Proceedings of IDETC/CIE 2005
ASME 2005 International Design Engineering Technical Conferences
& Computers and Information in Engineering Conference
September 24-28, 2005, Long Beach, California USA

DETC2005-85435

PREDICTABILITY OF CHANGE IN ENGINEERING: A COMPLEXITY VIEW

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ABSTRACT

Design changes can be surprisingly complex. We examine the problems they cause and discuss the problems involved in predicting how changes propagate, based on empirical studies. To assist this analysis we distinguish between (a) a static background of connectivities (b) descriptions of designs, processes, resources and requirements and (c) the dynamics of design tasks acting on descriptions. The background might consist of existing designs and subsystems, or established processes used to create them. The predictability of design change is examined in terms of this model, especially the types and scope of uncertainties and where complexities arise. An industrial example of change propagation is presented in terms of the background (connectivity) - description – action model.

Keywords: change, change prediction, structure, connectivity, description, complexity

INTRODUCTION

Many companies face the following situation: Customers request a new version of an existing design which incorporates useful changes, or marketing wants an update to an existing product. Initially it might seem like a small change which can be implemented quickly. But during the process designers find it takes them longer then expected. The new requirements may have affected parts of the design which were expected to remain largely unchanged. Even experienced designers may not have predicted how changes would propagate across the design from one part to another. This propagation, leading to changes in many parts across the design, may have several complications.

- The original designers may not be available or able to explain their decisions or the rationale.
- The different parts are more expensive to order.
- Designers of the new parts perceive that altering a complicated part involves high risk and try to avoid change, perhaps searching for work-arounds on simpler and perhaps more familiar parts.
- There may be several different records relating to the previous design but these may not be complete or it may not be clear which ones are relevant to the change. For example CAD models might exist but not functional descriptions and design sketches.
- The overall costs, in terms of time, resources and materials, can be large and unpredictable.
- The necessary time was not been planned into schedules and members of the project team need to move on to the next project. Customary practice may be abandoned and tasks compromised.

The modification or customisation of an existing design is not the only situation where change poses problems. A design process usually passes through several stages of signing-off parts and systems. Errors and mistakes in signed off designs as well as new requirements from suppliers or clients can initiate changes. If changes occur late in the process they can have serious effects, especially if the product has already proceeded to production. In this case the change takes place against the background of a nearly completed design rather than an existing one, but the problems are similar.

Responses to these problems include managing the change processes (see [1], [2], or [3]) and devising effective representations [4]. Recent research has comprehensively analysed types of engineering change [5] as well as providing methods to represent linkages between parts in complex products [6] and predict the risks associated with of propagation of changes through linkages among parts [7]. We will discuss these approaches in more detail later.

In this paper we put these findings on managing change processes and analysing change propagation into a broader context by examining some general characteristics of change in design. First, change takes place against a background of knowledge and experience embodied in the current design which is the starting point for change. Second, the process of change is a fast moving, dynamic process, often highly creative in finding solutions. Third, change processes work on descriptions of different aspects of the design such as function and geometry, the processes and resources available, and requirements of clients, customers, the company itself and its suppliers. These characteristics reveal several sources of complexity [8] in design change processes particularly the ordered background of existing designs, processes and requirements combined with uncertainties of change processes with their unpredictable outcomes.

CHANGE

The two scenarios of change outlined above, namely modifying an existing design or recognising shortcomings in a partially completed design, are part of a wider picture of design in general as an ongoing process of modification of previous designs. Change lies at the heart of almost all design processes. Cross [9] identifies modification as a key aspect of design processes. Even innovative designs can be viewed as changes in that pars are reused as well as ideas and solution principles from existing designs. Designs change to meet new requirements or put right shortcomings.

As with many areas of design research, 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 and its descriptions. The close attention that has been paid to the management of change processes ([10],[3]) 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 for managing change [11] 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. Further, change propagates in these descriptions from one part to another along the connections between parts. This complements the analysis of the propagation of change along these connections (see [5], [6], [7]).

Descriptions

Designers can interact with a physical object itself to make modifications, but mostly they rely on more abstract representations. The initial designs before change 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 available initially from the existing design or 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 descriptions. Appropriate and usable descriptions are critical. A description can refer to a specific object, perhaps an existing design, and represent certain features of this reference object. A description, once modified 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 choice 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 [12] and [13]).

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 in action consists of the mismatches between descriptions.

Mismatches and mistakes

Mismatches between how a design proposal behaves and its desired performance need to be rectified before the design can be brought to the market. However, it is also possible that changes introduce new mismatches – mistakes are made. Design proposals themselves serve to explore user requirements which in their full extent are not set firmly at the start of a design process.

The processes of change are not always smooth and well directed. Mistakes can occur in many ways. Designs, or parts of designs inherited from previous designs may not be appropriate for the new context or newly designed parts may contain mistakes which disrupt a design process. They 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. 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 dramatic knock-on effect has been referred to as an "avalanche" of change ([5], [1]) or the "snowball effect" [2]. Such an event can have a major affect on the budgets and schedules of a particular project as well as more generally on the way a company and its projects are organised.

The exact point in time when an engineering change occurs during product development can have a dramatic impact upon the schedule and cost of the project [14]. Costs rise the later a change is implemented: changes that require alterations in the design phase are much cheaper than those that occur during production ramp-up. Engineering changes lead to an increase in the amount of product data that must be handled, especially if one change propagates to many further changes. Ensuring that only correct, current data is available can be a major problem [15]. Once production has started the impacts spread further into many other business processes. For example changes affect the supply chain. Wänström [16] found that there was no consistent approach to handling the phase-out of old and phase-in of new parts.

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 [5] and an ongoing study in a diesel engine company. Initially we concentrated on the overall process of change and identified that understanding dependencies between components is key to managing changes and predicting their effects [17]. In response a matrix-based change prediction method has been developed [7] as well as a method to capture the linkages between components [6]. 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 [5].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.

Regardless of the type of the change, companies used the straightforward sequence to manage them: assess, generate possible solution, analyse implications and implement. However, the attitude with which the change is resolved is 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 there 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.

These extensive studies on helicopters, diesel engines and turbo-jets (products with many parts, strong connections among parts and processes involving many different areas of expertise and capability) show that design change is complex and difficult to manage. Connectivities among parts and the associated chains of connections as pathways for change propagation are sources of complexity. A small change propagates in an 'avalanche' of changes, whose scope and magnitude are hard to predict. Further, apparently insignificant changes in one part cause unpredictable and potentially large changes to performance of the design as a whole.

PREDICTABILITY

Companies have a vested interest in avoiding change avalanches, and therefore would like to know the risk of one occurring. Accurate change prediction would be useful beyond identifying worst case scenarios:

- In tendering to stay away from orders that involve costly knock-on effects
- In planning a change process
- In selecting between alternative possible solutions for a change request
- In scheduling the freezes of core components

In practice companies find change prediction an extremely difficult problem and as we shall argue in section 4 and 5, change prediction also poses theoretical problems.

Propagation and prediction

Propagation is not just about the chains of connectivities in which change in one part necessitates change to connected parts. Changes may also be said to propagate in that changes to one part cause through the connections change in the behaviour of the whole design which are then rectified by part change. Change prediction can have two senses. First, predicting what parts will be affected by a change and second predicting how the change itself will proceed in practice. The former is a structural view concerned with the product and its connectivities. The latter is a 'planning' view concerned with tasks, activities and process and prone to uncertainties such as partial information and limited time to assess options.

To predict the propagation of changes designers it is necessary to identify the links between parts through which a change could spread, and then estimate whether a particular change could propagate. This is reasonably straightforward for assessing geometric knock-on effects from initiating changes. Modern CAD systems can predict clashes between component geometries and therefore give an indication about the way geometric change might spread

Prediction gets more difficult for other types of linkages, as illustrated in Figure 1. Parts have multiple linkages which are dependent. The types of linkages (see [18]) fall within different fields of expertise, so that even expert designers are often not aware of them. For example the diesel engine company tried to replace a metal temperature sensor with a cheaper plastic, forgetting that the metal component also served as an earthing link for a connecting component, until the prototype engine failed.

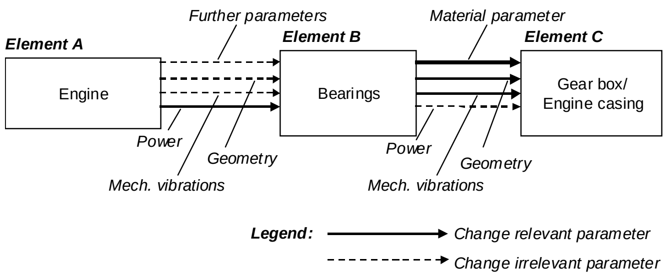

Figure 1 Change propagation

Predicting how a change will propagate in practice involves more than analysis of linkages. Designers make choices on how to implement a potential change. 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 system rather then passing it on, sometimes in fear of admitting mistakes or because they don't know how another component could cope with a change. As the design progresses more and more components get frozen, because they are long lead time items or define key parameters for other systems. 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 are not deterministic, but highly constraining.

Assessing change

Assessing change depends on the extent of the overview that designers have of the whole product. In complex products overview can be difficult to achieve. Eckert et al. 2004 [5] remark that the deputy chief engineers of a helicopter are expected to have the best product overview of their team understanding between 50 % and 70 % of a helicopter in detail. For a less complex product this could be higher.

In experiments to elicit product connectivity [18] experienced engineers displayed two different strategies for change prediction (see [19] for cognitive arguments), illustrated in an abstract form in Figure 2:

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

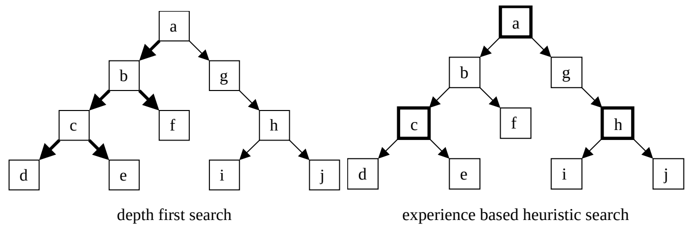

Figure 2 Strategies for change prediction

Planning for change

Is it possible to plan for change in the sense that a company selects changes (or at least routes to change) in a way which minimizes expected costs in time and resources? Predicting the possible chains of connection to achieve a desired result is of limited use without planning how resources are deployed. Each required change will have an associated probability distribution of resources such as engineer's time or use of test facilities. Each distribution has characteristics describing expected resources and expected variation in the resources (variance). A key problem is to keep overall variation under control. As overall variation is composed of variations in many individual changes it is necessary to understand how the variations add up. Methods for planning the design and manufacture of complex products with uncertain processes ([20],[21]) are relevant here.

One observation is that trying to reduce propagation by directing change to parts which can absorb change is not always advantageous. These paths to absorption may have a potential for high variability and uncertainty, whilst longer chains of change effects may be straightforward and have well constrained resource requirements.

Planning, becomes more complex when considering how limited resources are to be spread over the various change processes. Decisions on which changes should receive the most effective and capable resources, are not straightforward. All changes have high importance and are addressed in a 'firefighting' mode. Given the uncertainties in change processes plans will quickly become out of date and replanning will occur regularly.

The practical imperative to predict the consequences of change is clear. There are three aspects. First is how the change propagates and second how it affects the behaviour and performance of the product. Third is how to allocate design resources to the change processes. The extent and scope of methods and tools to aid the first aspect (and to some extent the second) of change prediction will be described in the next section. These concentrate on developing company processes and analysis of chains of connection between parts. Questions of predicting performance of a changed design and allocating resources to make changes, remain largely open. The former is prone to effects of accumulating margins and uncertainties whilst the latter involves the interrelations among different projects a company undertakes.

Support tools

There are few tools for change prediction currently. One tool [22] takes the approach of helping designers avoid later knock-on effects by planning changes. Clarkson et al. [7] look at change prediction from the view point of aggregate risk calculated conventionally as the product of impact and likelihood. They begin with a product change DSM (see [23] for a general discussion of DSM). A change DSM is not necessarily symmetrical because change is directional, for example heating is a flow from a hotter to a cooler component (while the inverse direction could be modeled as cooling). 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 Figure 3

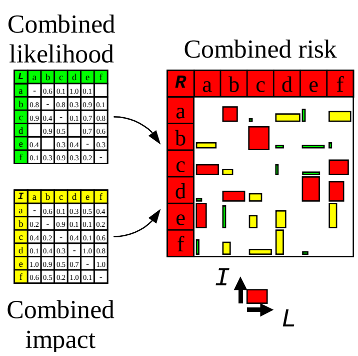

Figure 3 Change prediction matrix

As a product needs to be modeled at an aggregate high level in order to be described and displayed in a matrix, this method only gives a rough idea of change propagation. It was originally developed for tendering, but can also be applied in design review, for example, to quickly establish a rank order of team members, who need to be consulted on a change.

Another tool describes change through the linkages that exist between different components [6]. Starting with the same change DSM, designers indicate the nature of the link between tasks. Product connectivity can be explored using a visualization tool [24]. For example the diagram in Figure 4 allows the user to explore different change propagation roots (or starting points) by clicking on elements and reconfiguring the diagram. These tools aim to provide an overview and enable design teams to analyse and question product connectivity through shared visualisations.

This section has argued that change propagation predication is an important issue only partially supported by design support tools. Change prediction is not only difficult, because of the choices that human designers make, but also because of the connectivity properties of the product itself, the descriptions that are used and the processes with which change is carried out. Each of these factors is the source of complexity.

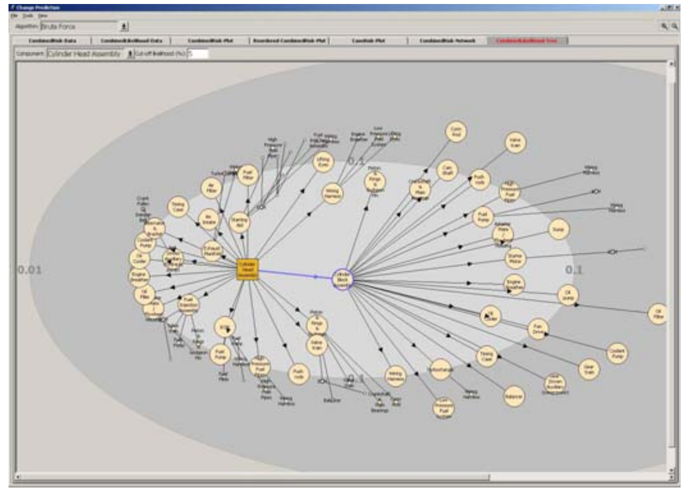

Figure 4 Visualising product connectivity

COMPLEXITY

In a recent analysis of complexity across the design process Earl et al ([8]) start from four main elements of design and product development: (i) Product - the design itself and its geometrical, physical and engineering characteristics, (ii) Process - the processes or activities used to create the design from initial specification to final product with the client or customer. These include the organisation, culture and resources of the company and its supply chain. (iii) Designer - the capabilities, knowledge and experience of designers and (iv) User – specifications, requirements and markets. Each element is a potential source of complexity, as are the relations between these elements. Further the elements and relations have both static and dynamic aspects. Mature products have extensive static elements in established product architectures, supply chains and well rehearsed processes with few uncertainties. Innovative products have large dynamic components in each of the four elements whilst customised products, may have relatively static product architectures but dynamic and responsive processes.

Connectivities and dynamics

Complexity is still 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. This mirrors the distinction between the static and dynamic aspects of design. Complex systems are dynamic, changing and evolving over time. Underlying connectivity representing how the different parts are related determines constraints on behaviour. Simon ([26]) considers the complex engineered or 'artificial' systems 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 almost decomposable systems. The connectivities between parts (through which change propagates for example) are static background whilst dynamics represent behaviour.

Connectivity and dynamics can also be viewed in terms of information complexity. This expression of information content or entropy ([28], [29]) takes into account both the underlying order described by connectivities in structure and the overall uncertainties of dynamic events (expressed as expectations) on that structure. Axiomatic design [30] aims to minimise complexity through reducing the connectivity between parts. This in turn is expected to reduce the uncertainties of dynamic events such as change propagation during design and unexpected behaviours in proposed designs. 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 [31]. Related models represent the connectivities of process tasks in product development directly ([32], [33]). Modelling connectivities is predominantly a static view.

Another view takes complexity as being predominantly about uncertainties in dynamic systems. Chaotic systems (e.g. [34]) 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. [35]).

Timescales

Product architectures and organisational structures develop more slowly than individual products or the rapid changes during product development. Over an extended timescale, individual product developments and the change processes within them will affect underlying connectivities in product architectures as well as the organisational structures of the company. Over a short time span of change processes, it makes sense to look at a static background of connectivities 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 background of the processes.

Complexity as experienced by participants in design at all stages, levels and timescales is dependent on the descriptions which are employed to represent products, processes, users and designer’s knowledge and expertise. Many descriptions, each partial, are used together and in parallel. We might view static complexities coming from the connections within and between descriptions. For example a geometric model in CAD has a complex structure of parts and layers. This shape description is intimately linked to a material strength description; indeed there may be considerable overlap between them. During change descriptions are modified as new parameters are calculated and properties analysed. 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 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 background of existing products and company processes as well as designers’ expertise and knowledge. Change processes are actions on descriptions in this background.

BACKGROUND, DESCRIPTIONS AND ACTIONS

The background includes the underlying connectivities of parts of a product type and general physical principles for the behaviour of that type of product. 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 [36]. This general picture of design is summarised in Figure 5. Complexity arises at each layer in this model, and in the interactions between levels. The background represents the underlying order expressed through structure and connectivity whilst the actions represent dynamics. Actions take place on descriptions.

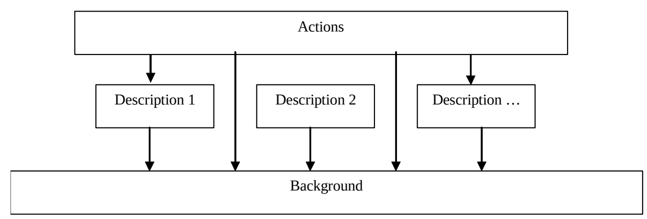

Figure 5 Layers

Examples of elements in the background 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 background for manufactured shapes) and (c) the physical principles for devices of a certain type. The structure of the background arising from connectivities can be analysed through multidimensional relations with methods such as Q-analysis ([27], [37], [38]), which models both connectivities and dynamics within a common hierarchical framework.

Eppinger et al. ([31]) and Suh ([30]) both consider complexity reduction via connectivities in the descriptions used. Complexity as information or entropy is about possible behaviours (as actions on descriptions) within the framework of background connectivities.

Problems in design change can arise from the misalignment between background, descriptions and actions. For example descriptions may not be consistent with the actual background or have insufficient scope to cover all aspects of the background. Further, in the background 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 background such as the potentially chaotic behaviour that can occur near conditions of optimal performance of a jet engine compressor. 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 background against which the designers operate on a particular project.

During the design process direct physical interaction with the background is limited. Physical prototypes are built to test some properties, but otherwise designers operate on descriptions that are part of their 'object worlds' [39] as. A design process moves from an interaction with descriptions which may be physical parts of the background, like an example of an existing product, through more abstract representations, and then returns towards a direct interaction with the background through a prototype and test. Delaying this direct interaction through using increasingly accurate product simulations is a current trend. With fewer and later tests there is limited scope for design iteration beyond the test.

Change processes are strongly constrained by their background structure and connectivities. In particular the connectivities determine how changes to one feature will affect related ones. Keeping changes within limits can ensure that only limited and acceptable changes are propagated elsewhere. These limits are expressed by margins on parameters. Researchers advocate setting these up explicitly so as to make future changes easier. Martin and Ishii [22] propose a method to analyse which margins will be critical in future for likely changes and design those into the product in the first place. Axiomatic design [30] advocates a structured approach to design with a clear assignment of functions to components or parts. Connectivities within the product itself are reduced and designers are more aware of the linkages and margins that do exist. The design process becomes less prone to mistakes and the design more robust in performance. A side effect is that a design might be more resistant to change in the future. These methods in setting up background structure to accommodate change will need to make the tradeoffs (a) between current product and future products and (b) between product complexity and process complexity.

Change prediction is probabilistic. Many product properties will be known and many can be modeled, but every time a change is carried out, designers have some choice over how this is done. These choices are stochastic. For example whether a new need really requires a weight increase and if it does then how is a supporting component to be reinforced. The product properties form the background for the decisions that designers are making. On this background, complexity phenomena are evident such as chaotic behaviour when small changes have huge effects. The product can also display emergent properties, e.g. unexpected vibration. As components serve multiple functions, the change can spread through these functions to seemingly unrelated parts, e.g. a mechanical balance relationship in a helicopter which is illustrated later. The information flows and dependencies are complex. Designers act on this background in stochastic ways - if something has been done in a certain way in the past, it becomes more likely to be repeated although the designer might choose not to. These high level stochastic predictions can provide useful insights as companies want to know the risk involved in making changes to existing components.

Many applications of artificial intelligence (see [40] for explanations and references to AI sources) are concerned with understanding and predicting the likely behaviour of systems of probabilistic causal connections or modeling the way humans reason about uncertain descriptions and data such as medical diagnosis. However, the conditional probabilities to construct these Bayesian networks are not available for change processes with much more extensive observations of recurring patterns. In consequence we are left with simple methods for high level change prediction, rather than detailed models.

Changes are often difficult to carry out, because they require considerable effort in to capture the background - understanding the current design and the reasons why it is the way it is. Design rationale is rarely captured and documentation does not identify potential changeability of parts. Although these and similar problems in change that seem to come from of the background process they actually arise from the description layer and need to be resolved there. This is recognised in a major new UK research 'grand challenge' that is looking at providing 'immortal' design information, i.e. background, description and action records for existing designs.

AN EXAMPLE OF DESIGN CHANGE

As we indicated above several studies have been conducted on change. Change processes in Westland Helicopters were reported [5] in some detail. Helicopters integrate many complex subsystems, from airframe to controls, avionics, power systems and transmissions, which are all customized and thus the targets of change processes. The background covers strong connectivities among its many, wide ranging, elements from existing product range and types, assessments of product performance in service, technical knowledge and expertise through to established processes for subsystem design and integration. The background is deeply embedded in company practices and capabilities. Descriptions used by designers have an extensive range across the company including for example, customer specifications, CAD, engineering analysis and simulations, test results and plans for process including schedules.

Helicopter design

The design of a helicopter at Westland is essentially a customization process. Westland does not have a base product, but uses various existing designs as a starting point for each new design. Therefore the company has incompatibility problems among the various designs used as the starting point as well as changes that come in later.

This background is not a nicely structured representation of the problem; it is a medley of designs, requirements and technologies. Other elements of the background are more structured including technical constraints on product architecture, company processes in tendering, design and manufacture, and supply chain relations. Our studies suggest that recognition of the extent of the internal background - context, starting points and constraints - on which the new design is based is as important as the external imperatives of customer need. The background includes the connections and linkages between parts of the helicopter. Mapping this aspect of the background has helped the company to identify sources of complexity in their products and how these affect their design processes. The map of connectivities is a first step in understanding the 'amount of uncertainty' or information complexity at the start of the design process. However, even with a map of connectivities changes can propagate unpredictably with a 'chaotic-like' complexity.

Example of two connected changes

In a helicopter most components are affected by overall product parameters, such as balance or rotational frequency. Changing just one component can alter these overall parameters which are then brought back on track by changing several other components and so on. Often changes go on in parallel, which although unproblematic on their own can cause large problems if they happen at the same time. For example a new version of a military helicopter (in the EH101 series, Figure 6) required a troop seat to be fitted to the inside of the helicopter and a large sensor on the outside of the fuselage. The fuselage could have carried the additional weight of one of the changes, but not both, so that the fuselage needed to be reinforced, taking up more space on the inside of the craft. However the fuselage could not be reinforced without upsetting the balance of the entire helicopter. Therefore other parts needed to be rearranged in the craft. Every time a component is moved, geometry needs to be re-evaluated and possibly changed with the cables or pipes leading to it rearranged. The knock-on effects were very costly, but as the company had contractual obligations to carry out both changes they had no choice. Another example of design difficulties caused by change is the addition of a large and heavy radar to the front of the craft which required changes to the tail of the craft for balance and manoeuvrability. In these examples, overall product parameters are cutting across those descriptions of the product which decompose it into functional or technology subsystems.

This change caused the company many problems and several designers independently commented on it as an example of how the company struggled with changes. The layer model proposed in this paper helps to explain this, presenting the change as difficult on all the layers. The background structure including the original design of the fuselage had insufficient margins available to accommodate the change. A decision was taken early in the design of the EH101 series on the extent of margins for parts and their behaviour, including overall margins for the product. These margins were designed in and allowed for uncertainties in product performance and operational conditions. Margins were eroded from version to version over the process of many modifications in the evolutionary development of the EH101.

Figure 6 Westland EH101

In the worst case eroding margins can cause cliff edge effects, where a tiny change in a design parameter near a margin can have a huge effect, perhaps catastrophic, on the behaviour of the part and the whole design. Similarly, a small change in behaviour of a part, within its allowed margins, can have large knock-on effects across the product. While theoretically the behaviour near each margin is predictable, the overall effect, as a design moves closer to several margins in different parts, is unpredictable and chaotic behaviour. The changes are originally evaluated separately with no single one pushing the product over the margin. This is essentially what happened in this case with changes to sensors and troop seats requiring an extensive cascade of change across the whole craft.

The design of the helicopter is highly interconnected, where parts like the fuselage connect many aspects of the product together, effectively transmitting information between the parts. The present helicopter design of the EH101 series is neither modular nor does it follow principles of form and function division, largely because of concerns of weight penalties. Margins were not noted in CAD models or 2D schemas, therefore the company depended on designers remembering and communicating changes to margins among themselves. In the example above, adding sensors and troop seats fall under the responsibility of different teams, who are only linked through a common interest in the properties of the fuselage and overall product parameters. This organization and associated project division has evolved to meet the core challenges of helicopter design. Problems arise when designers try to act on unconnected parts of the background, using descriptions from their own expertise area. The further the change propagates across the product, the less well the organisation is equipped to deal with it, especially if there is a lack of overview. The example of adding the heavy radar shows in an elementary way the importance of maintaining a design overview across the whole craft.

Could these changes have been predicted?

A simple superficial answer is "yes, with better co-ordination between different groups it should be possible to understand, that two parts can't target the same margin".

However the reality is more subtle. This problem went wrong in two stages

1. At the beginning of the design process insufficient margins were allowed for the fuselage through not accounting for all factors affecting it.
2. When decisions had been made which then caused a problem with key margins, the organizational processes did not provide ways to resolve it.

The nature of uncertainty changed between the stages. Initially there was uncertainty in the decision making itself – as to how the designers are to resolve a whole series of design problems and the effects of these decisions. Designers analyse the state of the background at the beginning of a change process and record changes to the background. At the second stage there are uncertainties in the action-upon layers; that is in how people interact with design descriptions and how they reason about them. Designers do not always know how and why their colleagues make particular design decisions.

The question of whether something is predictable is closely linked with the nature of the uncertainties that affect the problem. There are uncertainties of descriptions which include selection, naming, ambiguity and scope. Other uncertainties occur for the data on which descriptions are based. These include accuracy, consistency and completeness. Uncertainties and their associated distributions (if there is sufficient data to establish these) give rise to information complexity. Predictability of changes using the limited object world of design descriptions may not always be possible. The shortfall is made up by the processes of design - generation of possibilities, expertise and empirical tests which appear to be logically necessary elements in design.

CONCLUSION

In this paper we have reviewed recent work on change processes in design. A model of Background, Descriptions and Actions distinguishes the static background for design development from the actions on descriptions to effect design change. The background layer describes the inherent and persistent structural properties of the product and processes. The descriptions layer reflects that designers interact primarily with descriptions rather than directly on the background. Fragmented descriptions or those misaligned to the structure of the background may miss critical properties only revealed at later test. The actions layer describes change processes and reflects the complexity of the process of adaptation (and possibly co-evolution) of the design to requirements.

ACKNOWLEDGMENTS

The authors would like to thank Perkins Engines for all their support during this ongoing research. This project is funded by the UK Engineering and Physical Sciences Research Council Innovative Manufacturing Research Centre grant.

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