Design change and complexity

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Abstract: Design changes can be surprisingly complex. We examine the problems they cause and in what ways they are complex, mostly in the area of engineering design change. To assist this analysis we distinguish between (i) a static background of connectivities designs, processes, resources and requirements, (ii) descriptions of these elements and (iii) the dynamics of design tasks acting on descriptions. The background might consist of existing, similar designs, ways of describing them and established processes used to create them. We view design change, and design more generally, in terms of this model of background structure, associated descriptions and actions on descriptions. Sources of complexity in design change are examined and we indicate where these occur in different aspects of the model.

Keywords: change, structure, connectivities, description, action

Introduction

Many companies face the following situation: Customers request a new version of a design incorporating useful changes or marketing wants an updated 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 have affected parts 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 has several implications: (i) Different parts are more expensive (ii) The original designers may not be available or be unable to explain their decisions or their design rationale. (iii) 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. (iv) 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. (v) The overall costs of change, in terms of time, resources and materials, can be large and unpredictable. (vi) 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 change at any stage. 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 (Fricke *et al.*, 2000, Terwiesch & Loch, 1999, Lindemann et al. 1998, Pikosz, & Malmqvist 1998) and devising effective representations (Cohen et al 2000). Recent research has comprehensively analysed types of engineering change (Eckert *et al.*, 2004), providing methods to represent linkages between parts in complex products (Jarrett et al 2004b) and to predict the risks associated with of propagation of changes through linkages among parts (Clarkson et al 2004). We will 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 rich 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 general characteristics help to reveal different sources of complexity in design change processes, particularly the complexity originating from a combination of order and uncertainty (Earl et al 2005). The ordered background of existing designs, processes and requirements is combined with an uncertain change process and unpredictable outcome.

Change

The two scenarios of change outlined above, namely modifying an existing design or recognising shortcomings in a nearly completed design, are part of a wider picture of design as an ongoing process of modification of previous designs. Cross (1989) identifies modification as a key aspect of design processes. Even innovative designs reuse parts, ideas and solution principles from existing designs. For example Dyson cyclone vacuum cleaners although innovative are in many ways similar to conventional ones in shape, brushes and basic function.

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. The majority of activity has concentrated on the former, for example the studies presented in Lindemann et al. (1998) or Pikosz & Malmqvist (1998). 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 (Lyon, 2001) the focus is on document control and administration. Here we examine design change in terms of how descriptions change. This complements research on linkages among parts and analysis of the propagation of change along these connections (Eckert et al 2004, Clarkson et al 2004, Jarratt et al 2004).

Descriptions: Designers can interact with a physical object itself to make modifications, but mostly they rely on more abstract representations. The starting point of change can be represented by an existing design or abstract descriptions such as drawings, CAD files, indexed knowledge and in-service records. Whilst a design is being generated it exists as descriptions which may be partial and fragmented compared to the initial or finished design. Even physical prototypes may be partial descriptions. The process of designing is a 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 aspects of the design: the CAD models describe geometry, FEA models describe mechanical properties, the functional models describe functions etc. All but the simplest products have more detail than a designer can easily think about. Design features and elements are therefore grouped into higher level parts. For example a car engine is described hierarchically as engine block, pistons, sump etc. rather than a detailed list of all components. When thinking about those parts we again pick up on aggregate features, for example the sump consists of the sump, seals etc. Only when we focus on the sump itself, we might start looking at specific details which will determine the price and quality of a product. 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. These objects may be competitors' designs or sources of inspiration. Just pointing to a familiar object can be a parsimonious representation from which designers can recreate details. Such object references do not necessarily pick out relevant features explicitly. Design descriptions through object references can exist on many levels of detail and be temporary and fleeting as designers focus on them (Kosslyn, 1980, 1994). A new design can inherit global properties and detailed features from an existing design which may never be explicitly questioned. Object references are an essentially different form of abstraction from the hierarchical descriptions which are based on a conscious selection of 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 objects and features. The ways that designers conceptualise the context in which they work and the process by which they generate a product are also descriptions. Further the descriptions are connected and influence each other. Indeed key drivers of the actions in change processes are mismatches between descriptions.

Mismatches and mistakes: Mismatches between how a design proposal behaves and its desired performance (or user requirements) become critical as a design progresses. They need to be rectified before the design can be brought to the market. However, changes may introduce new mismatches – mistakes are made - as well as remove others. We note that design proposals are essential prompts and tests of user requirements which may not be set firmly at the start of a design process.

The processes of change are not always smooth and well directed. Mistakes occur in many ways. Designs, or parts, may be inherited wrongly from previous designs or newly designed parts may contain mistakes. These cause disruption to a design process and need further changes to put them right. 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. Although the majority of alterations made to parts of a design have little impact, a few can unexpectedly propagate to other parts, perhaps not even directly linked to the initially changed component. This knock-on effect has been referred to as an "avalanche" of change (Eckert *et al.*, 2004; Fricke *et al.*, 2000) or the "snowball effect" (Terwiesch and Loch, 1999). 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 (Lindemann & Reichwald,1998). Costs rise the later an alteration is implemented: changes that 'just' require alterations in the design phase are much cheaper than those that occur during production ramp-up. Once production has started the impacts spread further into many other business processes. Engineering changes lead to an increase in the amount of product data that must be handled, especially if one change propagates many further changes. Ensuring that only correct, current data is available can be a major problem (Wright, 1997). Further, changes affect the supply chain. Wänström et al. (2001) 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 (Eckert et al, 2004) 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 (Jarratt et al.2004a). In response a matrix-based change prediction method has been developed (Clarkson et al. 2004) as well as a method to capture the linkages between components (Jarratt et al., 2004b). The observed shortcoming of not recognising dependencies was confirmed in a parallel study with a jet engine company.

These industrial studies led to a distinction between two types of change (Eckert et al. 2004). First *initiated changes* are caused by outside factors, such as new customer requirement or new legislation. Second, what are called *emergent changes* arise from problems with a current 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.

Regardless of the type of the change, companies used the straightforward sequence - assess, generate possible solution, analyse implications and implement. Even if the process through which initiated and emergent changes are resolved is very similar, the attitude with which the change is handled is very 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.

Companies employ two strategies to manage engineering change (i) Changes by a core design team. Because a change often occurs when members have moved to another project, a change interrupts this project or is delayed until spare time becomes available. Changes generate additional connectivity between products. (ii) Changes are carried out by dedicated change teams, who have to invest considerable time and effort into learning about the original product, often through the original designers. 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. We have established that classifying types of change, understanding the connectivities and linkages among parts, and providing tools to help this analysis, are valuable to the companies. We have also examined the some of the sources of complexity in change processes. For example, the structure of connectivities among parts and pathways for change propagation are sources of complexity. A type of chaotic behaviour can be identified – with small, apparently insignificant changes in one part causing unpredictable and potentially large changes to the design as a whole. A small change propagates in an 'avalanche' of changes, whose scope and magnitude are hard to predict. We now consider this and other types of complexity which arise during change.

Complexity

An analysis of complexity across the whole design process (Earl et al 2005) started from four main elements of design and product development. Figure 1 shows these elements: (i) Product - the design and its geometrical, physical and engineering characteristics, (ii) Process - the tasks used to create the design from initial specification to final product. 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. The environment for this designing 'world' includes contexts, theories and influences as well as available methods and tools. Each element is a potential source of complexity, but perhaps more important is the recognition that complexities in design often arise from the relations between these four elements. Change complexities arise from these relations.

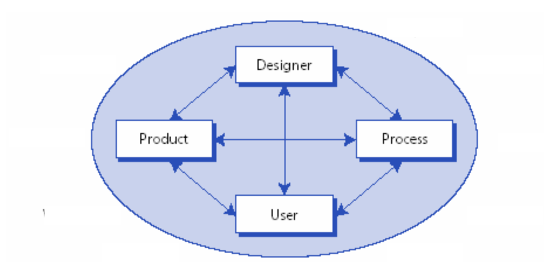

Figure 1 Elements of design

In this paper we take a complementary view of the sources of complexity. In creating a new design each of the four elements has a static and a dynamic component. For example in a change process the product has known and static parts as well as those parts which are subject to change. The process element may be dynamic but at a longer time frame than product. During each design the process will remain relatively static. Further, across different industries and types of product, the mix of static and dynamic components will vary. Mature products have extensive static elements in established product architectures, supply chains and well rehearsed processes with few large uncertainties. More innovative products have many dynamic components in each of the four elements. Intermediate types of design such as customised products, may have static product architectures but a dynamic and responsive process.

Characteristics of complexity- connectivities and dynamics: Complexity has enjoyed increasing attention as a research topic over the last decade. A science of complexity is taking shape, although complexity is still viewed in different ways according to the field of interest. However, there two key elements apparent. These are first the structural complexity of parts and connections, and second the dynamic complexity of behaviour. In the tradition of cybernetics (Wiener, 1948) complexity is distinguished from complicatedness. A system is complicated when its behaviour is predictable, even if it contains a large number of parts. On the other hand a complex system cannot be predicted in detail, even though its overall behaviour may be bounded. Complex systems are dynamic, changing and evolving over time. The underlying connectivity representing how the different parts are related determines the constraints and potential for behaviour. Simon (1969) considers the complex engineered or 'artificial' systems as almost decomposable, that is they are hierarchical to some extent, 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. 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' (Johnson 1983a). These routes overlap and interact with each other. These interactions transmit dynamic effects between different parts of the road system changing the flows of road traffic over the connected set of routes.

Connectivity and dynamics can also be viewed in terms of information complexity. This expression of information content or entropy (Jaynes, 1957, Frizelle & Suhov 2001) takes into account both the underlying order described by connectivities in structure and the overall uncertainties of dynamic events on that structure. Axiomatic design (Suh 2001) 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 and unexpected behaviours. Modelling connectivities can improve product development processes as shown in the application of design structure matrix (DSM) based methods to represent connectivity and identify where dependencies can be reduced (Eppinger et al, 1994). Related models represent the connectivities of process tasks in product development directly (Clarkson and Hamilton, 2000; O'Donovan et al, 2004).

Complexity is also about uncertainties in dynamically changing systems. Chaotic systems (e.g. Alligood et al. 2001) are examples of bounded (ie 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. Kauffman and Macready, 1995). Unlike chaotic behaviour these dynamics are unbounded in the sense that as changes to structure are allowed, new structures and radically new behaviours can occur. These distinctions are summarised in Figure 2.

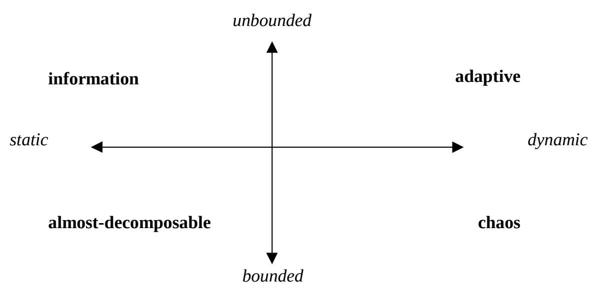

Figure 2 Types of complexity

Timescales: In drawing a distinction between static connectivities and dynamic behaviour we note that this is relative. For example the connectivities in a product architecture or organisational structure 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. These changes to underlying connectivities - the background structure for product developments - come about indirectly through management and strategic planning. On the other hand changes to the background structure directly affect product development.

Over a long period designs and 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.

But complexity as seen 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. Hanks et al (2003) present an analysis of problems with using descriptions across domains especially the propagation of misunderstandings arising from inadequate descriptions of design requirements. They provide evidence that attention to domain semantics and avoidance of informal heuristics can clarify connections within and between descriptions. Static complexities come from these connections within and between descriptions. For example a geometric 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 product development 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 reveal between proposed design and user requirements as inconsistent. In each case a change process involves tasks involving actions on descriptions.

Change processes take place against a highly structured background of existing products, newly designed parts and company processes as well as designers' expertise and knowledge. Change processes act on descriptions. In the next section we present a simple three level model of Background, Descriptions and Actions to help identify sources of complexity in change processes.

Background, descriptions and actions

The background might present 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 (Earl et al 2001). Complexity arises from interactions between 'flow' and background. A static background structure of connectivities is expressed through various mediating descriptions of product, process, designer and user (Figure 1). Some descriptions are changed though actions. This general picture of design is summarised in Figure 3. Complexity arises at each level 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 and uncertainties. Actions take place on descriptions or directly on the background for innovative and radical changes where appropriate descriptions may not be available.

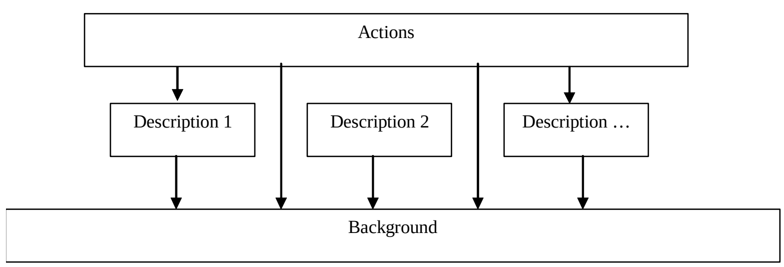

Figure 3 Three layer view of design

The background can evolve slowly over time and is essentially static. 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 (Johnson, 1983a,b, Johnson 1995), which models both connectivities and dynamics within a common hierarchical framework. The background is accessible through descriptions which have properties and structures of their own. The types of complexity discussed in the previous section have their focal points at different parts on the three level model (Figure 4). Adaptive (and co-evolving) properties are mainly on the actions level. Chaos is mainly concerned with how the structure of the background determines the predictability (or otherwise). For example, how change propagates depends on established linkages and connections among parts. Information complexity as information is about possible behaviours within the background connectivities. Almost decomposable systems characterise the descriptions of engineered or artificial systems (Simon 1967). Eppinger et al. (1994) and Suh (2001) both consider complexity reduction by understanding connectivities in the descriptions used.

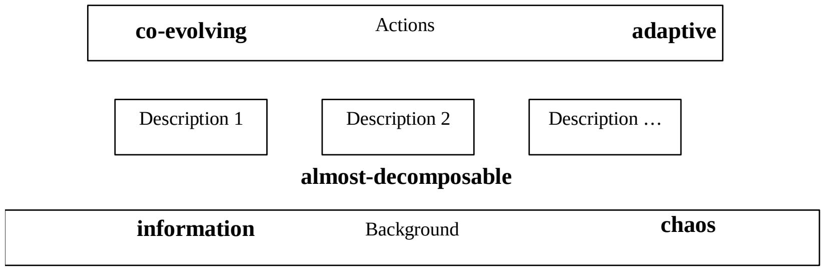

Figure 4 Types of complexity most appropriate at each level

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 may distort its properties. Further, descriptions may have insufficient scope to cover all aspects of the background.

In the background element of the model 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. The background also includes the physics of how the product works. For example the functioning of a jet engine depends on the physics of airflow through compressors. 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 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.

The idea of connectivities in a background can be applied more widely to design processes across an industry sector. An example is the development of fashion in clothing (Eckert & Stacey, 2001). When a season's fashion appears, it seems fairly coherent with similar trends, colours and materials. However designers have not directly collaborated. Perhaps they looked at the same sources of inspiration and followed the same trend predictions. They are connected through suppliers and customers who provide feedback on the developing design and constraints on materials and tools they make available. As the new fashion appears in the shops, designers look at it and use it as a way to refine their own ideas.

A description is an abstraction and a selection of features. For example a CAD model covers shape but not surface micro geometry. However tiny variations in the surface from manufacturing processes can have a large effect, for example where fatigue will occur over the life time of the product. During the design process direct physical interaction with the background is limited. Physical prototypes are built to test some properties, but otherwise designers create and operate on descriptions in what is referred to by Bucciarelli (1994) as an 'object world'. A design process involves actions on a range of descriptions. These may start with physical parts of the background (eg an existing product), through more abstract representations, and returns towards a direct interaction through a prototype and test. Delaying this direct interaction through using increasingly accurate product simulations is a current trend. Where designers ordered a test 10 years ago to see how a product or a part behaves, now there is only time for one test and little iteration beyond it.

Change processes are strongly constrained by background structure and connectivities. Researchers advocate setting these up explicitly so as to make future changes easier. Martin and Ishii (1997) propose a method to analyse which margins will be critical for likely changes and design those into the product in the first place. Axiomatic design (Suh, 2001) 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 might be that a design is more resistant to change in the future. These methods in setting up background structure to accommodate change will necessitate tradeoffs between current and future products as well as between product and process complexity.

Changes are often difficult to carry out, because they require considerable effort 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 seem to come from of the background process they actually arise from the description layer. This is recognised in a major new UK research ‘grand challenge’ that is looking at providing ‘immortal’ design information, ie background, description and action records for existing designs.

An example of design change

As we indicated above several studies have been conducted on change. Eckert et al 2004 report change processes in Westland Helicopters in some detail. Without going into extensive details these are products which 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.

The customisation of a helicopter, such as the current fleet of presidential helicopters, involves considerable design effort. Westland does not have a base product, but uses various existing designs as a starting point for each new version. Therefore the company has incompatibility problems between 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 elements whose connectivities include incompatibilities. 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 extends further to the connections and linkages between parts of the helicopter. Mapping this aspect of the background (Eckert et al, 2004, Jarratt et al 2004b) has helped the company to appreciate sources of complexity. The map of connectivities is a first step in understanding the ‘amount of uncertainty’ or information complexity at the start of the design process. Even with a map of connectivities changes can propagate unpredictably with a chaotic-like complexity.

In a helicopter most components are affected to some extent by overall product parameters, such as balance or rotational frequency which can lead to a wide range of change propagation. 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 5) a few years ago 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 cannot 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 descriptions of the product as decomposed into functional or technology subsystems.

This change caused the company many problems and several designers independently commented on it as an example of how Westland struggles with changes. The complexity model proposed in this paper helps to explain this. The change was difficult on all the layers proposed: the background of the fuselage they started with did not have the redundancy 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. These 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 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. In this case the changes are originally evaluated separately with no single one pushing the product over the margin.

Figure 5 Westland EH101

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. For example it would be theoretically possible to mount troop seats on the floor, thus distributing the weight over a larger area. 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 are not noted in CAD models or 2D schemas, therefore companies depend 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. Such an overview is important in dealing with changes such as adding the heavy radar at the front with its associated changes to the tail of the craft.

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. Complexities can include underlying chaotic behaviour of both products and change 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 sometimes coevolution) of the design to requirements.

References

Alligood K T, Sauer T, & Yorke J 2001 *Chaos: an introduction to dynamical systems,* Springer.

Bucciarelli, L.L. (1994): *Designing Engineers* MIT Press.
Clarkson P J, Hamilton J, 2000,Signposting: a parameter-driven task based model of the design process *Research in Engineering Design*, 12 (1), 18-38
Clarkson, P.J., Simons, C.S. and Eckert, C.M. (2004) 'Predicting change propagation in complex design' in *ASME Journal of Mechanical Design*, 126 (5), 765-797
Cohen, Navthe S, Fulton R 2000, ‘C-FAR Change favorable representation’ Comp Aided Des 32, 321-38
Cross, N. (1989*), Engineering Design Methods*, Chichester: John Wiley & Sons
Earl C., Johnson J. and Eckert C 2005 'Complexity', Ch 7 in *Design Process Improvement - a review of current practice*, Springer
Earl C, Eckert C, Johnson J (2001) Complexity of planning in design, *ASME DETC’01*, Pittsburgh,
Eckert C, Clarkson P J and Zanker W, 2004 'Change and customisation in complex engineering domains' in *Research in Engineering Design*, 15 (1), 1-21
Eckert C and Stacey M, 2001 'Designing in the context of fashion - Designing the fashion context' in *Designing the Context Symposium*, Delft University of Technology, The Netherlands, 113-129.
Frizelle G. and Suhov Y. M, 2001 "An entropic measurement of queueing behaviour in a class of manufacturing operations", *Proceedings of Royal Society Series A*, 457, 1579-1601,
Fricke E et al, 2000 Coping with Changes: causes, findings and strategies, *Systems Engineering*, 3, 169-79.
Hanks K, Kimberly S, Knight J, 2003 ‘Improving Communication of Critical Domain Knowledge in High-Consequence Software Development: an Empirical Study’, *ISSC'03*, Ottawa, Canada
Jaynes E. 1957, Information Theory and statistical mechanics, Physical; Review 106 620-630
Jarratt, T.A.W. (2004) 'A model-based approach to support the management of engineering change', PhD-thesis, Cambridge University Engineering Department
Jarratt T, Eckert C, Clarkson P.J & Stacey M 2004a 'Providing an overview during the design of complex products: the development of a product linkage modelling method' in *DCC'04, MIT*, 239-258
Jarratt T., Eckert, C. and Clarkson, P.J. (2004) b 'Development of a product model to support engineering change management' in *TMCE 2004*, Lausanne, Switzerland, 1, 331-342
Johnson J H (1983a). Hierarchical Set Definition by Q-analysis, Part I. The Hierarchical Backcloth. *International Journal of Man-Machine Studies* 18(4): 337-359.
Johnson, J 1983b. Hierarchical Set Definition by Q-analysis, Part II. Traffic on the Hierarchical Backcloth. *International Journal of Man-Machine Studies* 18: 467-487
Johnson J 1995 The multidimensional networks of complex systems, in: Networks in Action. Springer
Kauffman S &Macready W 1995 Technological Evolution and Adaptive Organizations *Complexity,*1 26-43
Kosslyn, S M 1980 *Image and Mind* Harvard University Press, Cambridge MA (1980)
Kosslyn, S M 1994 *Image and Brain* MIT Press, Cambridge MA (1994)
Terwiesch, C. and C. Loch, H, 1999, Managing the Process of Engineering Change Orders: The Case of the Climate Control System in Automobile Development. *J Product Innovation Management,* 16, 160-72
Lindemann, U. and R. Reichwald, (1998*) Integriertes Änderungsmanagement*, Berlin: Springer.
Lindemann, U., R. Kleedorfer, and M. Gerst, (1998) The Development Department and Engineering Change Management, in *Designers: The Key to Successful Product Development*, E. Frankenberger, P. Badke-Schaub, and H. Birkhofer, Editors, Springer, London. p. 169-182.
Lyon, D.D.(2001*) Practical CM - Best Configuration Management Practices*, Butterworth, Oxford
Martin, M.V. and Ishii, K. (1997) "Design for Variety: Development of Complexity Indices and Design Charts," DETC97/DFM-4359, *ASME DTC/CIE Proceedings* CD, ISBN 0-7918-1243-X.
O’Donovan, B. Eckert, C.M. & Clarkson, P.J. (2004) Simulating Design Processes to assist in design process planning , *ASME DTM* Salt Lake City, Utah, USA, September 2004.
Pikosz, P. and J. Malmqvist. (1998) A Comparative Study of Engineering Change Management in Three Swedish Engineering Companies, *ASME DTM*. 1998. Atlanta, GA, USA: ASME.
Simon, H. (1969). *Sciences of the Artificial*. MIT Press, Cambridge, MA.
Suh N P (2001) *Axiomatic Design - Advances and Applications*, Oxford University Press, New York
Wänström, C., P. Medbo, and M.I. Johansson. (2001) Engineering Change from a Logistics Perspective. in *NOFOMA Conference* - Nordics Logistics Research Network. Reykjavik, Iceland.
Wiener, N. 1948, *Cybernetics or control and communication in the animal and machine,* MIT Press,
Wright, I.C.(1997) A Review of Research into Engineering Change Management: Implications for Product Design. *Design Studies*, 18: 33-42.