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ENGINEERING CHANGE ANALYSIS DURING ONGOING PRODUCT DEVELOPMENT

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ABSTRACT
Engineering changes are part of any design process. Changes are often requested even before a product design has been completed. However, change requests during an ongoing design process are difficult to assess because the design is still evolving. Some parts, where only conceptual designs exist, may be easy to change; other parts may already be frozen and hence more difficult and probably more expensive to change. In order to find the best way to implement a change at a given time, the designer needs to be aware of not only the design and the interactions, but also of the state of development of every part. However, many designers are not always aware of all interactions and, hence, unexpected and expensive change alternatives are chosen.
This paper focuses on the question of how designers can be made aware of the impact of a proposed change before they commit. It discusses the links between the product, process and people domains that interact during product development, listing limiting factors that make change implementation risky and lead to increased change cost. The paper presents a tool to evaluate change proposals during ongoing design processes where the state of the development of parts is taken into account. The tool extends the Cambridge Change Prediction Method which assesses the risk of changes propagating between two parts. The paper concludes with the findings of two tool evaluation studies.

Keywords: Product development, engineering change, design state, design freeze

1 INTRODUCTION
Few new product developments immediately meet customer needs, technical requirements or market conditions. As a result, engineering changes have to be implemented in the design to improve the design or correct existing problems. Engineering changes, i.e. changes to components that are already signed off, are often required long before products have been released to market, for example, as the result of tests, when the customer changes the design requirements or when improvements become necessary.
In order to assess engineering change requests, designers require a good understanding of the product and the development process. When a design process is ongoing, designers need to be aware whether or not a part design has been completed, as this may determine how easily a change can be implemented. In a large product with many parts, few designers have sufficient overview in order to assess change implementation alternatives and identify the best solution. Needing to know the state of the design progress makes the solution process difficult. However, identifying the most appropriate solution is important. If engineering changes are underestimated, the impact on the project budget or time-to-market can be severe. A UK DTI study [1] has shown that even a relatively modest time delay can greatly compromise the profit margins for large projects.
The need arises to provide designers with the required information to assess engineering change proposals during ongoing design processes. This paper investigates how such knowledge can be provided and what it entails. The paper is divided into seven sections. The second and third section introduce the research by giving a brief description of the research methodology and the history of engineering change management, respectively. The fourth section provides some insights into the factors and constraints that influence change implementation. The next section describes a tool that assists designers in the engineering change analysis before the last section discusses the evaluation and limitations of the tool.

2 METHODOLOGY

The research commenced with a rigorous literature review on current engineering change management practices. To validate the findings, the authors carried out an initial study of 12 European companies, focusing on engineering change management and design freeze during the product development process. Based on the study, the existing Change Prediction Method (CPM) of the Cambridge Engineering Design Centre (EDC) [2]was extended. Discussion of the results with engineers from two companies that had participated in the study validated the work.

Since the conclusion of the study, the authors have gained further insights into the engineering change practices in a number of additional companies in the medical device and pharmaceutical industry. These insights reinforce the previous findings.

3 ENGINEERING CHANGE MANAGEMENT

From the beginning of the last century, the management of engineering changes has played an increasingly large role in product development. The advent of mass production and the increased complexity of products (cars, aircraft, engines etc.) required the coordination of the activities of many people. The division of labour and quality issues, for example the misfit of many parts, led to the introduction of such practices as stage-gateway processes (also called phased-review processes) or configuration management. These practices aimed to divide the design process into manageable stages and ensure quality at each stage. Engineering changes were recorded and managed [3].

The importance of engineering changes can still be observed today. Many projects significantly overrun the development budget or are late to market as a result of unexpected changes to product requirements, the product design or the manufacturing line. Even a small change that only seems to require little effort and time, for example to a specification on a drawing, may incur large cost when seen over the lifetime of a product or when including the management costs for the change. Many effects of engineering changes, such as a demotivation of the workforce or a loss of confidence in the company, have a significant effect but are difficult to quantify [4].

In order to control the impact of engineering changes, many companies have introduced formal engineering change procedures. In such procedures, engineers have to raise change requests or change proposals in order to modify a product design. Before the change request can be implemented, it often needs to be approved by a project manager or a change committee, depending on the size of the proposed change and the size of the organisation. In some companies observed for this research, the signature loop required for authorisation involved more than 20 people in as many groups or departments. While the change request forms and management systems were initially paper-based, many of these systems are now computer-based. However, even if documents can be signed electronically (which is not always the case for security reasons), large signature loops still require many days before a change request can be turned into an approved change to be implemented. Furthermore, such management systems assist in the documentation of changes but are less useful in assessing the impact of a change. While a signature loop forces every department to assess the impact of the change on its own operation, further knock-on effects and interaction effects between departments are usually not assessed. Modern CAD systems allow an analysis of dimensional changes on a design, for example by highlighting part interferences, but these systems cannot help in determining other non-product-specific knock-on effects or help in identifying a change implementation solution. The estimation of the impact of engineering changes is still often a problem in industry [5].

Academia has tried to support industry when dealing with engineering changes. While many papers focus on the recording and organisation of engineering changes, some literature describes methods for engineering change risk assessment. For example, the “RedesignIT” method uses directed dependency graphs and relationships between parameters to model change propagation in existing products; changes to parameters ripple through a network of related parameters to achieve a desired end state [6]. The C-FAR method allows change visualisation and the qualitative evaluation of the impact of changes [7]. A third method, the Change Prediction Method (CPM), which models direct likelihood and impact of change between two components and calculates indirect risks, will be discussed in more detail in Section 5 of this paper. These and other methods focus on assessing change impact for existing products based on a static product model. However, many changes already occur during earlier phases of the development process when a product is still being designed. The methods appear not to take account of the state of development of the design and are hence less useful.

For this research, engineering changes are defined as modifications to a design as soon as parts of the design have been signed off or frozen. Although design freezes, used in many companies as the starting point for formal change control, are meant to reduce and control further modifications, engineering change requests are frequently raised and implemented before the complete product has been signed off [8]. For example, in one case study, the crankshaft and the conrod design were frozen before most other engine part designs were started. Changes to the engine requirements resulted in engineering change requests while the product development process was still ongoing. The company was struggling to incorporate all changes without jeopardising the development budget and the proposed manufacturing start date.

4 ENGINEERING CHANGE FACTORS

In order to fully understand the impact of a proposed change, the product and its environment should be seen as a system. Hales considers a design process as just one element of a larger system consisting of many other domains such as the project, the organisation or the market [9]. Figure 1 indicates three domains for the product development process: the product, the process and the people domain. Each of the three domains can be decomposed into sub-systems. The product consists of sub-assemblies and parts, the process can be divided into tasks and the people domain, or organisation, may be split into departments or groups. The domains interact at all levels in the hierarchy. A product development process in a company can also link to other product development processes, for example when competing for resources. In the system view, the parts of the system should be analysed together as an analysis of a single part does not provide a complete picture.

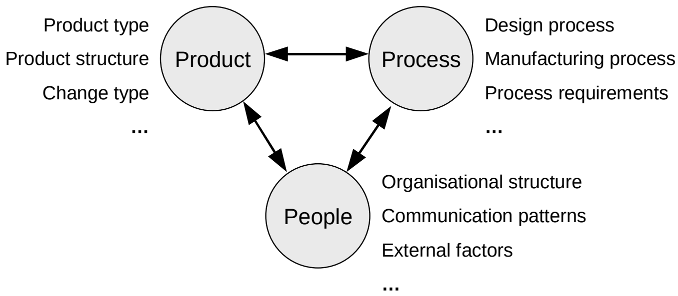

Figure 1. Interactions in the product development process and the change process

The system view helps to understand the characteristics and effects of a change. Changes can result from all domains of a system. Organisational changes may force the outsourcing of design work; a new manufacturing process may require a different product design; the product itself may require redesign in order to meet some customer requirements, reduce costs, incorporate new features etc. Eckert *et al.* distinguish between initiated and emergent changes to separate between changes that arise from outside sources (initiated changes) or that result from within the product due to problems etc. (emergent changes) [5].

Given this system view, a change to any part of the system is likely to have repercussions for other parts of the system. The repercussions depend to a large degree on the properties of the change itself, but also on the properties of the product, the process and the people, i.e. the organisation. Figure 1 indicates some of the properties that determine the effect of a change. For example, the organisational structure of a company may influence how a change is implemented, just as the design process may determine which product changes can no longer be implemented in the current product generation. Although not all changes affect the product at the highest level, at lower levels in the system hierarchy any product change can have repercussions for the process and the organisation. The levels of the hierarchy affected depend on the type and size of the change requested. The magnitude of a change within a single domain also depends on the properties of the change. In the worst case, a change may require the redesign of the complete product; a small change may only affect one or a few parts. Whether there are knock-on effects to other parts depends both on the nature of the part and the nature of the links to other parts. Eckert *et al.* classify parts as change absorbers, which absorb a change passed on to them, and change carriers or multipliers where a change is passed on to one or more parts, respectively [5].

During an ongoing development process, any design is also subject to a range of constraints, where constraints are defined as limiting factors for changes to the design. With respect to the product and its ability to change, this paper distinguishes between time-independent and time-dependent constraints. The effects of the time-independent constraints do not change throughout the design process. For example, product parts which are carried over from a previous design (legacy parts, platform parts) or that are bought in (standard parts), can be considered defined from early in the development process. Time-dependent constraints describe additional constraints that are imposed throughout the design process when the design progresses and previously undefined parts become defined. The design state of each part is defined by describing how far the design of a part has progressed. Design states can be expressed through a number of predefined classes, as will be explained in Section 5 of this paper. In this view, an initial design is largely conceptual (except for some pre-defined components) but will progress to a detailed design of all parts and tooling by the end of the design process. The design space, defined here as the space of available changes to the design without breaking any constraints, decreases with design progress and becomes zero when the whole design has been defined.
The cost of a change implementation partly depends on the design state of the part to be changed. A "Rule-of-Ten" initially expressed how the cost of a software error increases exponentially with the design phase in which it is corrected [10]. In the design community, this rule has been turned into a design heuristic, expressing the increased cost of a change the later the change is implemented (Figure 2). For example, a change ought to be cheap to implement when only a rough definition of the product exists, while it should be more expensive when the detail design has been completed. It ought to be even more expensive when manufacturing tooling has been designed or purchased. On a part level, parts that have been change absorbers when they were not yet designed or still easy to change in early design phases may become change carriers or multipliers once they have been defined, leading to the need for further redesign elsewhere and hence to increased redesign cost [5].

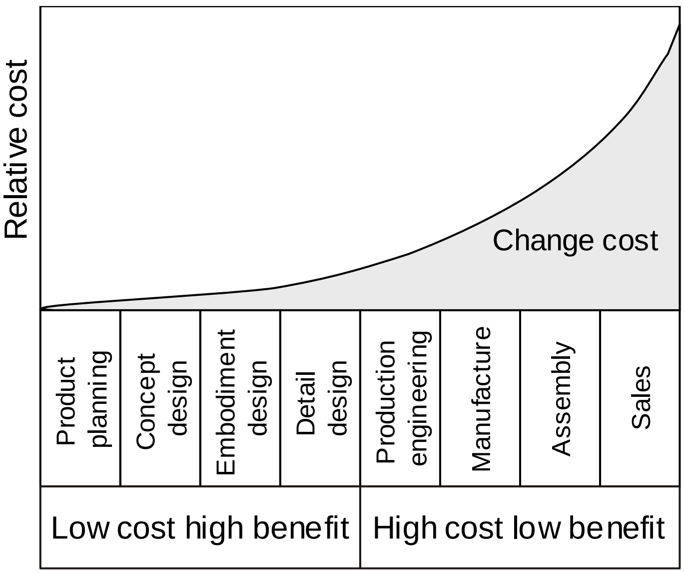

Figure 2. Change cost at different design phases [11]

In order to minimise the impact of a change, the designer should ideally be aware of all possible change effects in all domains of the system. The designer needs to trade off the benefits of the change with the impact and the costs for the system. To do so, the designer should understand the system and the interactions between parts. For large and complex products in complex environments, this becomes increasingly difficult; designers are no longer able to understand every aspect of a system. The understanding of most designers usually includes their own area of expertise and areas where they are actively involved in the design process. However, even for these parts, designers may not know all design inputs and outputs to other components [5]. The need for engineering methods and tools that support designers by providing a system overview and by reminding them of the properties of the change and the system arises. Such methods or tools may help to reduce engineering change impact.

5 A PRACTICAL APPROACH

In conjunction with the industrial study of engineering change management, the authors developed a tool to assist designers in change analyses during ongoing design processes. The tool limits itself initially to the product domain of the overall system.

In order to investigate the impact of a change, the product is decomposed into parts or sub-systems. The detail of the decomposition should be a compromise between the ease of creating a product model and its utility. In the example given here to demonstrate the functionality of the tool, a medical device, a needle-less drug injector, was decomposed into 15 parts. To be able to create a correct parts list, the conceptual design for the product should have been completed. Then, expected design links between parts can be indicated. Experience with previous designs may also assist with the decomposition and identification of links. Note that the design links are not just the physical links between parts but also include other connectivities such as performance or spatial links (see [12] for a discussion of linkage types in the design process).

The tool is based on the Change Prediction Method (CPM) [2] developed in the Cambridge Engineering Design Centre. The Change Prediction Method allows the risk assessment of a change, where risk is defined as the product of change impact and change likelihood. The method is based on Design Structure Matrices (DSM [13]), where the links between parts are assigned change likelihood and impact values. From a set of direct likelihood and impact values, i.e. for direct links between parts, a set of indirect values is calculated between any two parts. A detailed explanation of the method and the change prediction algorithm is given in [2].

The Change Prediction Method is based on a static product model in which the likelihood and impact values are defined when the model is created. While this is useful for existing products in which these values can be assumed as static, it is less useful for ongoing design processes where the likelihood and impact of change propagation depend on the design progress and may change with time. To enhance the original method, the concept of design states, discussed in the previous section, is introduced to the Change Prediction Method, linking the design states to the change likelihood and impact values. For the example of the medical device, five design states were created. The definition of these design states can be seen in Table 1. The terminology matches the definitions observed for design progress in one of the companies investigated in the engineering change study. Different numbers of states, terms or definitions are possible. In this example, the tool works with discrete design states, but continuous states are also feasible. Continuous states could for example be represented by percentages.

Table 1. Definition of design states

Constraint type	**Design state**	**Definition**
Time-dependent	Unrestricted	Part design has not started.
	Restricted	Part design is in progress.
	Chilled	Part design has been completed. Prototype tooling design and tests are in progress.
	Frozen	Prototype tooling design and tests have been completed. Series tooling design is in progress.
Time-independent	Pre-defined	Part design is defined from the outset (legacy part, platform part, standard part, …)

Parts in the “pre-defined” design state are assumed to be time-independent as discussed in the previous section; these parts are defined from the outset of the design process. Parts that are time-dependent are assumed to evolve from a conceptual design to a detailed design within the design process. These parts move from an “unrestricted” design state to a “restricted”, “chilled” and “frozen” state. At the beginning of the detailed design phase, all time-dependent part designs are assumed to be unrestricted; at the end of the design process, all part designs should be frozen. In practice, time-dependent design states should be updated throughout the design process in real-time, for example in regular formal meetings of the management or design team. Such meetings have been observed in most design companies where more than one designer works on the same project. Figure 3 shows a CPM matrix for the example medical device with an additional column indicating the current design state of each part.

CPM: Change likelihood			Initiating component						
Component Name	**Design state**	No	1	2	3	4	5	6	**...**
Actuator sleeve	Restricted	1	1		H				M
Nitrogen gas	Pre-defined	2		2	L	L	L		
Chamber	Restricted	3	H	H	3	H	H	M	
O-rings	Pre-defined	4		H	H	4	M		
Ram	Chilled	5		H	M	M	5		
Coupling clip	Restricted	6			M			6	
:	:	:	H						7

Figure 3. CPM matrix and design states

Information on how change likelihood and change impact values evolve throughout the design process is added to the design states. Change impact is captured by a change implementation cost which, although only one part of the change impact (other costs such as service cost may also add to the impact), is an important factor in the decision between alternative solutions. However, the limitation that change impact is only expressed through implementation cost has to be kept in mind. The Rule-of-Ten, discussed in the last section, is used to model an increase in change implementation cost with design states. The heuristic states that the cost of a change generally increases as parts become better defined. Figure 4 shows an exponential increase of change implementation cost with design state. For different parts the exponential factor is expected to be different, depending on part properties, design time, tooling cost etc. Initially, the designer has to guess the exponential factor based on experience. Figure 4 also indicates a decrease in change likelihood value with design state, given that designers are less likely to change parts that have already been defined and approved than parts that have not yet been defined. The shapes of the curves in Figure 4 have been assumed to be continuous and relatively simple. In reality, this kind of judgement about the shape of a curve for change implementation cost or likelihood is difficult to make. However, for an initial investigation of the feasibility of a change in a partly frozen product, this approach seems sufficient. For more exact analysis, the curves should be adjusted to better indicate the change behaviour of a part.

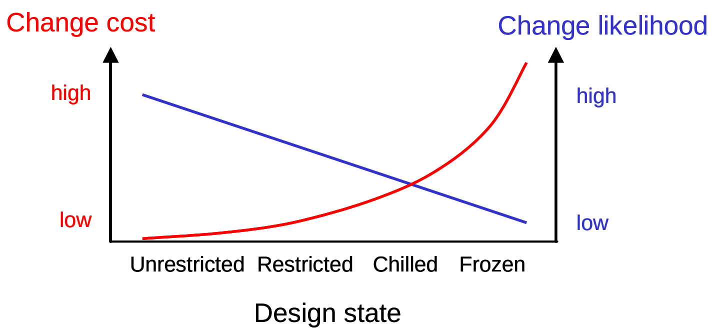

Figure 4. Change implementation cost and change likelihood vary with design state

Figure 4 does not indicate the change implementation cost and change likelihood for pre-defined parts. As discussed, pre-defined parts are expected to be costly to change. For example, customising a standard part is generally expensive, just as is changing a legacy part if economies of scale no longer apply. On the other hand, a replacement of a standard part by another standard part may be cheap.

Change implementation cost for pre-defined cost is therefore modelled as high but this has to be confirmed when the designer investigates a specific change. The tool models change likelihood initially as low for pre-defined parts; because the parts are pre-defined they are unlikely to change. However, as in the example above, designers may be willing to exchange one standard part for another standard part. In this case, the tool user can manually alter the change likelihood to reflect the part properties.

Once the design states of the parts have been used to adjust the change implementation cost and the change likelihood, the risk of change propagation is calculated as in the original CPM algorithm described in [2]. The tool also allows the deliberate modification of design states in order to investigate "what-if" scenarios for various changes. For example, the tool can be used to evaluate the effects of deliberately excluding a part from a change process, although the design state indicates that the part is still unrestricted. Similarly, a part that has been frozen can be "unfrozen" to evaluate if this leads to cheaper change implementations. In later stages of the design process, when most parts have already been defined, unfreezing may be the only feasible option to implement a change. By analysing various scenarios, alternative solutions can be investigated and compared.

While the use of design states within the Change Prediction Method allows a mathematical analysis of likelihood and cost, the visualisation of product links, design states and design space already appears useful for the designer. A node-link diagram indicating design states allows the designer to monitor design progress. The diagram also gives an indication of the available design space by indicating what can easily be changed and where changes will be costly. When a change is requested, an up-to-date product model may be used to investigate current constraints, possible change implementations and what-if scenarios. The tool provides an exploded view of a change propagation tree that illustrates the design links from a change-initiating part and indicates where current constraints make change implementation difficult (Figure 5). In any case, the designer has to make the final decision whether and how a change should be implemented. The visualisation reminds the designer of the current design states and connectivities within the product [14].

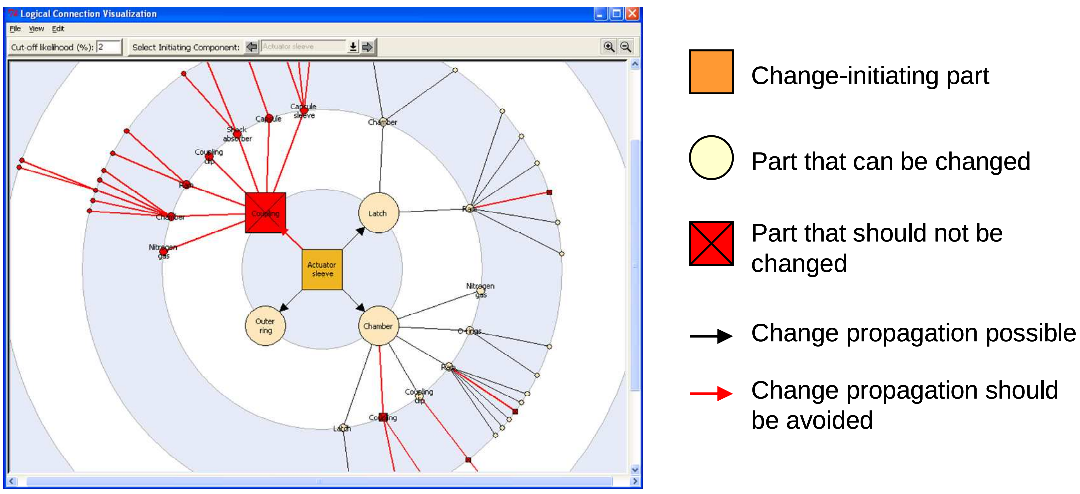

Figure 5. Visualisation of possible change propagation paths

6 EVALUATION

The tool was implemented as described using Microsoft Excel and Visual Basic Applications. It could therefore be used and demonstrated on computers equipped with the Microsoft Excel software. Although the implementation in Excel has not led to a user-friendly or practical tool, and indeed the product model and the change relationships have to be entered manually, the language allowed the authors to change the source code rapidly, and therefore served as a good practice ground for theory development and prototype design. Further work will have to turn the tool into a stand-alone tool with a graphical user interface.

An Excel screenshot is given in Figure 6. The screenshot shows the 15 components of the medical device in a node-link diagram. This visualisation is an alternative to the change propagation tree in Figure 5. Figure 6 shows all parts and all links in the product. Based on the design state of each part and the direct change likelihood between parts, an indirect change likelihood has been calculated with the Change Prediction Method algorithm. In the figure, a change request to the capsule, the initiating part marked in brown, is investigated. As the node-link diagram shows, there is a relatively low change propagation likelihood to the directly connected parts in yellow and the device chamber, which is two parts removed. The likelihood of resulting changes to the capsule sleeve, highlighted in red, is high. Diagrams like this remind designers of the links and the resulting danger of change propagation between parts.

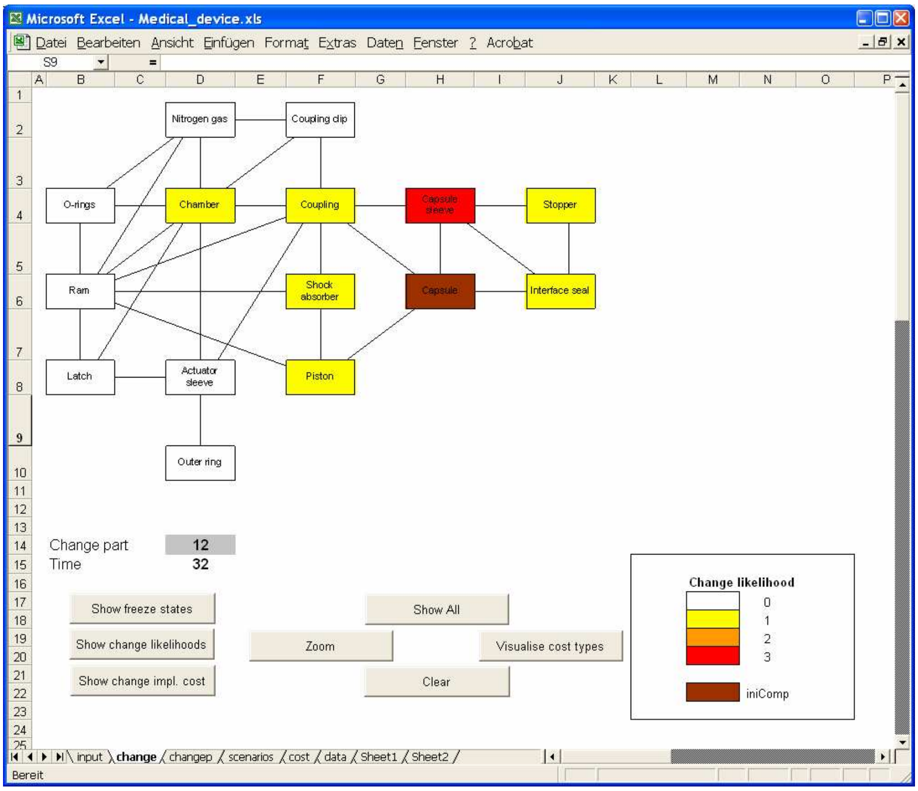

Figure 6. A node-link diagram for the medical device, indicating the likelihood of change propagation from the capsule

In order to test the idea and the tool, two case studies were carried out with engineers already involved in the study of engineering change management practices in their companies. Change processes for a car seat and for the medical device used as an example above were evaluated. The engineers recognised the problems with engineering change management as described in this paper and agreed on the need to provide support for change analysis and implementation during ongoing design processes. The engineers admitted that in the past they had been surprised by unexpected change propagation even though they had thought that they had a good understanding of the product. Work pressure also forced them to quickly select a change implementation without investigating the complete solution space. The engineers thought that a tool that was able to indicate the possibility to unfreeze and investigate what-if scenarios could indeed be useful to evaluate change implementation alternatives that would otherwise not be considered.

While the engineers involved saw the value of the tool presented, they also suggested further improvements. Limitations discussed with the engineers are the difficulty to generate quantitative data for change likelihood, and the sole focus on change implementation cost when many other change costs may be incurred. The greatest limitation is the focus on the product model alone without considering the impact of changes on the process or people domain. As was discussed, the quantitative capture of all aspects of change impact is difficult in any case. With the limitations in mind, the tool presents an attempt to at least partially quantify the change impact in ongoing design processes.

7 CONCLUSION

This paper discusses some of the interactions that engineers need to consider when investigating a change request during an ongoing design process. A change that is not minor or routine is likely to have repercussions not only for the product but also in related domains such as the development process or the organisation. Constraining factors can arise in any of these domains, making change implementation difficult.

In the product domain, a difficulty for engineering change analyses during ongoing design processes is the evolution of part designs from conceptual to detail designs. When implementing a change, designers need to be aware of the current part design states in order to avoid unexpectedly large change impacts. Tools that assist in the change risk assessment should take these design states into account. This paper describes a tool that links part design states to the change propagation likelihood and change implementation cost. The tool reminds the designers of the connectivities between parts, the current design progress and the impact of engineering changes, hence supporting designers in the analysis of engineering change.

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