Supporting change processes in design:
Complexity, prediction and reliability

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Abstract

Change to existing products is fundamental to design processes. New products are often designed through change or modification to existing products. Specific parts or subsystems are changed to similar ones whilst others are directly reused. Design by modification applies particularly to safety critical products where the reuse of existing working parts and subsystems can reduce cost and risk. However change is rarely a matter of just reusing or modifying parts. Changing one part can propagate through the entire design leading to costly rework or jeopardising the integrity of the whole product. This paper characterises product change based on studies in the aerospace and automotive industry and introduces tools to aid designers in understanding the potential effects of change. Two ways of supporting designers are described: probabilistic prediction of the effects of change and visualisation of change propagation through product connectivities. Change propagation has uncertainties which are amplified by the choices designers make in practice as they implement change. Change prediction and visualisation is discussed with reference to complexity in three areas of product development: the structural backcloth of connectivities in the existing product (and its processes), the descriptions of the product used in design and the actions taken to carry out changes.

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1. Introduction

Designing complex products is often accomplished through incremental changes to existing products. This is done for many reasons including product economics and the inheritance of established features especially in safety critical products. Customers do not want to carry the risk of innovation and companies want to design new products with minimum cost and design effort. In safety critical products, such as power plants, satellites, aircrafts or medical devices, incremental design is one way to reduce these risks, through reusing tried and tested parts. Reused parts may not need to be recertified. As many safety critical products are produced in small numbers, using standard parts or at least existing parts, can significantly reduce the cost. For example, each version of a military helicopter is rarely designed and manufactured with more than 20 craft. However, military contracts often specify dual sourcing of each component from suppliers who guarantee delivery, perhaps for up to 30 years. The management of the supply chain alone is a complex and expensive activity.

In this paper the design of safety critical systems is addressed from the viewpoint of the behaviour of design teams rather than directly as research into safety critical systems. This viewpoint is, in a sense, broader in that it examines a variety of design domains, concentrating on how individual designers and design teams think about safety critical issues and bring their products into existence. Our detailed studies of design have been mainly in the aerospace and automotive industries. These studies have involved interviews with over 100 design engineers and managers and observations of design teams in six major UK companies (see [1–3]). Further studies have examined comparison between different design domains (see [4,5]). In these studies safety criticality emerged as one driver amongst many others that influenced the behaviour of designers and the characteristics of their design processes.
Consequently isolating safety criticality as a factor in design behaviour appears virtually impossible. For example, the reuse of tested and well-working parts is part of a conscious strategy of making sure the product is safe and reliable, but at the same time it is also a cost saving exercise. In their day to day work, designers rarely distinguish between these drivers, but concentrate on meeting the requirements that are set for them. For the aerospace and automotive designers that we studied safety criticality issues manifested themselves in several ways, such as regulation requirements for products and services and tests that need to be performed. Through the explicit terms of the regulatory authorities or company strategy, product characteristics and testing schedules are set as requirements. Designers concentrate primarily on meeting these requirements, rather than underlying safety issues, which are the specialist concern of a small group of safety specialists in the companies we studied. Yet designers need to be aware of the complexity of product and design processes, including safety critical issues, to make decisions in meeting specific requirements.

Design by modification is a pragmatic strategy to control design effort and to assess safety risks, but it is also a cognitive strategy used by designers to cope with the complexity of products. By reusing chunks of a product, designers can reason about these chunks on a high level of abstraction recreating the details as and when required from the original reference design. This allows designers to refer to a specific, familiar object as a parsimonious representation whose details can be recreated on request. Such a description does not necessarily pick out relevant features explicitly but leaves this choice as a matter of interpretation. Design descriptions through object references can exist on many levels of detail and be temporary and fleeting as designers focus on them (see [6,7]). A new design can inherit global properties and detailed features from an existing design, which may never be explicitly questioned.

While there are sound reasons for reuse, it is not entirely straightforward. First of all designers need to identify which parts of the design they can reuse and which parts they need to change. This requires an understanding of the product geometry and the functions that each part or system carries out, particularly how new or modified parts could carry out new functions. Only rarely can new needs be met through direct reuse of parts or systems. Further, changes to one part can lead to many ‘knock-on’ changes to other parts of the overall system. This paper is concerned with predicting and visualising these knock-on changes. They can be a serious threat to product safety and reliability. Incompatibilities between reused and newly designed parts can lead to faults, that are not instantly apparent, e.g. material fatigue. Propagation may lead to unexpected changes which increase design effort. In product development this leads either to costly delays or may tempt designers to cut corners.

At the beginning of any new product development process and in particular in the development of safety critical products, it is important to assess where the risks (see [8] for a review) lie in the product and its design processes. We introduce a meta-model for design process to help understand where complexity occurs in design (Section 2), particularly in change propagation (Section 3). In Section 4, problems of change propagation and implications in safety critical systems are discussed. To aid designers in handling these problems a Change Prediction Management (CPM) tool is presented in Section 5 which concentrates on visualisation.

2. Complexity

Many safety critical systems involve complex products or simple products embedded in a complex context. A helicopter (Fig. 1) is a complex product, with over 10,000 different parts involving over 1000 person years design time and an expected in service life of over 30 years. As the product is highly interconnected it is difficult to predict the exact behaviour, yet it is to be totally dependable during operation. In contrast a simple medical device, illustrated in Fig. 1, has around 20 components designed by a team of about 20 designers over a period of a year. This example is a needle-less injection device, which patients can safely use.

Fig. 1. Examples of complex safety critical products: (a) military helicopter and (b) medical device for needle-less injection.
Complexity is viewed in different ways depending on the field of interest. However, two common concerns emerge. These are first, the structural complexity of parts and connections, and second, the dynamic complexity of behaviour. Complex systems are dynamic, changing and evolving over time. Underlying connectivity represents how the different parts are related and determines constraints on behaviour. Simon (see [9]) considers the complex engineered or ‘artificial’ system as almost decomposable, that is hierarchical, but not fully decomposed into separate, independent parts.

Connectivities of a complex design form a lattice structure rather than a tree structure although the latter is often an adequate approximation for these almost decomposable systems. The connectivities between parts (through which change propagates for example) are a static backcloth whilst dynamics represent behaviour. A familiar example of a complex system with underlying connectivities and associated dynamics are road networks. The network of roads itself or more usefully the sets of routes are a connected ‘backcloth’ [10]. These routes overlap and interact with each other. The interactions transmit dynamic effects between different parts of the road system. The dynamics are expressible as the changing flows of road traffic over the connected set of routes.

Connectivity and dynamics can be viewed in terms of information complexity. This expression of information content or entropy (see [11,12]) takes into account both the underlying order described by connectivities in structure and the overall uncertainties of dynamic events on that structure. Axiomatic design [13] aims to minimise complexity through reducing the connectivity between parts and uncertainties in process. This can make design processes more effective in their use of resources and improve the reliability of the product. Modelling connectivities can improve product development processes as shown in the application of Design Structure Matrix (DSM) methods to represent connectivity and identify where dependencies can be reduced [14]. Related models represent the connectivities of process tasks in product development directly (see [15,16]). Modelling connectivities is predominantly a static view.

Another view takes complexity as being predominantly about uncertainties in dynamic systems. Chaotic systems (e.g. [17]) are examples of bounded (i.e. characterized by limits to behaviour) unpredictability. An adaptive system changes its connectivities and dynamic behaviour in response to its environment whilst coevolving systems develop mutual changes of structure and behaviour (e.g. [18]).

2.2. Timescales

In drawing a distinction between static connectivities and dynamic behaviour, we note that connectivities are relatively static compared with the system dynamics of the product’s behaviour or the design changes in adapting to requirements. Over a short-time span, it makes sense to look at a static backcloth of connectivities between its parts on which quick-change processes occur. Over a longer period the designs and the processes both affect each other and mutually change. For example, new people design different products and the new properties of these products require different people to develop them further. At an even longer timescale one could argue that the processes that designers carry out to create a product remain relatively constant, while the products that they are creating change. In this sense the descriptions of the products change or ‘move’ over the backcloth of the processes. Similarly, descriptions that are used in parallel in design processes are both static and dynamic. They have structural properties and afford certain actions on them (see [19]). These are static for the duration of the product. However new descriptions are added all the time and descriptions supersede each other.

New descriptions may be added or previously abstract and uncertain descriptions become more detailed. For example, a new requirement from a customer which initiates change may involve a new description; a test result may reveal previously unexpected behaviour (although we remark that new behaviour is rarely completely unexpected) which necessitates a new description. Descriptions can also be found to be inconsistent, for example when mistakes are recognised or inconsistencies appear between proposal and requirements. In each case a change process will act on descriptions. Possible actions depend not only on resources and capabilities available but also on the descriptions used and how they can be modified. Change processes take place against a highly structured backcloth [10] of existing products and company processes as well as designers’ expertise and knowledge.

2.3. Backcloth, descriptions and actions

The backcloth includes the underlying connectivities of parts of a product type and general physical principles for
the behaviour of that type of product. Backcloth is a structural concept, representing the underlying order expressed through structure and connectivity whilst the actions represent dynamics. It is important to distinguish the idea of backcloth from a wider concept of cultural background or environment in which the designers also operate, but which may not be described in a well-defined way. Further, this wider environment although important in design is not part of the subject of this paper. The backcloth structure is essentially made up from the descriptions of product and process which designers use. Actions take place on these descriptions. Descriptions of a specific design proposal are developed through iterative action of synthesis, analysis and test. In a sense the product ‘flows’ through the processes. This general picture of design is summarised in Fig. 2. Complexity arises at each layer in this model, and in the interactions between levels.

The backcloth can evolve over time but it is essentially static. Examples of elements in the backcloth are (a) The starting point of a change process, perhaps a competitor’s product, (b) manufacturing capabilities and the technical properties of materials (which form the backcloth for manufactured shapes) and (c) the physical principles for devices of a certain type. The structure of the backcloth arising from connectivities can be analysed through multidimensional relations with methods such as Q-analysis [10], which models both connectivities and dynamics within a common hierarchical framework.

Systems theory (see [20]) draws distinction between system elements which can be controlled and those features of the environment which influence and disturb the system elements. Systems theory makes particular use of the idea of a system boundary dividing internal system elements from the external environment. The model of backcloth descriptions and actions takes a slightly different but closely related view. The idea of backcloth is that there are known and identifiable structures which make up the system itself. These are not strictly environment although they represent the world in which, in our case, designers’ work. The environment, in systems terms, lies in the wider and deeply uncertain features of the political, economic and physical environment. Our aim is to bring the structures within which designers work in their companies, projects, products and design processes, into the domain of interest. Designers act upon this rich picture and its associated descriptions.

The types of complexity outlined in the previous section have different focal points on the three layers. Adaptive (and co-evolving) properties are mainly focussed on the actions layer. Chaos is mainly concerned with the structure and the behaviour of the backcloth and the types of predictability (or otherwise) in the system. Change propagation arises from established linkages and connectivities among parts. Eppinger et al. [14] and Suh [13] both consider complexity reduction by understanding connectivities in the descriptions used. Complexity as information or entropy expresses the possible ways the product (or the design process itself) behaves, within the framework of backcloth connectivities. The company organisation, supply chain, markets, the skills levels or the personalities of the designers and a whole host of other properties can be seen as a backcloth against which the designers operate. A design process moves from an interaction with descriptions which may be physical parts of the backcloth, such as an existing product, through more abstract representations, returning to direct interaction with the backcloth in prototype test.

Problems in design change can arise from the misalignment between the layers of backcloth, descriptions and actions. For example descriptions may not be consistent with the actual backcloth or have insufficient scope to cover all aspects of the backcloth. Further, in the backcloth layer there will be many properties of the product which are beyond the control of an individual designer, perhaps inherited from past products or through product platforms adopted by the company. Some properties are side effects of other highly desired properties. For example, if a material is chosen for its weight properties, the thermal or conductive properties are side effects. Manufacturing processes enforce properties on products. General characteristics of performance are part of the backcloth. One example is the chaotic behaviour that can occur near conditions of optimal performance of a jet engine compressor.

3. Change

Change lies at the heart of many design processes [21] and in particular for safety critical systems. In complexity terms, changes to a product are operations on a stable backcloth. The environment might provide the triggers for the change and some constraints in what can happen. Changes are carried out on descriptions of products, which are well specified. Change processes should ensure that a product established as safe under a particular required profile of use is modified into another which is safe for a different profile of use. Specific requirements on reliability will be included in the profile of use. Many of the requirements for the products studied in this paper relate to both safety and reliability. In our context the former has its focus on general liabilities and consequences of failure whilst the later is on contractual liability. Relations
between safety and reliability have been explored extensively in other areas (see [22]).

The focus of research on design changes has been on managing process and product data. As the management of such data is central to designing safety critical systems we examine briefly the different approaches to design change understanding and managing design change in our industrial studies. Investigations into change can be split into those that focus on the process of making an alteration (especially the management of the change) and those that examine the design itself. The majority of activity has concentrated on the former, for example the studies presented in Ref. [23] or [24]. The close attention that has been paid to the management of change processes has in part been driven by the needs of companies to comply with Configuration Management and Quality Management standards (e.g. ISO10007 and ISO9000). Although ideally Configuration Management can be regarded as the general ‘umbrella’ process of managing change, the focus is on document control and administration. Our intention is to take a view of change which recognizes that processes take place on the various descriptions of the design. This complements the related work on linkages and connections among parts and analysis of the propagation of change along these connections (see [1,25,26]).

3.1. Descriptions

Sometimes designers can interact with a physical object itself to make modifications, however designers mostly rely on abstract representations. The initial designs can be represented by the product itself as well as more abstract descriptions such as drawings, CAD files, indexed knowledge and in-service records. Likewise whilst a modified design is being generated it only exists in its current descriptions which may be partial and fragmented compared to what is required for a finished design. Even physical prototypes are descriptions that do not necessarily share all properties of the final product. The process of designing may be pictured as the transformation of several descriptions. A description can refer to a specific object, perhaps an existing design representing features of this reference object. Once modified it does not strictly describe its reference object, although it retains several features. A description may also exist independently of a reference object or refer to many potential objects.

Design descriptions concentrate on particular features: CAD models describe geometry; the functional models describe functions, etc. Design features are grouped hierarchically. For example a car engine is described hierarchically as engine block, pistons, sump, etc. each associated with a detailed list of all components where price and quality are firmly established. Descriptions at different levels in this hierarchy are used for different purposes during the design process. Practically, designers often talk and think about one design by reference to other objects, such as competitors’ designs or external sources of inspiration such as pointing to a familiar object can recreate details although relevant features have not necessarily been picked out explicitly but choosing them is left as a matter of interpretation. Design descriptions through object references can exist on many levels of detail and be temporary and fleeting as designers focus on them (see [6,7]). A new design can inherit global properties and detailed features from an existing design, which may never be explicitly questioned. Object references are a different form of abstraction from the hierarchical descriptions which are based on selected features. The object itself remains the primary mental cue for organising other descriptions derived from the object itself.

A change process involves more than just descriptions of product. The ways that designers conceptualise the context in which they work and the process by which they generate a product are also descriptions. One challenge of designing lies in understanding how these descriptions are connected and influence each other. One driver of change processes is mismatches between descriptions.

3.2. Mismatches and mistakes

The processes of change are not always smooth and well directed. Mistakes can occur in many ways. Designs, or parts of designs, may be inherited wrongly from previous designs or newly designed parts may contain mistakes. They cause disruption to the design process and necessitate further changes. But mistakes, if based on shared assumptions about capabilities and competence across the design team or buried in the complexity of the project schedule, may not come to light until late in the whole process. By then many of the parts of the design are finished and tested in their details so fixing the mistakes can be costly, especially if the changes propagate to the finished parts. Although the majority of alterations made to parts of a design 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 (see [1,27]) or the ‘snowball effect’ [28]. Such an event can have a major effect on the budgets and schedules of a particular project as well as more generally on the way a company and its projects are organised.

3.3. Industrial studies on complex products

Since 1999, we have been carrying out empirical studies of change processes in complex engineering products including a helicopter manufacturing company [1] and an ongoing study in a diesel engine company. Initially, we concentrated on the overall process of change and identified the lack of understanding of dependencies between components as a major problem in managing changes and predicting their effects [2]. In response, a matrix-based change prediction method has been
developed [26] as well as a method to capture the linkages between components [25]. The importance of recognising dependencies was confirmed in a parallel study with an aerospace jet engine company. These industrial studies led to a distinction between two types of change (see [1]). First, there are initiated changes, which are caused by outside factors, such as new customer requirement or new legislation. Second, there are emergent changes, which arise from problems with the current state of a design proposal in terms of mismatches with requirements and specification. These can be caused by mistakes, supplier constraints and factors internal to the process such as resources, schedules and project priorities across the company.

Eckert et al. [1] have noted that regardless of the type of the change, companies used the straightforward sequence—assess, generate possible solutions, analyse implications and implement. The processes through which a change is resolved and the problems that arise from change remain the same regardless of causes and types of change. The changes, discussed in [1] involved safety-critical systems, ranged from avionics changes to routine changes (for example changes to cabling and piping). However, the assessment and execution of the change was very similar across the types, besides obvious scale effects. As time progresses in a design project more and more parts of design are frozen (see [29]), that is they cannot be changed for logistical reasons. Later changes are more constrained than earlier changes. In a safety critical system, designers are more reluctant to change the parts that they perceive as safety critical or those that are more subject to elaborate testing requirements. There designers will attempt to ensure that a change does not propagate to a safety critical part.

Even if the processes through which initiated and emergent changes are resolved are very similar, the attitude with which the change is handled can be different. If an emergent change arises from a mistake or a late modification from the supplier, designers often resent it as avoidable, while initiated changes are considered as normal business and designers regard their company’s ability to accommodate customers’ wishes as an asset. Two strategies were employed to manage engineering change:

- Changes by a core design team. By the time a change occurs members have often moved on to the next project. A change either interrupts their current task or is delayed until spare time becomes available.
- Changes by a dedicated change team, who invest considerable time and effort into learning about the original product. They often have to interact with the original designers.

In reality many companies employ a mixture of both strategies, using dedicated teams to handle routine changes and experienced designers to handle difficult changes.

3.4. Change management and safety criticality

Change is difficult to manage in any design process and particularly important in the design of safety critical systems. Complex products can display chaotic behaviour, in that a very small change can have a significant effect on the entire product. These effects often occur when the tolerance margins of a component are exhausted or the product behaviour deteriorates sharply beyond an optimum. A small change propagates in an ‘avalanche’ of changes, whose scope and magnitude are hard to predict.

We have observed that a designer’s capability to take an overview of a product and identify potential weaknesses appears critical in change management. In many engineering companies, experts who have sufficient product overview (see Fig. 3) to understand the impact of change across a product, are in short supply, especially the full cost or safety implications. Eckert et al. [1] identify that the deputy chief engineers in a helicopter company are expected to have the best product overview of their team with understanding between 50% and 70% of a helicopter in detail. For a less complex product this could be higher.

![Fig. 3. Overview over product (see [1]).](image-url)
In summary, two basic questions are raised about effective change management. First, to what extent are changes predictable in design and second, what kind of overview is useful for designers? Sections 4 and 5 consider these two questions in turn.

4. Predictability of change

Changes propagate through connections among parts. To predict change, designers need to identify these connections or links and then estimate whether a particular change could propagate. This is reasonably straightforward for assessing the knock-on effects from changes in size and shape: if one part gets larger then another might have to move or change shape. Prediction gets more difficult where a connection specified by one parameter affects a different type of connection specified by a different parameter, as illustrated in Fig. 4. The types of linkages (see [30]) fall within different fields of expertise, so that even expert designers are often not aware of them. For example, we observed that an engine company tried to replace a metal temperature sensor with a plastic one, forgetting that the metal component also served as an earthing link for a connecting component. This mistake was only revealed when the prototype engine failed to work.

Predicting how a change will propagate in practice involves more than analysis of linkages. Designers make choices on how to implement a potential change, considering cost and resource availability. These decisions can lead to seemingly sub-optimal choices, if looked at from the product viewpoint. These practical responses to change can have significant consequences for safety critical systems and assessment of their residual risk. While many changes are unavoidable, designers can choose whether to pass a potential change on to another part of the design. In some cases they try to contain a change within their own domain of expertise rather than passing it on, sometimes in fear of admitting mistakes or because they do not know how another part could cope with a change. As the design progresses parts get frozen, because they are long lead-time items or define key parameters for other parts. Designers will avoid change propagation to these frozen parts. In the attempt to stop change propagation, designers often come up with highly innovative solutions, which one automotive designer terms aptly ‘emergency innovation’. Overall it is possible to say that change propagation paths identified through part connections do not completely determine the process of change but they do constrain it significantly.

4.1. Change prediction

In experiments to elicit their understanding of product connectivity [30] experienced engineers displayed two different strategies for thinking about change prediction (see [31] for cognitive arguments), illustrated in Fig. 5:

- **Analysis-based depth-first search**: Two analytically trained engineers both looked at one chain of possible knock-on effects, backtracking very slightly, but exploring only a small part of the search space (a→b→c→d, c→e, b→f).

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**Fig. 4.** Indirect Change Propagation.

**Fig. 5.** Reasoning strategies on change prediction.
Experience-based heuristic search: A very holistic conceptual designer reasoned in terms to past effects of change (a→c, a→h), but as his colleagues observed did not distinguish between direct and indirect changes.

In the development of new products companies employ a number of practical strategies, with different suitability for safety critical products:

Work one case out in great detail: A first tier supplier with well-established customers links and therefore fairly sure to receive an order, places an experienced designer on the task of working out one change scenario in a great deal of detail, but alternative solutions are not explored.

Submit many tenders: A company with many potential customers invests lightly in each initial tender which were prepared by a tendering specialist and later elaborated if required. However, fundamental design decisions are made during the initial tender.

Anticipate later changes in conception design: A first tier supplier, who produces generations of customised products driven by legislation, freezes design parameters during conceptual design to avoid change spreading to areas that are regarded as sensitive to change.

A careful examination of one particular way of carrying out modifications carries the least safety risk whilst submitting many tenders carries a larger risk. Anticipating future changes, by designing margins into components or freezing components early in the design process could be effective provided companies understand the implications of these early decisions.

Changes later in the design process, perhaps as the result of earlier mistakes are usually handled through formal design change requests handled through mini-design processes. Generally, companies discourage ‘fixing’ mistakes in a debugging mode (see [1]) and this is especially the case for safety critical system.

4.2. Support tools for change prediction

There are few tools for change prediction currently available. One tool [32] helps designers avoid later knock-on effects by planning changes. Clarkson et al. [26] look at change prediction from the viewpoint of aggregate risk calculated conventionally as the product of impact and likelihood. They begin with a product change DSM (see [33] for a general discussion of DSM). Impact and likelihood values are gathered for each connection in terms of high, medium and low or FMEA values. Monte Carlo simulation is applied to calculate indirect impact, likelihood and risk. Risks are calculated and displayed as a risk matrix, which draws the designers’ attention to high-risk connections, as illustrated in Fig. 6.

As a product is modelled at an aggregate high level in order to be displayed (visually) in a matrix, this method only gives a rough idea of change propagation. It was originally developed for tendering, but can also be used in design review to quickly establish a rank order of team members, who need to be consulted on a change. Another approach describes change through the linkages between components in a product model [25]. Starting with the change DSM, designers indicate the nature of the link between tasks. This analysis of product connectivity is particularly amenable to visualisation. It was the starting point for examining a range of visualisation tools for helping designers predict change.

5. Visualising change

Designers have difficulty exploring change options. Further, individual descriptions of the product are partial and effective prediction must work across different descriptions. As Zeitz [34] points out, experts need representations at a medium level of abstraction—between overview and detail. However, few commercial tools address the visualisation of product connectivity on this level of abstraction. This section introduces different visualisations of product connectivity. The visualisations shown are all implemented as part of a Change Prediction Method (CPM) tool that supports engineering change management.

5.1. Visualisation

An appropriate level of abstraction is critical for effective visualisation. In the CPM tool, abstraction takes place mainly during the model building stage. However, even with suitable abstractions, displaying a large amount of information about a complex system is difficult. Two strategies are employed in CPM:

Multiple viewpoints: Most designers have a limited overview and their understanding is biased by their
knowledge, interest and role in the company (see Fig. 3). Multiple viewpoints may be represented in information visualisation by fisheye views [35]. Interest is concentrated on the part of the environment which is close by and accessible. The further away something is, the less attention and interest it receives. The user sets a viewpoint and screen space is then assigned to the objects based on a ‘Degree of Interest’. The idea of viewpoints used here is about selecting the information, about change and its consequences in this case, which has meaning and significance for a particular stakeholder in the process. Our particular attention is directed towards different designers and managers in, or associated with, the design project team, who may work with specific descriptions of products or processes, whilst keeping the bigger project picture in mind. However, in other cases a designer is not so closely directed in the focus of attention and may need to build several more general views representing different aspects of the process or product.

- **Multiple views**: Multiple views are widely and successfully used for the visualisation of complex information [36], in software engineering [37] and to some extent in engineering design [38]. In the case of complex products, there are two reasons for using multiple views: (a) The amount of information in a complex product is too large to be displayed in a single graph. Different graphs show different information. A network diagram for instance is often used to represent relational data, but very dense networks display confusing edge-crossings and the compact form of a DSM can be a better display [39]. DSMs on the other hand do not show the structure of the network in an intuitive way, especially the indirect connections between components. (b) Different people involved in the design process have different viewpoints and demand different views on the product data. For example, we observed one designer requesting the capability to ‘fade’ out all but the one linkage type in a product model that had the biggest impact on his design.

Visualisations that are able to adapt their viewpoint to a particular user would be effective but few tools in current design practice offer such functionality.

### 5.2. Visualising change propagation

This section introduces several visualisation techniques and discusses their value for change propagation. The illustrative example of a diesel engine (see [25]) shows the advantages and disadvantages of the different visualisations. Attention is concentrated on the *fuel injection assembly*, which was identified as one of the problematic change components by a senior design manager.

#### 5.2.1. Design structure matrices

Matrix-based techniques are used frequently in representing designs. DSMs are seen as ‘a simple, compact, and visual representation’ [40]. However, matrices have limitations when used to display large and complex products and indirect linkages (see [39]). An experienced designer said during a model building exercise: “*Let’s face it, a DSM is not a representation designers like using*”. Nevertheless, a DSM is a widely used representation for displaying direct linkages between components and is the underlying representation in the CPM tool.

Fig. 7 shows the DSM of a diesel engine. Binary information about the existence of a direct link between components is provided but it is not clear through which linkage types the components are connected or how likely changes propagate through this link. Querying (such as provided in the CPM tool), allows interactive presentation of additional information. Colour coding to represent different linkage types draws attention to specific types of links (in Fig. 7, all mechanical static connections are highlighted).

#### 5.2.2. Change risk plot

The change risk plot (see Fig. 8 and [41]) is similar to a DSM. Instead of visualising direct linkages between components, it shows the combined (direct and indirect) risk of a change to one component, given that another component is changed. The width of each rectangle represents the likelihood of a change and its height is proportional to the impact [26]. The area of the corresponding rectangles thus represents the risks and colour coding indicates high-risk connections.

The change risk plot does not show information about direct links or about propagation paths. However, it identifies high-risk component connections. In the case of the diesel engine, there are two such high-risk connections, both resulting from a change of the *fuel injection assembly*. Although there is no direct connection to the *wiring harness* (there is no corresponding mark in Fig. 7), it still has a high change risk. A reordering of the change risk plot reveals that the *fuel injection assembly* is the largest source for propagating changes but only the ninth largest recipient of propagated change. The biggest recipients of change propagation are the *wiring harness* and *ECM*.

#### 5.2.3. Propagation networks

The matrix-based techniques described above, display either direct linkages (DSM) or combined linkages (change risk plot), but not both simultaneously. A network representation can also show the same relational data but with more degrees of freedom by arranging the nodes freely in 2D or even 3D (for a discussion of different possible layout algorithms for networks see Battista et al. [42]). Note that a DSM is restricted to changing the vertical and horizontal component order. Another advantage of network representations is that it is easier to assess indirect linkages or propagation paths between components [39].
In the CPM tool, two network layouts for visualising component connectivity are implemented using different ways to calculate the distance between each component and the root component. In Fig. 9, the distance of each component to the root component is proportional to the length of the shortest change path between these two components. The second layout sets the distance anti-proportional to the combined risk of a change in the component resulting from a change in the root component (see Fig. 10 for a similarly constructed propagation tree).

The less the risk of a change propagating, the further apart is a component from the root component. The background is used to display either the product structure level distance or risk information. Fig. 9 (with the focus on the wiring harness according to a fisheye strategy) shows the resulting component connection network of the change resulting from the fuel injection assembly against a level distance background. It is still difficult to identify all propagation paths, but interactive controls, such as highlighting all connected components, show that there are...
many propagation paths of length two between the fuel injection assembly and the wiring harness.

5.2.4. Propagation trees

While component connection networks provide a representation of indirect linkages, not every propagation path can be seen and analysed easily. A representation designed to show different propagation paths is the propagation tree with multiple entries for each component (see multiple appearance of wiring harness in Fig. 10). The construction of the tree starts with a root component. All components that are directly connected to this component are drawn as children of this component. For all these children, this is repeated until the probability of each particular branch falls under a certain user specified threshold (in Fig. 10 this threshold is 5%). The tree is laid out in one of the two radial layouts (level distance or risk) described in the previous section, having a root and focus component. The layout based on the likelihood of a change propagating from the root component is shown in Fig. 10.

A propagation Tree that takes likelihood values into account is shown in Fig. 10 for the diesel engine. With the interactive possibilities offered for the diagram in the CPM tool, we notice there are seven different links from the fuel injection assembly to the wiring harness with a probability of 5% or higher and none of them is direct. In Fig. 10, two paths from the fuel injection assembly to the wiring harness have a very high likelihood of change propagating: one via...
the fuel pump and one via the ECM, another high risk component.

5.3. Discussion

Table 1 summarises the different findings that can be provided by these displays. It can be seen that there is no ‘best’ representation that is able to display all different aspects of change propagation properly and no one representation technique seems to be superior to others. Each type makes a particular feature salient leaving the user a choice which diagram they want to use. Providing several, possibly linked, graphics is applied widely in several fields outside engineering design, such as exploratory data analysis (see [36]) and information visualisation (see [43]).

The usability of the interfaces that are part of the CPM tool are validated using two approaches: One is a User Centered Design approach [44] with close cooperation with our industrial partners through interviews, meetings and prototype evaluation. The second approach is experimental testing of the usability of DSM vs. networks-based display. Strong personal preferences were observed.

6. Implication for safety critical systems

Change prediction is important in the development of safety critical systems for two reasons: (i) unexpected changes can push up the high development costs of safety critical systems and (ii) potential change propagation paths can indicate where problems with product reliability might lie. In both cases, visualisation can help designers explore connectivities in an explicit way and gain an intuitive understanding of the properties of the whole product.

This paper has concentrated on the processes of design change and tools to help manage this process including an examination of predicting the effects of engineering change as it propagates across a product. The capability to predict the effects of change has several rather indirect consequences which contribute to the overall effect of potentially increasing safety. First, prediction, albeit in a probabilistic sense, can enable planners to allocate resources more effectively, particularly in reducing the contingency resources which need to be kept available to concentrate on areas of the product likely to be affected by the change. Further, since these resources may be specialist engineers with several calls on their time, predicting change can help them allocate adequate time to change problems and reduce confusion. Second, prediction allows the designers to identify where in the product major uncertainties, and associated resource allocation, will lie. Third, prediction allows designers and project managers to gain better control of design processes. These processes may have significant variance both in duration and quality of the design produced in terms of fitness for purpose.

The visualisations also provide a discussion tool, through which different team members can assess and discuss properties of a product. In a simple way, the change propagation risk assessment provides an indication about which experts need to be consulted if a potential change were to occur. Particular changes and their consequences for reliability can be made explicit through the visualisation. With shared representations and common points of reference available through visualisation, designers from across different parts of a complex product can assess the effects of changes and their impact on safety and reliability.

The change propagation tool and associated visualisations are not primarily to analyse reliability in a product. However, it is a tool that can guide the effort of costly verification and validation. It can pinpoint those areas of a product where change is likely to propagate. By supporting the design process of a safety critical system, the change tool can help to reduce the risk of unexpected changes late in the process, which pushes a product over time and over budget. Planning with these change propagation tools helps to allocate resources where they are most needed. Predicting where and when to have appropriate expertise available is particularly important for those high-profile safety critical projects, such as space projects, which have highly publicised launch dates.

Changes, either as generators of new products, through customisation and reuse, or through the in-process modifications or ‘fixes’, can have wide and potentially unintended consequences. In each case it is critical for designers to know how a change propagates—what other parts are affected and in what ways. Without this information designers expose themselves to dealing with ‘avalanches’ of change with associated resource implications or leave parts of their products vulnerable to increased risk of failure. This paper has presented approaches to help designers understand the connectivities in their products which take account of the multiplicity of descriptions used in a design process.

Complexity of change arises from the backcloth connectivities in existing product and processes as well as the range of models and descriptions used during design.
Finally, the actions on these descriptions—in this case the change processes—present their own complexity in the ways they are implemented through the choices and options taken by designers. The complexities of connectivity in the product and descriptions are compounded by complexities in the dynamics of product development. This paper has described the significance of change processes, identified some of their complexities and presented tools to help designers manage changes through visualising how changes propagate.

Reliability depends critically on connectivities among parts especially in dependencies and redundancy. This is similar to the way that change propagates though the connectivities. In the latter changes in one part, designed for new functionality, imply that design changes are required in other parts. In reliability analysis, the parts of a design change their behaviour because of their connections, leading to consequences for the behaviour of the whole product.

However, the main thrust of the paper is that by exploring the consequences of a design change systematically, designers identify parts whose functional requirements have changed because of changes to connected parts. These new functional requirements set new requirements for part performance and change how it contributes to the reliability of the whole product. Predicting the paths of change propagation can, in addition to helping to manage the design process, increase product reliability. In particular, this paper proposes that visualisation tools for predicting change offer usable and practical ways to support designers in dealing with the development of complex products.

References


