative (component connections) and quantitative (likelihood and impact of changes) information is then utilised to compute combined change risks for each component pair [19]. The model-building process involves a workshop where a number of designers decide together on direct component connections. This data is then used for the prediction of change propagation. The analysis presented in this paper builds on assessing risks visually [20].

4.1 CPM Product Model

The CPM model of the *Lower Arm* of the ARMAR-III robot was created with designers who had dealt with it over several years. The model was created in parallel with the C&CM model.

The resulting CPM model for the lower arm of the ARMAR-III robot can be seen in Figure 3 in two different representations, a component DSM on the left and a node-link diagram on the right. Both representations show the linkages between components in the *Lower Arm*. One can see easily that especially the *Lower Arm Pipe* is a highly connected component, having connections to almost all other components of the lower arm.

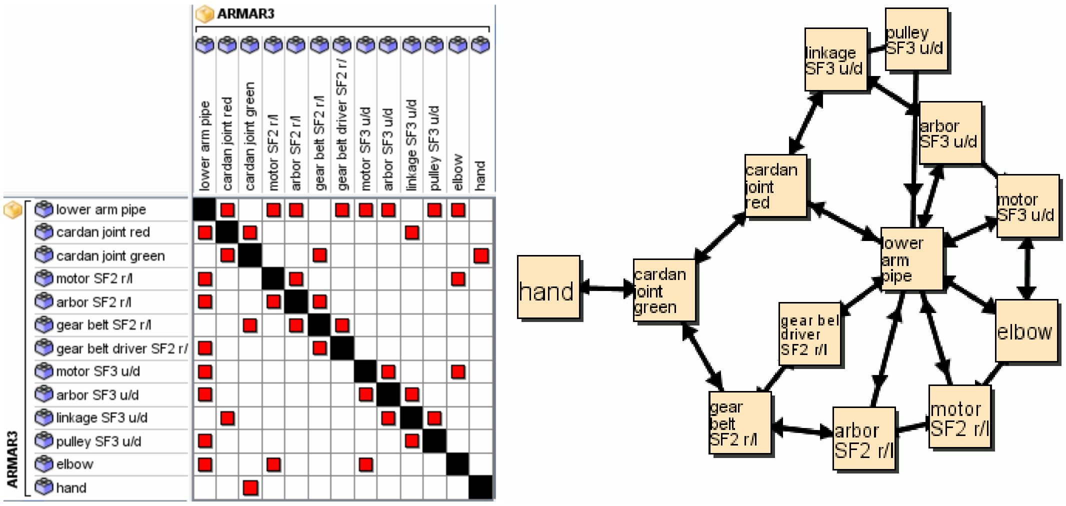


Figure 3: Initial CPM model of the lower arm. Left: Matrix representation. Right: Node-link representation

This is also mirrored in the combined change likelihood, i.e. the probability that a change to one component affects another component through all possible component interactions that is shown in Figure 4. The *Lower Arm Pipe* is highly affected by changes to most other components (highlighted row) and that the two components that are most likely to change other components are the *Gear Belt SF2* and the *Linkage* (highlighted columns).

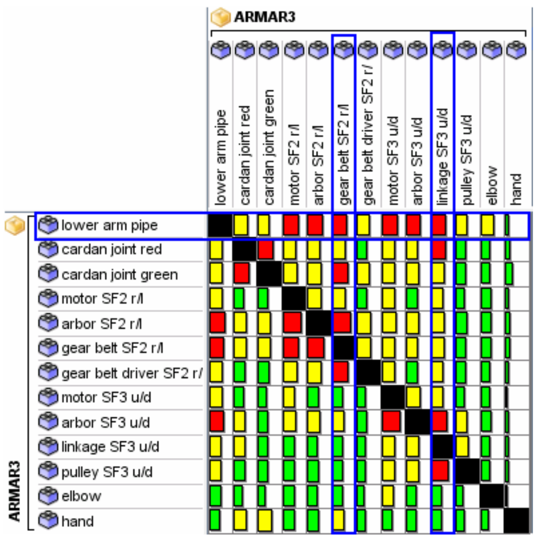


Figure 4: Combined risk model of the lower arm. Right: Propagation paths resulting in changing the Ball Screw Spindle in Arbor SF3

4.2 Exchanging the Ball Screw Spindle

The *Ball Screw Spindle* is a small component within the *Arbor SF3* and is involved in the transformation of the rotation of the motor to the lengthwise movement of the *Linkage SF3*. The

reason for this change was performance improvements. The former *Ball Screw Spindle* was manufactured in-house. The new component is produced by a company with more experience in producing screw spindles.
The question that needs answering is whether exchanging the *Ball Screw Spindle* causes severe risks to other components. Using the algorithms for predicting combined change which are part of the CPM method, the *Lower Arm Pipe* and the *Motor SF3* are most likely to be affected by changes to the *Arbor SF 3* (see Figure 5-left). This diagram shows the same connectivity information as Figure 3, but the distance of a component to the component in the centre of the diagram is proportional to the inverse change risk. Thus, the closer a component is located to the central component the higher the combined change likelihood of a change propagating from the Arbor SF3 to this component [20] – which is identical to the risk shown in Figure 4..
In Figure 5-right, all propagation paths resulting from a change to the *Arbor SF3* are depicted. The layout is the same as in Figure 5-left, but now each individual path is highlighted resulting so that each component can be represented multiple times. The *Lower Arm Pipe* is highlighted showing five high-risk propagation paths leading to this component showing that also the indirect propagation paths play an important role when one has to consider possible effects of a change.

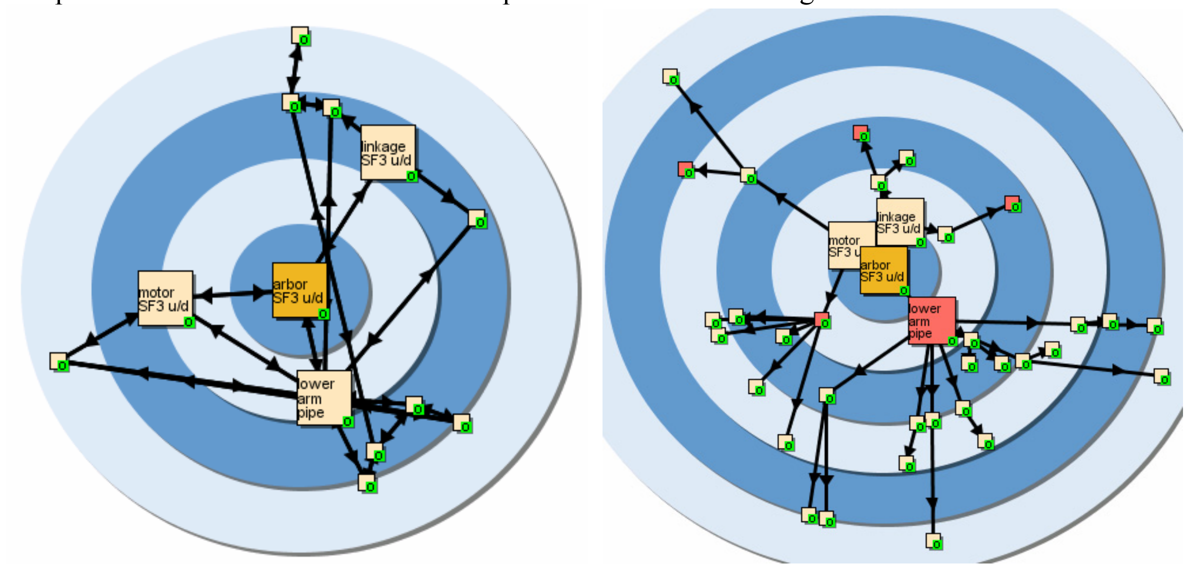


Figure 5: Left: Risk Network showing that changing the arbor is most likely to affect the Lower Arm Spindle. Right: Propagation paths resulting in changing the Ball Screw Spindle in Arbor SF3

4.3 Validation against experts´ judgements

As already mentioned the *Ball Screw Spindle* is a component of the *Arbor SF3*. In the elicitation process the *Arbor SF3* was not broken down into further components. Thus, the change of the ball screw spindle is seen as a change of the *Arbor SF3*, which makes it possible to predict the influence of a change to the components of the system.
The designers predicted that the *Linkage*, the *Lower Arm Pipe* and the *Motor SF3* are influenced by a change on the *Arbor SF3*. In Table 1, one can see that the predictions made by the CPM model matched their expectations.

Table 1: Comparison of experts' judgement and predictions of the CPM model

CPM	Experts' Judgements
Lower Arm Pipe	Linkage
Motor SF3	Lower Arm Pipe
Linkage	Motor SF3
Pulley	
Arbor SF2	

5 MODELLING WITH THE CONTACT & CHANNEL MODEL

For the C&CM product model it is important that the functional structure – which is not explicitly captured in the previously described CPM example – and its relation to the physical structure are considered equally important because an abstract product model is longed for. A focus on functions assures that the product model stores the information about what the design should do and what is its intention. The functional information about relations within a product provides a deeper understanding of the product than just a physical linkage model, and thus has the potential to better predict the consequences of a change.

Deeper information about the quality of a function is captured as the properties of WSPs and CSS and represents knowledge about why every WS is shaped in its way. Though the C&CM product model is a way to reveal and document systematically design decisions of designing engineers. Building up a C&CM product model is thus revealing and reproducing the thought a single designer or a team of designing engineers put into the shape of a product. Overlooking all the knowledge put into a design would make it easy to predict all consequences, caused by further changes.

5.1 Building a C&CM Product Model

Analysing an existing product in terms of tracing design decisions which were made earlier requires a systematic way to ask and argue about function and components in the same way. Any product consists of functional elements that are implemented via physical building blocks [21]. The arrangement of these elements determines the product architecture. For a systematic change prediction these relations must be made explicit.

The model preparation process is executed as follows:

- Naming the principal function.
- Identification of the WSPs, which define the input and output location of energy, material and information, i.e. defining the system boundary.
- Revealing sub functions on the next lower level in a function hierarchy. These functions are named and also located by identifying the C&CM elements WSPs and CSS.

The further steps are accomplished starting from the physical description of the product as it is very difficult to name the functions on the lower levels of the function hierarchy:

- Systematic examination of geometric features according to locations of WSPs, i.e. where an effect happens, which contributes to a technical function.
- Identification of related WSPs and CSS, because a function requires at least two WSP and a connecting CSS.
- Naming of the function for which the identified elements are responsible.

These two ways of revealing the functional structure strongly depend on the knowledge of the model-building persons about the product. The analysing procedure is comparable to the zigzagging between the function structure and the design parameters as proposed by Suh [22]. A difficulty of building a complete C&CM product model is to reveal all functions that occur, and order them logically with low effort. The procedure requires asking from different points of view i.e. from different levels of abstraction. In particular, it is difficult to exactly determine where a function "begins" and "ends", because abstract descriptions are inherently ambiguous. However, a strict sequence of questions changing systematically between functional view and component representations for the build up of the product model is not prescribed. A free way of changing the point of investigation – abstract functional or concrete physical is proposed. For the designer building up the model, it is important to know when and how to switch between the different approaches.

Resulting product model of the ARMAR III Robot lower arm

The resulting product model in an adjacency matrix form is shown in extracts in Figure 6. Functions are listed in the rows. Each function is assigned two WSPs. In order to keep overview, functions and WSPs can be extended, so that either the name of the function or the assigned WSPs are visible (see Figure 6). Similarly WSs and components can be split up and grouped in more detail in the columns. The reference between the functional- and component structure is captured in the marks in the matrix fields. The shaded rows and columns in Figure 6 display the assignment of WS to WSP and thus components to functions.

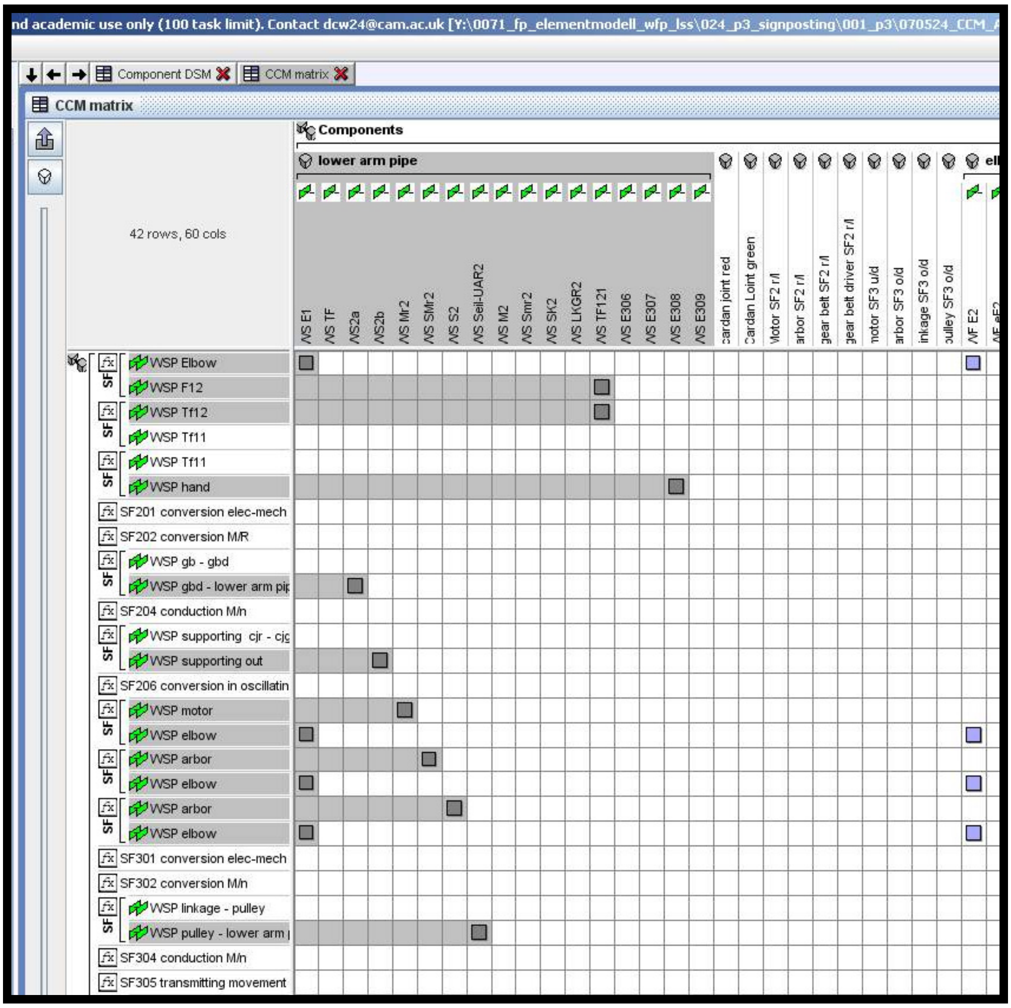


Figure 6: C&CM matrix representation of the Lower Arm system

5.2 Changing the Power Train Location

The C&CM product model highlights linkages between components which are established through the functional context and serves here as a information base for change prediction.

In this example, the location of the *Power Train* is changed. In the actual version the *Power Train* is located in the body of the robot. The new version should integrate the *Power Train* into the *Lower Arm Pipe*. The *Power Train* is responsible for the *Rotation of the Lower Arm* function.

A C&CM judgment on the risk of change propagation

A C&CM product model is generally built up to gather a comprehensive system understanding. In our case study the product model was used to examine the possible consequence of a change. For assessment of changes the C&CM matrix representation was found to be suitable as it provides a compact description of relations.

Assessing a change based on the C&CM product model means highlighting which components and functions are directly linked to the changed component or function and thus getting an overview over the complexity and consequences of the change. For the change case of this section this means that another function and another assembly will have to be introduced into the system. Introducing the new sub-system into the *Lower Arm Pipe* directly has impact on many functions within this system. Figure 6 shows that a function that builds up WSPs with *Lower Arm Pipe* is connected to many other components (highlighted interactions in Figure 6).

6 COMBINED STRATEGIES

The ultimate goal in engineering design research is the introduction of new tools and methods into industry. There are many high quality methods promising an improvement of the results of product development but are not applied due to high complexity of the method. The first use of these methods is frustrating and causes users to fall back on old procedures. In order to address this problem, two combined strategies for the use of the CPM and C&CM is suggested.

6.1 Effort

A major barrier to the use of models in general is the effort of building and maintaining them. There is a trade-off between the expected value a model can provide and the effort that is going into the model.
When building a CPM model of a product, one of the main problems is to establish an appropriate component breakdown. A model must be detailed enough to capture the essential information. However, a detailed model requires a lot of commitment, the effort of model building grows with the square of the number of modelled components in the model. For example, if a product is to be modelled containing 100 components, in total 9900 different component pairs have to be assessed for direct change effects.
The C&CM model also grows with the number of components and the number of functions a product has. As functions are assigned to Working Surface Pairs (which need two Channel and Support Structures), the potential number of functions can be up to the number of components squared. Thus, building a C&CM model at an appropriate level of abstraction requires even more effort than the CPM method.
As both models can be beneficial to the change process, building two models is usually too costly and would outweigh the benefits. A combined strategy that is driven by the effort of building the models would involve only building one model and then using the information that the other model provides for further analyses.

6.2 Strategy 1: Considering the Functional Information

The application of the CPM tool in industry has demonstrated the benefit of this method. The strength of the CPM is its simplicity. The project described in this paper was triggered in order to also consider functional influences on the change propagation. A pure DSM linkage model cannot serve this requirement as it only focuses on component connections. Attempts to include information on functional behaviour was introduced by Jarratt [19] when linkage types were integrated into the linkage model used for CPM.
The deep use of the C&CM product model is advisable when local component relations are unclear, when it is necessary to know what happens and what is the purpose of a component and its features. The component-component mapping of the CPM method hides most of this functional information. The project shows that change prediction by means of C&CM reveals a further sight on the product that is a worth full extension for the Change Prediction Method.
The combined strategy would involve a) building a high-level CPM model and b) based on predictions of high risks, certain parts of the product can be modelled using the C&CM method which gives a more detailed and deterministic view on the effects of possible changes (see also Figure 8).

6.3 Strategy 2: Translation of C&CM Models into CPM models

The data contained in the C&CM product model provides view on a complex product and thus helps to increase the basis of information for decisions about changes to be made. The matrix representation of the product model is an adjacency matrix where the functions are related to components (Figure 6) by means of WSP and CSS. Yet the CPM is grounded on a DSM based product model. The C&CM product model must be transformed into a component-component DSM that suits the CPM software. The transformation can be conducted through multiplication of adjacency matrix with its transposed matrix after a certain rearrangement of the matrix cells. This is automatically achieved by a C&CM meta model which was implemented into the P3 signposting software [25]. By this procedure the functional information is reduced and remains as values of the matrix cells which represent the linkage between two components. The matrix fields of the C&CM component-component DSM (shown in Figure 7-left in extracts) save the information about the number of WSPs two components share for a the obtaining of functions. The next step in the consecutive use of C&CM and CPM is the estimation of the likelihood and the impact values for a change propagation (described in section 2.2).

Assessment of functional linkages – likelihood and impact values for WSPs

The difference to a direct CPM product model (like described in section 4) is, that the linkages within the C&CM based DSM (in extracts in Figure 7-left) are filled with the number of WSPs i.e. the number of functions obtained by the components. For example, the number 21 is a straightforward addition of WSs of the *Lower Arm Pipe* and represents the amount of WSs the *Lower Arm Pipe* has on it. Also the numbers outside the diagonal matrix field represent a straightforward addition of functional interactions between components resulting in a number of WSP.

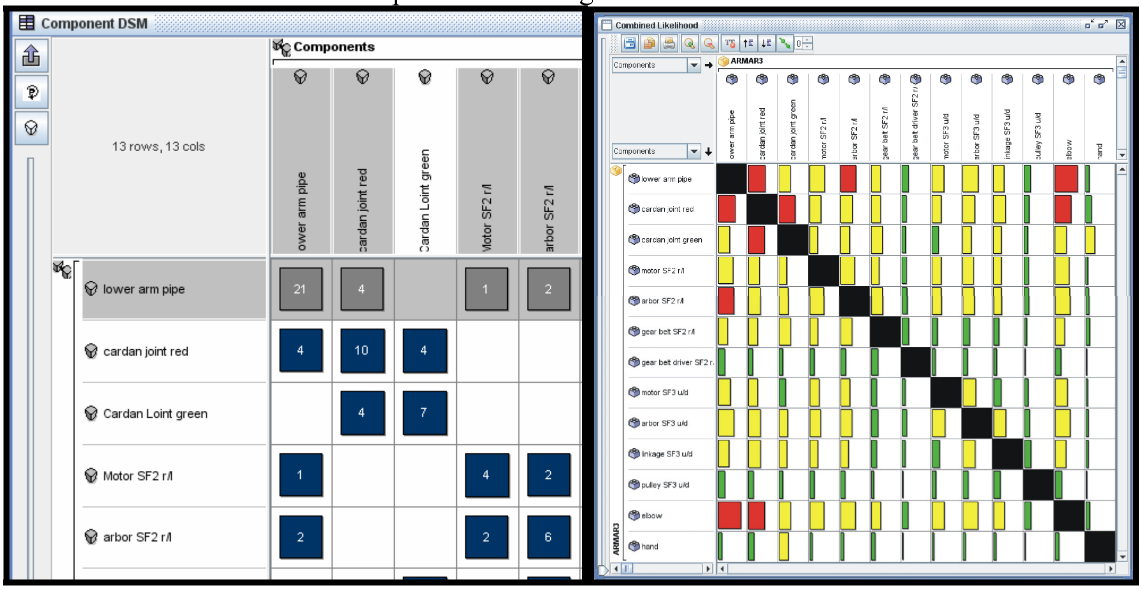


Figure 7: C&CM DSM with number of WSP and C&CM likelihood DSM.

Differently to the direct CPM assessment of the linkages by means of estimated likelihood and impact values is the assessment of relations by weighing the change-importance of WSPs independently from the pure existence of a linkage. This means that the likelihood and impact values are obtained through a weighing of the importance of functions and an addition of the number of functions fulfilled within the linkage.

For the ARMAR project the evaluation value of the likelihood of a change to propagate via a WSP was set to 0.2 (average value from the CPM). Thus, the matrix field values for likelihood in the DSM which is used as input for the CPM software results from the addition of WSP numbers in the C&CM DSM. The addition of likelihood values in case of several numbers of WSPs within a matrix field is based on the means of inclusion/exclusion because the value must stay below 1. In further works the weighing of functions will be addressed more thoroughly with the goal to further objectify the method.

Validation against Experts´ Judgements

The comparison of the computed validation and the expert's judgement shows differences. Table 2 shows the compared ranking of validation by means of the consecutive C&CM and CPM change prediction against expert's judgment.

Table 2: Comparison of experts' judgement and predictions of the C&CM with CPM

C&CM with CPM	Experts' Judgements
Elbow	Elbow
Cardan joint red	Motor SF2/SF3
Arbor SF1	Arbor SF2/SF3
Arbor SF2	Pulley/gear belt driver
Motor SF2	

The C&CM computed validation and experts' judgement both revealed the *Elbow* component, which is the adjacent system to the lower arm, as most likely to be affected by a propagating change. The experts know about the importance of the *Elbow* as a very sensitive part of the product as it "caused many problems during the design". The appearance of the *Elbow* as the most likely part to be affected by change propagation stems form its influence on many functions of the *Lower Arm* although it is not explicitly part of the examined system. The only part not considered in the experts' judgement is the *Cardan Joint Red*.

The advantage of a consecutive use of CPM and C&CM is the existence of both representations. The availability of more information, i.e. functional information helps to increase the understanding of a system, and thus improves the decision-making process by providing a larger information background of the system.

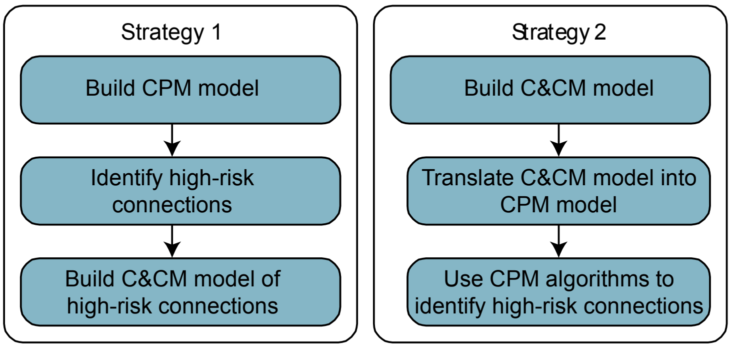


Figure 8: Two combined strategies

7 CONCLUSIONS

Both the CPM and the C&CM models described in this paper have been shown to be valuable when trying to assess the impacts of knock-on changes in the design of a complex product (the ARMAR III humanoid robot). Both approaches individually can guide designers in industry towards high-risk component connections. However, the designer has to decide which change should or should not be implemented in the end. Two combined strategies presented in Section 6 making use of both models can overcome some of the shortcomings of either model by guiding the attention of the more detailed C&CM analysis with CPM. Nevertheless, both product models systematically support the generation and storage of a system understanding and therewith the chance of considering knock-on effects. On a very general level both methods force designers to think about the product in a systematic way. This assures a thorough problem definition and thus builds up a solid basis for a successful product development process with small loops of iteration. Future research will investigate further change scenarios that require a combined use of the models. Ultimately, the combined strategies will be integrated into a software tool that can be applied in industrial contexts.

REFERENCES

[1] Nichols K. Getting engineering changes under control. Journal of Engineering Design, 1990, 1(1), 5-15.

[2] Wright I.C. A review of research into engineering change management: implications for product design. Design Studies, 1997, 18, 33-42.

[3] de Weck O.L. and Suh E.S. Flexible product platforms: Framework and case study. In ASME 2006 Design Engineering Technical Conferences, Philadelphia, Pennsylvania, USA, 2006, pp.CD-ROM.

[4] Fricke E. and Schulz A.P. Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle. Systems Engineering, 2005, 8(4), 342-359.

[5] Brown J. Managing Product Relationships: Enabling Iteration and Innovation in Design. The Managing Product Relationships Business Value Research Series (AberdeenGroup, Boston, Massachusetts, USA, 2006).

[6] Deubzer F., Kreimeyer M., Rock B. and Junior T. Der Änderungsmanagement Report 2005. CiDaD Working Paper Series, 2005, 1(1), 2-12.

[7] Clark K.B. and Fujimoto T. Product Development Performance: Strategy, Organization and Management in the World Auto Industry,, 1991 (Harvard Business School Press, Boston, Massachusetts, USA).

[8] Fricke E., Gebhard B., Negele H. and Igenbergs E. Coping with changes: causes, findings, and strategies. Systems Engineering, 2000, 3, 169-179.

[9] Maull R., Hughes D. and Bennett J. The role of the bill-of-materials as a CAD/CAPM interface and the key importance of engineering change control. Computing & Control Engineering

Journal, 1992, 3(2), 63-70.
[10] Ollinger G.A. and Stahovich T.F. RedesignIT - a model-based tool for managing design changes. Journal of Mechanical Design, 2004, 126, 208-216.
[11] Cohen T., Navathe S.B. and Fulton R.E. C-FAR, change favorable representation. Computer-Aided Design, 2000, 32(5), 321-338.
[12] Schach S.R. and Tomer A. A maintenance-oriented approach to software construction. Journal of Software Maintenance-Research and Practice, 2000, 12(1), 25-45.
[13] Hassan A. and Holt R. Predicting change propagation in software systems. In 20th IEEE International Conference on Software Maintenance, Chicago Illinois, USA, 2004, pp.284-293.
[14] Clarkson P.J., Simons C. and Eckert C.M. Predicting change propagation in complex design. ASME Journal of Mechanical Design, 2004, 126(5), 765-797.
[15] Matthiesen S. 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. Institute for Product Development (Technical University Karlsruhe, Karlsruhe, Germany, 2002).
[16] Eckert C.M., Albers A. and Ohmer M. Engineering Design in a different way: cognitive perspective on the Contact and Channel Model approach. In International Conference on Visual and Spatial Reasoning, Cambridge, USA, 2004.
[17] Albers A. and Meboldt M. SPALTEN Matrix - product development process on the basis of systems engineering and systematic problem solving. In Cirp- The future of Product Development (accepted), Berlin, Germany, 2007.
[18] Albers A., Brudniok S., Ottnad J., Sauter S. and Sedchaicharn K. ARMAR III - Design of the Upper Body. In Workshop of Human Centered Robotic Systems (HCRS'06), Muenchen, Germany, 2006.
[19] Jarratt T., Eckert C.M. and Clarkson P.J. Development of a product model to support engineering change management. In Tools and Methods of Competitive Engineering (TCME 2004), Lausanne, Switzerland, 2004, pp.331-342.
[20] Keller R., Eger T., Eckert C.M. and Clarkson P.J. Visualising change propagation. In International Conference on Engineering Design (ICED 05), Melbourne, Australia, 2005, pp.CD-ROM.
[21] Ulrich K.T. and Eppinger S.D. Product Design and Development, 2004 (McGraw-Hill, New York, USA).
[22] Suh N.P. Axiomatic Design - Advances and Applications, 2001 (Oxford University Press, New York, USA).

René Keller
University of Cambridge
Engineering Design Centre, Department of Engineering
Trumpington Street
Cambridge, CB2 1PZ
United Kingdom
Tel.: +44 (1223) 332828
Fax: +44 (1223) 766963
rk313@cam.ac.uk