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PRODUCT ARCHITECTURE AND THE PROPAGATION OF ENGINEERING CHANGE

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1. Background

Much design literature focuses on the creation of new, novel products, but the reality is that *"…most designing is actually a variation from or modification to an already-existing product or machine."* [Cross 1989]. Therefore, as the majority of design activities involve adapting a known solution to meet new requirements, understanding the issue of engineering changes is of vital importance if companies are to deliver product development projects on time and to budget.

Making a change to a product is, in most cases, a relatively simple process. However, unexpected propagation of the change can occur. Thus, what may initially appear as a simple procedure, involving the alteration of a single sub-system, can dramatically turn into an expensive redesign that requires alterations to a wide range of components. A recent report surveyed engineering companies in the UK that design and manufacture products; just over one half of the firms regarded engineering changes as a major source of problems in their development processes [Acar 1998].

This paper investigates how product architecture influences change propagation and uses a redesign case study to highlight the complexity of this issue as faced by designers during product development.

2. Engineering change

Changes that are made to engineering products can be categorised in several ways. One method defines changes as either *initiated* or *emergent* [Eckert 2001]. *Initiated* changes arise from the marketplace – either the customer requests a change or the manufacturer, through market analysis, perceives that change is required to maintain the position of the product. *Emergent* changes refer to errors and mistakes that appear in the product and must be removed in order for the product to function correctly.

Before examining the concept of change on an individual component or sub-system, it is important to grasp the effects of change at the macro level. Two categories of change process have been proposed and are illustrated in figure 1 [Eckert 2001]:

- *Ending* change processes – consist of *ripples* of change, which are a small and quickly decreasing volume of changes, and *blossoms*, which are a high number of changes that are brought to a conclusion within the expected time frame;
- *Unending* change processes – characteristic of this type are *avalanches* of change, which occur when a major change initiates several other major changes and all of these cannot be brought to a satisfactory conclusion by a given point.

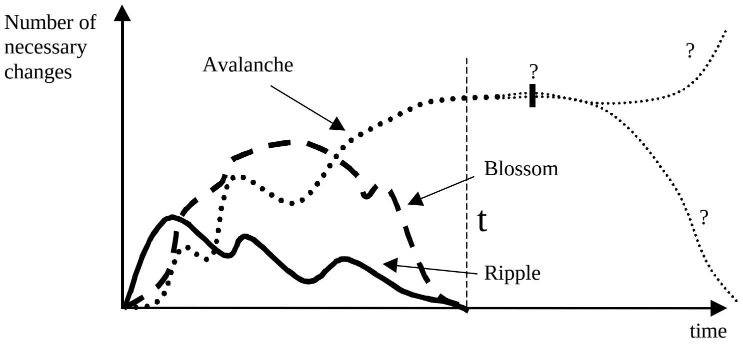


Figure 1. A macro representation of change processes [Eckert 2001]

2.1 Product architecture

How change affects a product is fundamentally linked to the makeup of the item. This is the product architecture, which is defined as *"(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of interfaces among the interacting physical components"* [Ulrich 1995]. There are two main types of product architecture:

1. *Modular*: each physical component of the product carries out only one element in the function structure and the interfaces between the components are de-coupled. Two components are said to have a coupled interface if a change to one causes a change to the other;
2. *Integrated*: each physical component carries out more than one functional element. This is termed function sharing [Ulrich 1990].

In practice most products are situated somewhere in the spectrum between full modularity and full integration. Indeed whether a product is deemed modular or integrated depends upon the level at which it is examined. Products can be composed of sub-systems that are modular in the way that they link together, but each one is highly integrated.

There are cost implications associated with product architecture. Without function sharing many items, for example cars, would become prohibitively expensive [Ulrich 1990]. Modular designs generally cost more to manufacture and assemble than integrated ones and this is why most mass-produced products possess an integrated architecture. However, savings are possible through modularization when a particular subassembly can be used on a variety of products – a process termed *"Modularizing Product Families"* [Otto 2001]. The trend in many industries has been to promote modularity and this, as well as creating adaptable and competitive products, has had the effect of promoting innovation as specialist companies are able to concentrate all their expertise and resources on one particular module; this has been very evident in the personal computer industry [Baldwin 1997].

2.2 Change Propagation

In terms of change, modular designs can be adapted much more easily to changing requirements, if the interfaces between the modules are able to remain the same. However, once the interfaces between modules need to be altered, the complexity of the change issue will increase dramatically. Lindemann *et al.* talk of *local change*, which just involves one component or system, and *interface-overlapping change*, which involves many components and is especially common in complex products with high connectivity between parts [Lindemann 1998]. Another categorisation system groups components or sub-systems into three approximate types with regards to their change properties and is illustrated in figure 2 [Eckert 2001]:

1. *Absorbers* – these can be either 'partial' or 'total'. A total absorber causes no further change whilst accommodating a number of changes. This is a rare situation. Much more likely is a partial absorber that contains many changes and passes on only a few. Absorbers lessen the complexity of the change issue.
2. *Carriers* – neither reduce nor add to the change problem. They merely transfer the change from one component to another.

3. *Multipliers* – expand the change problem making the situation more complex. Such components may lead to an ‘avalanche’ situation arising.

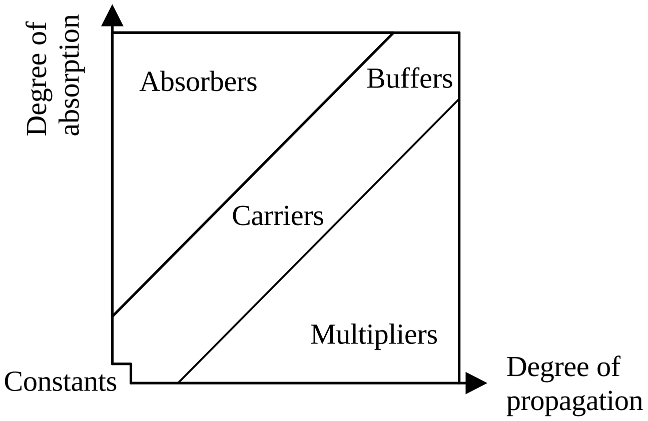


Figure 2. Representation of the change propagation of components [Eckert 2001]

It is critical to appreciate that components can change between the three roles depending upon the size of the change. A component may be an absorber of small changes, but when a large alteration is necessary, it may develop into being a carrier or worse a multiplier. The two factors affect whether a change can be absorbed are the initial specification of the component and the tolerances designed into the component. Eckert *et al.*, reporting on the specific case of helicopter design, comment that *“the designers typically added a 25% safety margin to the specification of many components, which was gradually used as the design was put together”* [Eckert 2001]. Once the safety tolerances are all used up, the component will switch to being a carrier or multiplier.

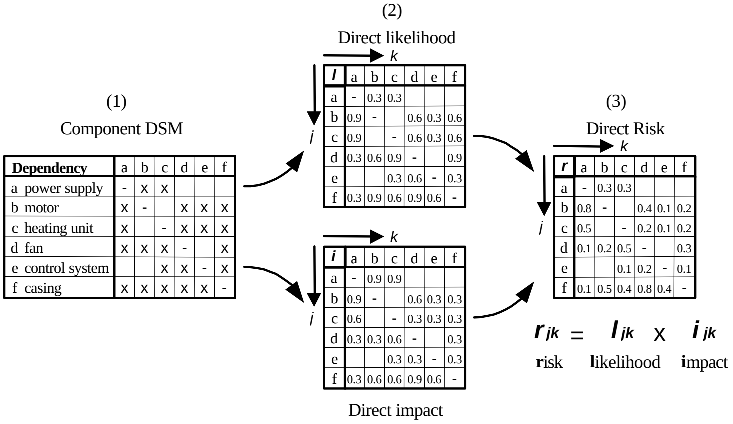
3. Predicting Change Propagation

There is wide agreement that mechanisms are needed to support the management of engineering changes. Paper based systems are generally inefficient and so most authors concur that computer based tools are essential [Lindemann 1998]. Commercially available computer software for change management is often incorporated into Enterprise Resource Planning systems. However, it supports the administration of change after it has been initiated rather than predict the likelihood of occurrence. To meet this need, a tool called the Change Prediction Method (CPM) is being developed at Cambridge to assist in the understanding of how change propagates through a product.

At the core of the CPM tool is a combination of the representation and analysis methods used with Design Structure Matrices (DSM) with risk management techniques. Due to space constraints there is only room for a brief description. Full details can be found in earlier publications [Clarkson 2001]. Design Structure Matrices are used by the CPM to model the connectivity between the components and sub-systems that make up the product. The CPM uses a simple model of risk, where the likelihood of an event occurring is differentiated from the impact of such an occurrence. Risk is defined as the product of likelihood and impact. Likelihood is defined as the *“average probability that a change in the design of one sub-system will lead to a design change in another by propagation across their common interface”*, whilst impact is the *“average proportion of the design work that will need to be redone if the change propagates”* [Clarkson 2001].

The major issue at the start is the granularity of the representation. Whilst a model that incorporates every single part of a product may have a certain completeness to it, there is a loss of focus to the technique along with the difficulty of handling and understanding such large arrays of information. Various methods of breaking down the product are possible. The key aspect is that the representation used provides complete coverage of the product and identifies the important interfaces within the design. Once the interconnectivity between the sub-systems is characterised, the change relationships can be shown. Matrices for likelihood and impact are generated with values between 0 and 1. The two matrices can then be combined to create a direct risk matrix as shown in figure 3.

The impact and likelihood matrices created are *direct* matrices in that they represent the risk of change propagating between linked sub-systems. *Indirect* change propagation requires the involvement of at least one intermediate sub-system and this forms a chain of change propagation. The combined impact of changing one component on another is the sum of the direct and indirect affects. Various algorithms are being trialled for the calculation of the combined relationships. For the work in this paper, a route counting method was used [Clarkson 2001].



Dependency	a	b	c	d	e	f
a power supply	-	x	x			
b motor	x	-		x	x	x
c heating unit	x		-	x	x	x
d fan	x	x	x	-		x
e control system			x	x	-	x
f casing	x	x	x	x	x	-

l	a	b	c	d	e	f
a	-	0.3	0.3			
b	0.9	-		0.6	0.3	0.6
c	0.9		-	0.6	0.3	0.6
d	0.3	0.6	0.9	-		0.9
e			0.3	0.6	-	0.3
f	0.3	0.9	0.6	0.9	0.6	-

i	a	b	c	d	e	f
a	-	0.9	0.9			
b	0.9	-		0.6	0.3	0.3
c	0.6		-	0.3	0.3	0.3
d	0.3	0.3	0.6	-		0.3
e			0.3	0.3	-	0.3
f	0.3	0.6	0.6	0.9	0.6	-

r	a	b	c	d	e	f
a	-	0.3	0.3			
b	0.8	-		0.4	0.1	0.2
c	0.5		-	0.2	0.1	0.2
d	0.1	0.2	0.5	-		0.3
e			0.1	0.2	-	0.1
f	0.1	0.5	0.4	0.8	0.4	-

$$r_{jk} = l_{jk} \times i_{jk}$$

1 – define product architecture   2 – define direct change characteristics   3 – define direct change risk

Figure 3. Construction sequence for a CPM model [Clarkson 2001]

4. Valve redesign case study

The CPM tool was used to analyse a design case study investigated by the Department of Product Development at the Technische Universität München. An existing pressure relief valve, normally used in the pneumatic braking systems of railway vehicles, was redesigned in conjunction with the manufacturer, Knorr Bremse AG [Lindemann 2001].

4.1 Original design

The original valve design dated from the 1960s and consisted of 15 parts. It is shown in figure 4. The manufacturing process was complicated, expensive and labour intensive; for example the piston had to return to be re-sanded during production. There was a strong pressure to improve productivity by reducing the part count, the amount of labour required and the time for assembly.

Figure 4. Picture and diagram of original design – main components marked [Lindemann 2001]

4.2 Revised design

During the redesign, extensive use was made of Design For Assembly (DFA) methods to assess all aspects of the manufacturing process. The form and size of each part along with the type and direction of fitting were all examined. Various solutions were proposed which were reduced to the revised design shown in figure 5. The part count was reduced to 6 through increased function sharing and at the same time the cost of manufacture and assembly was reduced. A major factor in this was the ability of the valve to be assembled using a robot. Assembly time for the redesigned valve took only 35% of the time for the original design and the overall cost saving was 50%.

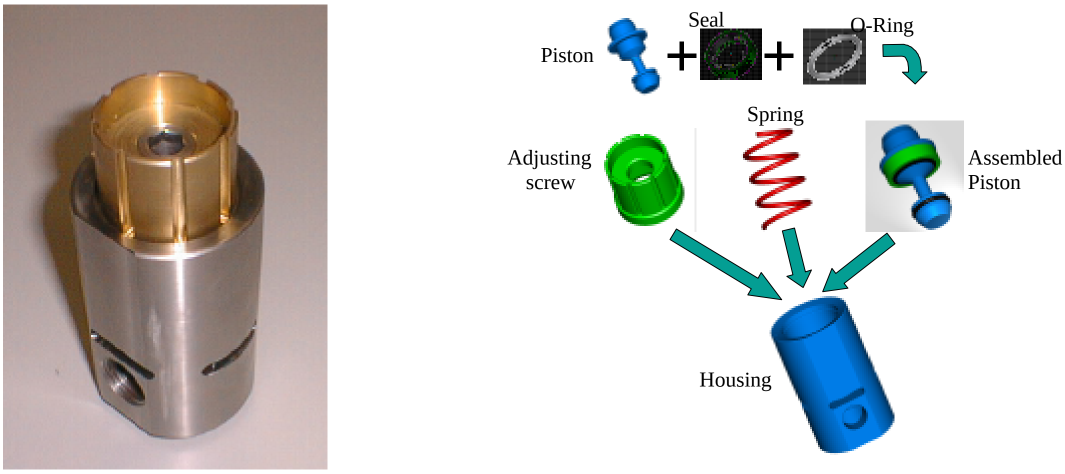


Figure 5. Picture and diagram of redesigned valve [Lindemann 2001]

4.3 Evaluation of valve design using the CPM tool

The CPM tool was used to evaluate both the original design and the revised design. In both cases the design was broken into 9 components or sub-systems. For the revised design three aspects of the automated assembly process were included (gripping tool, screwing tool and assembly line connection). The combined risk matrices for both designs are shown in figure 6. The columns and rows have been reordered so that the column farthest to the right has the highest risk of initiating change, whilst the uppermost row has the greatest susceptibility to change.

Combined Risk (old design)	Train connector	Spring	Hand grip	Spring connector	Cover	Cone	Piston	Seal	Housing
Piston	0.0	0.1	0.1	0.0	*0.3*	*0.4*		**0.8**	**0.8**
Seal	0.0	0.1	0.1	0.0	0.3	*0.5*	**0.7**		**0.7**
Housing	0.0	0.0	0.0	0.0	0.1	0.3	*0.4*	*0.4*	
Train connector		0.0	0.0	0.0	0.1	0.2	0.3	0.2	*0.4*
Spring	0.0		0.2	*0.4*	0.2	0.0	0.0	0.0	0.1
Cover	0.0	0.1	0.1	0.1		0.1	0.1	0.1	0.2
Cone	0.0	0.0	0.0	0.0	0.1		0.1	0.1	0.2
Spring connector	0.0	0.0	0.1		0.1	0.0	0.0	0.0	0.0
Hand grip	0.0	0.0		0.1	0.0	0.0	0.0	0.0	0.0

Combined Risk (new design)	Screwing tool	Gripping tool	Spring	Piston	Housing	O-Ring	Seal	Cover	Assembly line
Piston	*0.3*	*0.5*	**0.7**		**0.8**	**0.7**	**0.8**	**0.8**	**0.8**
Housing	0.2	*0.5*	*0.6*	**0.7**		**0.6**	**0.6**	**0.6**	**0.7**
Spring	0.1	*0.3*		*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*
Seal	0.1	*0.3*	*0.4*	*0.4*	*0.4*	*0.4*		*0.4*	*0.4*
O-Ring	0.1	*0.3*	*0.4*	*0.4*	*0.4*		*0.4*	*0.4*	*0.4*
Assembly line	0.1	0.3	*0.3*	*0.4*	*0.4*	*0.4*	*0.4*	*0.4*	
Cover	0.1	0.3	0.3	0.3	*0.3*	*0.3*	*0.3*		*0.3*
Gripping tool	0.1		0.2	0.2	0.2	0.2	0.2	0.2	0.2
Screwing tool		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Key - **Bold:** high risk *Italic:* medium risk Standard: low risk

Figure 6. Combined risk matrices

As can be seen from figure 6., the new more integrated design has an increased susceptibility to change propagation – the areas of high and medium risk are larger than with the original design. With the old design, alterations to both the piston and the seal have medium risk of propagating to the housing. However, in the redesigned valve, 5 parts have a high risk of propagating change to the housing.

However, the situation is not as simple as the initial obvious trade-off between susceptibility to change propagation and degree of integration. There are linked issues, one of which is the quality of the device; the new design is a much better product. With the old design, a number of variants were required to cover the full extent of pressures, but with the redesign, one product can cover the whole range – the design is more flexible. Therefore, although the cost of a future redesign would increase (the high susceptibility of change would lead to avalanches) when compared with the old design, the likelihood of that event occurring is lower because the design is more flexible. Added to this, by reducing the part count and enabling automated assembly to be considered, massive immediate savings are possible as opposed to hypothetical future redesign costs.

5. Conclusions

At a general level, as function sharing increases so too does the susceptibility to change propagation – highly integrated products are much more likely to suffer blossoms or, more critically, avalanches of change than those with a large degree of modularity. However, as the case study shows, the situation is complex, involving more considerations than just a single trade-off. Careful redesign of a product can bring about immediate cost reductions in areas such as manufacturing, especially if part counts are cut. This can lead to an increased risk of change propagation for future variants, but if the proposal better covers the spectrum of customer needs, the possibility of a future redesign being required is lessened.

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