Chapter 10
Engineering change

Timothy Jarratt, John Clarkson and Claudia Eckert
University of Cambridge

Change or adaptation has always been a fundamental part of engineering design; the vast majority of product design activity consists of taking a current product, concept or solution and adapting it to meet a new set of requirements. This view, whilst seldom emphasised in text books on design, is supported by a number of authors, for example:

> *…most designing is actually a variation from or modification to an already-existing product or machine.*
>
> (Cross, 1989)

> *History matters – no design begins with an absolutely clean sheet of paper.*
>
> (Bucciarelli, 1994)

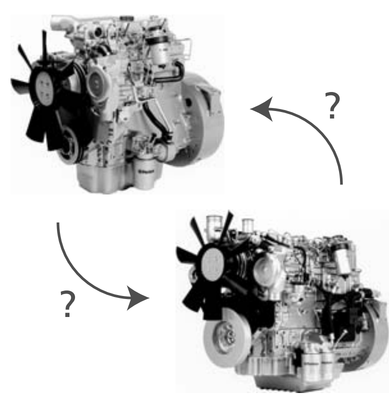
From a business perspective, changes to a design are "a fact of life" in taking a product from concept, through design and manufacture and out into the field (Nichols, 1990); they are the rule and not the exception in product development processes in all companies and in all countries (Clark and Fujimoto, 1991). From a high-level viewpoint, changes are made for two reasons: to remove errors from a product (rework) or to improve/enhance/adapt it in some way.

As an example of the importance of engineering change, a survey of German engineering businesses found that approximately 30% of all work effort was due to engineering changes (Fricke *et al.*, 2000); this included rework as well as the adding of functionality to a product. Terwiesch and Loch (1999) reported that engineering changes consumed between a third and a half of the engineering capacity at the firm they examined, along with 20–50% of tool costs (Figure 10.1).

The attitudes of engineers and managers towards engineering changes are important, as the ability of a company to implement changes effectively and efficiently is hugely dependent upon the people carrying out the task, and the way they communicate. Engineering changes are often perceived negatively because they can cause schedules to slip and budgets to overrun, but they can also be regarded as an opportunity for well-organised companies to meet the requirements of demanding customers rapidly and compete successfully with their rivals (DiPrima, 1982).

The issue of engineering changes has been gaining prominence in industry over the past two decades due to dramatic changes in markets. Maull *et al.* (1992) state that the move from the seller-dominated markets of the 1970s

" History matters—no design begins with an absolutely clean sheet of paper."
(Bucciarelli, 1994)



10.1 Change is most often a planned activity
Based on images © Perkins Engines Company Limited

and early 1980s to the buyers' markets of today has led to a situation of greater diversity in products, smaller production runs and shorter product life-cycles. An increasing volume of engineering change is the inevitable consequence of such an environment (Coughlan, 1992).

Markets are now fragmented and populated by sophisticated customers who demand individualised offerings (Clark and Fujimoto, 1991). Today, there is also much more competition because of the increased globalisation of industries, such as automotive, aerospace and electronics. "The time when an innovatory product could be launched with confidence and remain unchallenged has passed" (Inness, 1994).

In order to maintain or increase market share, companies must be constantly prepared to improve and update existing products, and rapidly introduce new ones. Engineering change has always been an important part of the product design and development process, but today it is an essential aspect. For businesses to survive and compete, gaining a thorough understanding of all the issues involved is a vital design research activity for industry in conjunction with academia. This situation may be summed up by the following statement:

" ... it's absolutely necessary to understand changes and to have a good grip on them as the entire product development process can be described as a continuous change management process."
(Fricke *et al.*, 2000)

> ... *it's absolutely necessary to understand changes and to have a good grip on them as the entire product development process can be described as a continuous change management process.*
>
> (Fricke *et al.*, 2000)

This chapter first takes a general look at engineering change and configuration management, as currently practised in industry. This is followed by definitions of change. The change life-cycle and a change process are then introduced. Finally, the impact of change and its relationship to a product's architecture are discussed. The purpose of this chapter is to define what is meant by an engineering change, to show when in the product life-cycle engineering change processes occur and discuss what their typical elements are.

Engineering change and configuration management

The attention that is now being 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 such as ISO10007 (ISO, 1995) and ISO9001 (ISO, 2000), which demand clearly documented processes for all key business activities. Defining configuration management is difficult. Probably the clearest official definition comes from ANSI/EIA 649 (ANSI/EIA, 1997), which states that configuration management is

> *a management process for establishing and maintaining consistency of a product's performance, functional and physical attributes with respect to its requirements, design and operational information throughout its life.*
> (ANSI/EIA, 1997)

Change management is a formal discipline that allows complex products to be designed and produced concurrently by several business units or separate businesses separated by thousands of miles (Lyon, 2001). It is used throughout the product life-cycle from the selection of a concept to the wind-down of production. One of the key aspects of configuration management is the control of engineering changes, because uncontrolled changes will have a dramatic impact upon a product's performance and its functional and physical attributes. The engineering change process is the core process of the larger configuration management process. Each change of the product or its documentation causes a change in product configuration (Pikosz and Malmqvist, 1998).

Change management is a formal discipline that allows complex products to be designed and produced concurrently by several business units or separate businesses separated by thousands of miles.

Although originally developed for electro-mechanical goods, most recent literature on configuration management has focused on software products (Huang and Mak, 1998). The main focus is on document control and the administration of product options; the more-technical issues involved in making changes are either ignored or covered in little depth.

Configuration management is practised with differing intensities in different industries. It is a key process for the design and manufacture of complex mechatronic products such as cars and aeroplanes. As such, configuration management is a vital issue in such industries and for the companies that supply them. For example, it is doubtful whether a company such as Airbus, which has a widely distributed design and manufacturing capability, would be able to design new aeroplanes effectively and efficiently without the discipline of configuration management. Configuration management can also assist communication; it provides a framework to support contacts between groups, especially if they are geographically spread (Leech and Turner, 1985).

10.2 Configuration management is a key process for the design and manufacture of complex mechatronic products

Approximately 95% of UK firms that design and manufacture products have adopted a formal approach to engineering change management (Huang and Mak, 1999). However, it must be noted that although all companies that adopt robust configuration management procedures must have a formal engineering change process, this does not mean that all companies that have a formal approach to engineering changes must be following configuration management practice. Although the two issues are highly interrelated, they are not the same.

Defining engineering change

"An Engineering Change is a modification to a component of a product, after that product has entered production."
(Wright, 1997)

"[engineering changes are] the changes and modifications in forms, fits, materials, dimensions, functions, *etc.* of a product or a component."
(Huang and Mak, 1999)

"Engineering change Orders—changes to parts, drawings or software that have already been released."
(Terwiesch and Loch, 1999)

It is important to distinguish engineering change from the general concept of change in a business/organisational context. Change management is a term that is common in management and business literature, especially that concerning business process re-engineering (e.g. Kettinger *et al.*, 1997). It refers to the administration and supervision of corporate or organisational transformation, be it the results of merging two firms or implementing a new business process.

Engineering change management refers to the organisation and control of the process of making alterations to products. In this chapter, any mention of change refers to engineering change. It is important to establish what is meant by an engineering change or an engineering change order (ECO). Many authors use the terms interchangeably as they are approaching the issue from a management perspective, but most do not attempt to define terms, making the tacit assumption that the reader has a clear understanding of the situation.

Authors often use slightly different terms such as 'product change' (Inness, 1994), 'design change' (Ollinger and Stahovich, 2001), 'product design change' (Huang and Johnstone, 1995) and 'engineering design change' (Leech and Turner, 1985). Close inspection of these authors' work indicates that they are all referring to the same phenomenon. Throughout this chapter the term 'engineering change' is used.

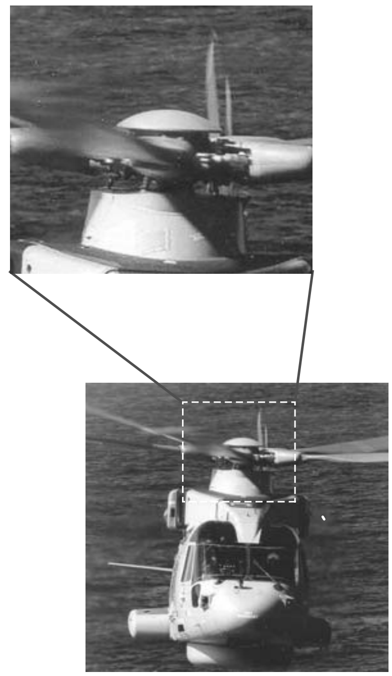
On the occasions when a definition is supplied there are subtle differences which are helpful to highlight and discuss. Three definitions from often cited papers are as follows:

> *an Engineering Change (EC) is a modification to a component of a product, after that product has entered production*
> (Wright, 1997)

> *[engineering changes are] the changes and modifications in forms, fits, materials, dimensions, functions, etc. of a product or a component*
> (Huang and Mak, 1999)

Engineering Change Orders (ECOs) – changes to parts, drawings or software that have already been released

(Terwiesch and Loch, 1999)



10.3 Change may be localised or apply to the whole product

Wright's (1997) definition restricts engineering change to the production stage and in doing so ignores the whole range of alterations that can occur during the design and development of a product. This has been the common approach in much of industry, with engineering change being regarded solely as a manufacturing issue that must be addressed to ensure product quality and to meet delivery deadlines; change before manufacture is regarded as a natural iteration of the design process. This approach creates an artificial division between engineering change and 'normal' product design and development.

The other two descriptions are more general and support the view that engineering change is an integral part of all design activities. These could range from changes made to a prototype during the development phase to an old product being updated to extend its life. Both definitions are much more suited to an environment of concurrent engineering. The definition of Huang and Mak (1999) is too general, in that it makes no mention or reference to the administration or management of design.

Terwiesch and Loch (1999) specifically mention the issue of software design, a vital aspect of modern mechatronic product design, which the other two ignore or at least fail to mention explicitly. By using the term ECO they are clearly approaching engineering change from a management point of view, where it is the management of change that is the big issue, especially when many changes are 'live' at the same time. They also imply that changes only occur once design details have been formally released. This links in with the formal processes for engineering change which are prescribed by configuration management standards.

It is important to appreciate that none of the definitions discussed above mention the size, scope or origin of the change. An engineering change can be anything from a small revision of a diagram taking one engineer a few minutes to a major redesign operation involving a large team of engineers working over a period of many months or even years. Designs are modified for a variety of reasons: to remove errors that have become apparent (through testing, manufacture, *etc.*); to adapt the device to open a new market sector; or to respond to customer demands.

In response to these issues, the definition of engineering change used in this chapter is based upon that given by Terwiesch and Loch (1999), but has been modified to include reference to the magnitude of the change:

"An engineering change is an alteration made to parts, drawings or software that have already been released during the design process. The change can be of any size or type, can involve any number of people and can take any length of time."
(Jarratt *et al.*, 2003)

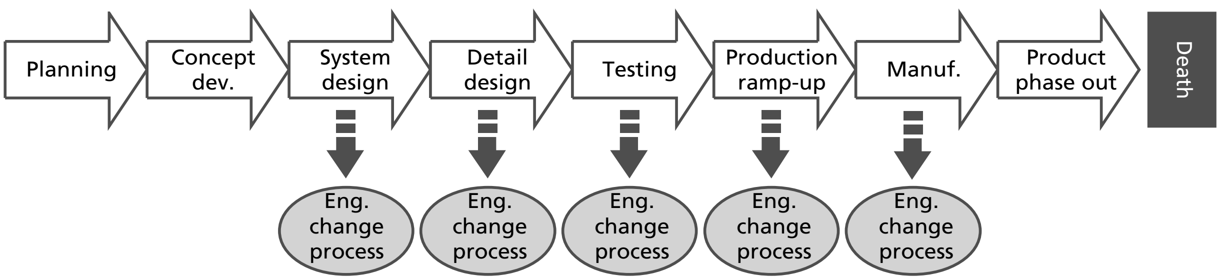
An engineering change is an alteration made to parts, drawings or softare that have already been released during the design process. The change can be of any size or type, can involve any number of people and can take any length of time.

(Jarratt *et al.*, 2003)

Engineering change in the product life cycle

Virtually all texts on product development discuss the concept of product life cycles (e.g. Otto and Wood, (2001)). Iness (1994) describes moving from the 'birth' of a product idea, through design and development to production and shipping. Eventually, after a period of growth, the product matures; finally, its position can no longer be maintained and so it is phased out: product 'death'. Obviously, engineering change activity varies significantly depending upon which phase of its life-cycle a product is in.

An engineering change can be triggered at any point in the product life cycle once the concept for the design has been selected and defined, since at this point the design data and information start to be formally released to design teams, suppliers, potential customers, *etc*. Any changes to this data, as the product evolves, must be regarded as an engineering change. Figure 10.4 illustrates this point by using the generic product development process proposed by Ulrich and Eppinger (2003).



10.4 Engineering change processes can occur during the design and production life of a product – based upon the generic product design process proposed by Ulrich and Eppinger (2003) in *Product design and development*
© McGraw-Hill – reproduced with permission of The McGraw-Hill Companies

Design research, especially that which attempts to model the design process, often gives the impression that the design and development phase of a product's life has a definite end point at which the finished product is handed over to production and marketing. Although many of the original designers and engineers will move on to new projects, the product can still be developed and enhanced, engineering changes will still occur and engineering change processes will need to be controlled and managed. Thus, for the sake of completeness, two extra phases have been added to Ulrich and Eppinger's model of the product design process: manufacturing and product phase-out.

Companies will often use different terminology to describe the change processes that occur at various points in the product lifecycle (although in Figure 10.4 only the term engineering change process is used for simplicity). For example, the authors have witnessed the following terms being used in different companies: 'product change process' used to describe changes during production ramp-up and manufacture; 'prototype change process' for changes during the testing phase; and 'design changes' for changes made during the system and detail design phases.

Although different terminology can be used, the basic engineering change process is the same whenever it is triggered in the design process. It is important to realise that there are two lifecycles connected with any product: the in-production lifecycle and the in-service lifecycle. For a number of products, especially those with medium to long in-service lives, a situation can arise where production will have ceased long before the last product is retired from service and decommissioned. Examples of such products are automotive vehicles, aeroplanes, helicopters, ships, military equipment and industrial plant.

Change processes in different companies may refer to:
- product changes;
- prototype changes; or
- design changes.

The engineering change process

Most authors refer to the engineering change process, but only a few actually outline the elements or phases within it. This section will discuss some of the different engineering change processes proposed in literature and outline a generic process.

Engineering change processes

All of the engineering change processes suggested in literature and used in industry contain most of the same ideas/themes irrespective of the industry or product involved. This is because the proposed processes are similar at a macro level.

Pikosz and Malmqvist (1998) investigated the engineering change processes in three Swedish engineering companies: an automotive manufacturer, a supplier to the defence industry and a supplier of test equipment for military aircraft. They discovered that, whilst companies may perform similar tasks when examined at a high level, organisational, market and product issues lead to significant differences when the processes are investigated in greater detail. For example, if the company produces a safety-critical product, the engineering change process is focused much more on quality than on time-scale or costs.

The change process is a mini, highly constrained design process or project.
(Leech and Turner, 1985)

Perhaps the clearest description of the engineering change process is provided by Leech and Turner (1985), who state that the process is a mini, highly constrained design process or project and "like any project, is only worth undertaking if its value is greater than its cost".

Different authors split the engineering change process into different numbers of elements, for example:

- Dale (1982) – (i) procedure to approval; (ii) procedure on approval.
- Huang and Johnstone (1995) – (i) before approval; (ii) during approval; (iii) after approval.
- Rivière *et al.* (2002) – (i) engineering change proposal; (ii) engineering change investigation; (iii) engineering change embodiment.
- Maull *et al.* (1992) – (i) filtration of engineering change proposals; (ii) development of solution to proposal; (iii) assessment of impact of solution; (iv) authorisation of change; (v) release and implementation of change.

Another element that is highlighted is that of review. DiPrima (1982) places an emphasis on following up any change to learn lessons. A month gap is suggested from implementation of the change to a review session. The review should examine whether everything is functioning as expected.

Learning from previously implemented changes is one of the key strategies proposed by Fricke *et al.* (2000) to cope with engineering changes, "Changes should be accepted as a chance, first, to improve the product and second, to do it better the next time".

"Changes should be accepted as a chance, first, to improve the product and second, to do it better the next time."
(Fricke *et al.*, 2000)

A generic engineering change process

Figure 10.6 shows a generic high-level engineering change process based upon the elements outlined above. The process is initiated by a change trigger: this is a reason for change. Eckert *et al.* (2004) describe changes as emerging from the product (*i.e.* errors) or being initiated from outside (*i.e.* customer requests, legislation, *etc.*). Once the need for change is identified the six-phase process begins:

1. A request for an engineering change must be made. Most companies have standard forms (either electronic or on paper) that must be completed. The person raising the request must outline the reason for the change, the priority of the change, type of change, which components or systems are likely to be affected, *etc.* This form is then sent to a change-controller who will enter it onto an engineering database.
2. Potential solutions to the request for change must then be identified, but often only a single one is examined. This can be for a variety of reasons:

time pressures, the fact that the solution is "obvious" or because engineers stop investigating once one workable solution is found.

3. The impact or risk of implementing each solution must then be assessed. Various factors must be considered: for example, the impact upon design and production schedules; how relationships with suppliers will be affected; and will a budget overrun occur? The further through the design process a change is implemented, the more disruption is caused.
4. Once a particular solution has been selected, it must be approved. Most companies have some form of Engineering Change Board or Committee, which reviews each change, making a cost–benefit analysis for the company as a whole and then granting approval for implementation. The Engineering Change Board must contain a range of middle to senior ranking staff from all the key functions connected to the product: for example, product design, manufacture, marketing, supply, quality assurance, finance, product support, *etc*. A thorough list of suitable functions to consider is provided by DiPrima (1982).
5. Implementation of the engineering can either occur straight away or be phased in. The option followed will depend upon various factors, such as the nature of the change (for example, if it is a safety issue, then immediate implementation must occur) and when in the product lifecycle it occurs. Paperwork must be updated. "One of the major problems frequently associated with engineering change, is that of ensuring that only current documentation is available to manufacturing areas" (Wright, 1997).
6. Finally, after a period of time, the change should be reviewed to see if it achieved what was initially intended and what lessons can be learnt for future change processes. Few companies carry out such a review process.

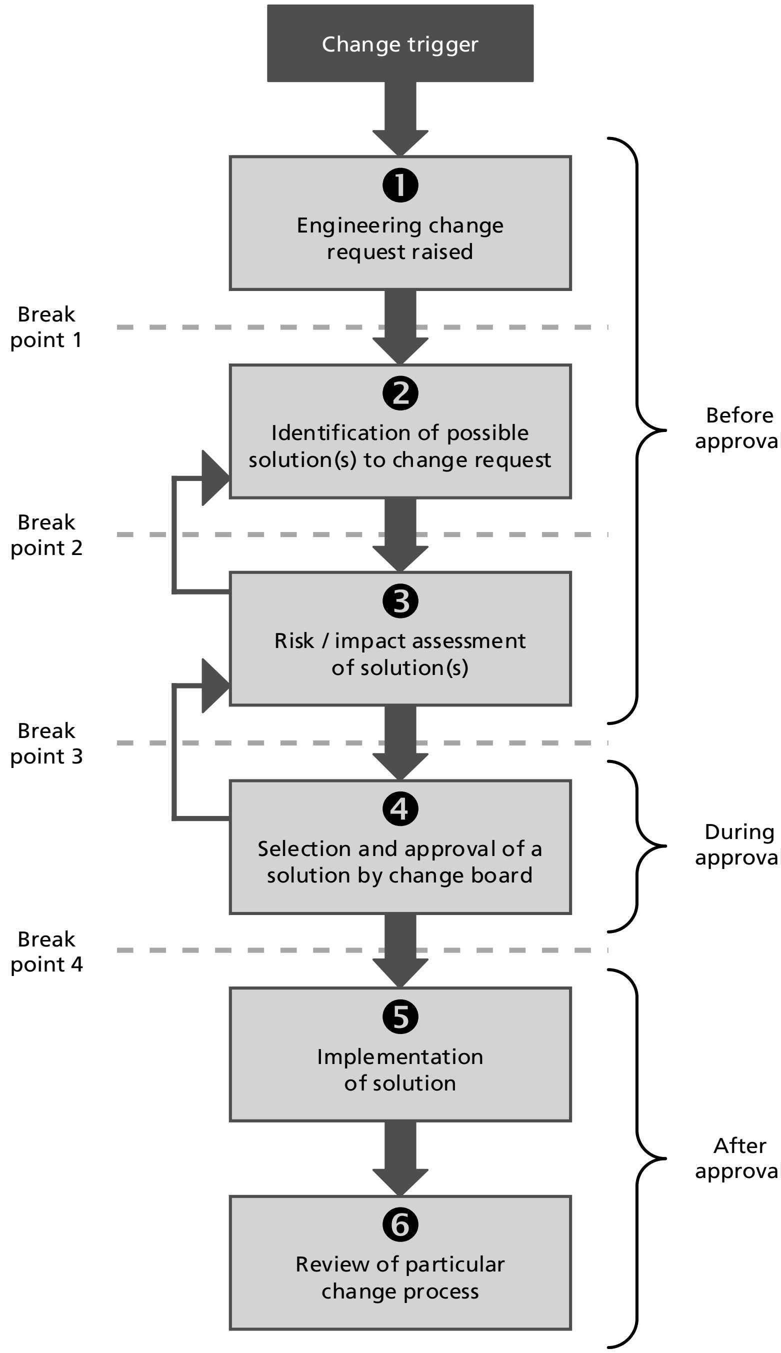
There are possible iterations within the process, two of which are marked by arrows in Figure 10.6. For example, a particular solution may be too risky for the company to implement and so the process will return to phase two, in order that other possible solutions can be identified. At the approval stage, the Engineering Change Board may feel that further risk analysis is required (maybe in the form of more testing) and so the process will return to phase three.

There are other possible iterative loops, but they are not marked for the sake of clarity. The most extreme loop would be when it was realised during the review phase that the solution implemented had been ineffectual or made matters worse. In that instance the process would return to the start with a new change request being raised.

10.5 Each aircraft will have a unique, and changing, build description

"One of the major problems frequently associated with engineering change, is that of ensuring that only current documentation is available to manufacturing areas."

(Wright, 1997)



10.6 A generic engineering change process

So far, it has been tacitly assumed that the process will eventually progress to the end point of an implemented change being reviewed for lessons learnt. Only those changes that actually provide an overall benefit to the business must be allowed to proceed to the end of the process. Sometimes there is no choice if the change is as a result of a safety issue or legislation, but the majority of changes faced by a company are not so clear cut.

Fricke *et al*. (2000) state that, in their study of German manufacturing firms, only 40–60% of engineering changes were technically necessary. They report that, in the cases where a change was not technically necessary, the final decision came down to the experience and knowledge of the company members involved. As Clark and Fujimoto (1991) stress, it is important to differentiate between meaningful and meaningless changes.

Break points in the change process

There are four break points in the engineering change process shown in Figure 10.6. At each of these points the change process can be brought to a halt. They can be likened to the 'stage-gate' points used by many businesses in evaluating progress during new product development projects.

The first break point comes after the request for change has been raised. As Maull *et al*. (1992) point out, there must be a filtration of the change requests so that those which are truly impractical can be removed from the process early.

Employees must be encouraged to raise engineering change requests as part of continuous improvement, but, as many employees may not appreciate the full ramifications of their suggestions, there must be a mechanism to filter out the totally impractical proposals. Boznak (1993) states that effective screening can enable a company to identify improvement opportunities effectively while avoiding unnecessary change costs.

Employees must be encouraged to raise change requests, but, as many employees may not appreciate the full ramifications of their suggestions, there must be a mechanism to filter the proposals.

The second break point comes after the search for possible solutions. Although the request may have been suitable on initial inspection, further investigation may reveal that there are no sensible solutions.

The third break point comes after the impact/risk assessment phase. Analysis and testing may show that the proposed solution(s) are far too risky for the company to consider. The final break point comes when the Engineering Change Board meets to consider the proposed solution. Board members may feel that, given the risk analysis, the interaction of the product with other products and processes, end where the proposal is being raised in the product life cycle, the proposal is not worth proceeding with.

Engineering change process paperwork terminology

Several terms are used by different authors and companies to describe the paperwork that accompanies the engineering change process. These include engineering change request (ECR), engineering change notice (ECN), ECO and engineering change proposal (ECP). As with the definitions and processes discussed above, there is some contradiction depending upon which author's work is read or which company's process is examined. In the majority of cases ECRs and ECPs are synonymous, as are ECNs and ECOs. Definitions of these two groups are taken from Monahan (1995):

> *[the Engineering Change Request is] a form available to any employee used to describe a proposed change or problem which may exist in a given product;*

> *[the Engineering Change Order is] a document which describes an approved engineering change to a product and is the authority or directive to implement the change into the product and its documentation.*

The impact of engineering change

The assessment of the impact of a change is at the core of the engineering change process.

The assessment of the impact of a change is at the core of the engineering change process. As a result, the effects of making a change are a subject that has received much coverage in academic literature. In general, changes affect planning, scheduling and project costs.

Several authors refer to a 'Rule of 10' (e.g. Clark and Fujimoto, 1991; Anderson, 1997): the cost of implementing a change increases on average by a factor of 10 between each phase of the design process. Thus, a change made during manufacture would be 1000 times more expensive than making the same change during the detail design phase.

Terwiesch and Loch (1999) break down the costs of engineering changes into three categories:

- design;
- changes in prototype tools;
- changes in production tools.

One change that they tracked in an automotive company affected production tooling and cost by approximately $190,000. Another change to the same component cost less than $10,000 because the change was implemented before any tooling was manufactured. Changes that occur late on in the design process also affect far more people than those triggered early on. Once manufacturing, suppliers, marketing, *etc.* are involved, the number of people who must be notified of a change increases dramatically.

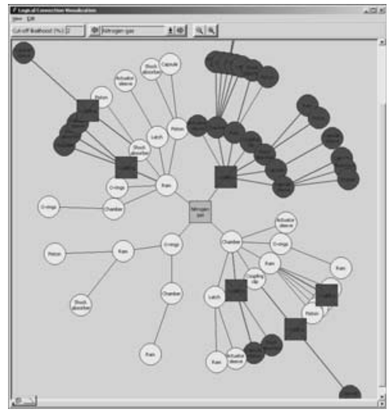
Engineering changes during the design process result in 'information deficiencies' for other development teams, whereby decisions about the product may be made without up-to-date data (Fricke *et al.*, 2000). This situation is increasingly common with the compressed development schedules that are now required in most markets.

Changes can propagate, *i.e.* a change can spread from the initially affected component or system to impact upon other parts of the product. The change can also spread to other products (for example, other members of the product family), processes (for example, manufacturing) and businesses (for example, suppliers, partners, *etc.*). Terwiesch and Loch (1999) have identified three key couplings that can lead to propagation:

- between components and manufacturing;
- between components within the same subsystem;
- between components in different subsystems.

Two other authors (Fricke *et al.*, 2000; Eckert *et al.*, 2004) have identified propagation as a key potential impact of implementing an engineering change. In particular, Eckert *et al.* (2004) have identified two different types of propagation event (see Figure 10.8):

- *Ending change propagation* – consists of *ripples* of change, a small and quickly decreasing volume of changes, and *blossoms*, a high number of changes that are nonetheless brought to a conclusion within the expected timeframe.
- *Unending change propagation* – 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. Fricke *et al.* (2000) also talk of an avalanche of engineering change, whilst Terwiesch and Loch (1999) refer to 'a snowball effect'.



10.7 Changes may propagate via a number of different routes from an initiating change to an affected sub-system

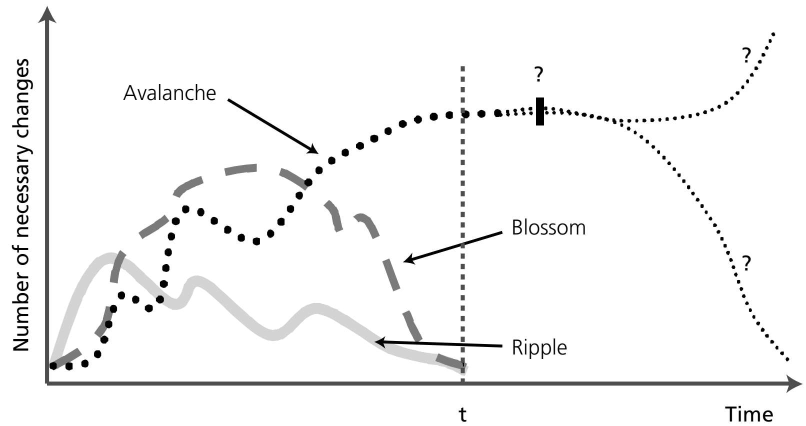
Product architectures and change

How change affects a product is fundamentally linked to the product architecture, which is defined as:

(1) *the arrangement of functional elements;*
(2) *the mapping from functional elements to physical components; and*
(3) *the specification of interfaces among the interacting physical components.*

(Ulrich, 1995)

Changes can propagate, *i.e.* a change can spread from the initially affected component or system to impact upon other parts of the product.



10.8 Types of change propagation (Eckert *et al*., 2004)
© Springer-Verlag

There are two main types of product architecture:

- *Modular* – where each physical component of the product carries out only one element in the function structure and the interfaces between the components are decoupled – two components are said to have a coupled interface if a change to one causes a change to the other;
- *Integrated* – where each physical component carries out more than one functional element – this is termed function sharing (Ulrich and Seering, 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 subsystems that are modular in the way that they link together, but each one is highly integrated. For example, when considering a car, the radio can be considered as modular in relation to the rest of the vehicle, but when examined in isolation it is extremely integrated with high connectivity between components.

There are cost implications associated with product architecture. Without function sharing, many items, e.g. cars, would become prohibitively expensive (Ulrich and Seering, 1990). Modular designs generally cost more to manufacture and assemble than integrated ones, and this is why most mass-produced products, e.g. white goods, possess an integrated architecture. However, savings are possible through modularisation when a particular subassembly can be used on a variety of products.

It must be noted that few products are truly modular, especially as the complexity of the device increases. A good example comes from the automotive industry, where the same engine is used in a variety of car types.

Although it may appear a simple process of inserting a new module, actually the process requires a great deal of adaptive work; often this is to make the engine fit into the slightly different space offered by the new automobile. Successful modularisation allows the possibility of mass customisation, where individual products are tailored to individual customers.

Mass customisation

The assumption has always been that increased variety equates to increased costs for the manufacturer, but this is being challenged by concepts such as mass customisation (Pine, 1992). Three factors are making mass customisation possible:

- The designing of products with variety in mind (e.g. Martin and Ishii (2002)).
- Having flexible manufacturing facilities based on intelligent automated plant – for example, advances in rapid manufacturing mean that batch sizes as low as one are now economically feasible (Burton, 2003);
- Having the capability for effective and efficient product change.

Here an understanding of change propagation is critical if product architectures are to be developed that enable economic mass customisation. Early identification of those parts of a product that can vary, and those that must be kept unchanged, reduces the possibility of change avalanches (or blossoms) during customisation. Conversely, the limits of mass customisation may be set through consideration of the likely changes required.

The assumption has always been that increased variety equates to increased costs for the manufacturer, but this is being challenged by concepts such as mass customisation.

Modularity

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 (Baldwin and Clark, 1997). Nowhere has this been more apparent than in the personal computer industry.

A linked trend is the concept of platform development, which is now seen widely within the automobile business. A platform is defined as:

> *a relatively large set of product components that are physically connected as a stable sub-assembly and are common to different final models*
>
> (Muffatto, 1999)

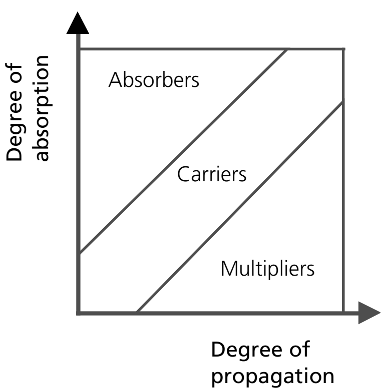
The main advantages of following a platform strategy are that it can lead to reduced production costs and, perhaps more importantly, it allows for delayed product differentiation, which enables producers to meet the requirements of increasingly demanding customers more efficiently (Lee and Tang, 1997).

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 magnitude of the change issue will increase dramatically. Lindemann *et al.* (1998) 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.

Components and change

Successful mass customisation and modularity rely on the designer's ability to minimise the changes required to modify a product. In turn, the level of change required is defined by the architecture of the product and the ability of the parts of the product to 'absorb' change. Hence, a product's components or subsystems may be categorised into three approximate types with regard to their change properties (Eckert *et al.*, 2001):

- *Absorbers*. These can be either 'partial' or 'total', where a total absorber causes no further change whilst accommodating a number of changes (a rare situation), and a partial absorber contains many changes and passes on only a few.
- *Carriers*. These neither reduce nor add to the change problem – they merely transfer the change from one component to another.
- *Multipliers*. These expand the change problem making the situation more complex – such components may lead to an 'avalanche' of change.



10.9 Component change properties (Eckert *et al.*, 2004)
© Springer-Verlag

These categories are illustrated in Figure 10.9. 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. Two factors affect whether a change can be absorbed (Eckert *et al.*, 2001): the initial specification of the component and the tolerances designed into it. When reporting on the specific case of helicopter design, they comment:

> *the designers observed typically added a 25% safety margin to the specification of many components, which was gradually used as the design was put together.*
>
> (Eckert *et al.*, 2001)

Once the safety tolerances are all used up, the component will switch to being a carrier or multiplier. Successful design under these conditions requires the use of a robust design change process.

Strategies and methods to cope with engineering change

Engineering change will always be associated with engineering products. Equally, such change is likely to cause major upheavals during design and manufacture. As a result, many authors (e.g. Nichols, 1990; Terwiesch and Loch, 1999) have suggested strategies to cope with it. These help to reduce some of the negative aspects whilst maximising the positive. The most comprehensive list is from Fricke *et al.* (2000), who suggest five:

- prevention;
- front loading;
- effectiveness;
- efficiency;
- learning.

Before examining each of these strategies in detail, it is worth quoting a passage from Clark and Fujimoto's (1991) examination of the automotive industry. One aspect they identified that differentiated Japanese firms from their Western counterparts was how engineering changes were handled. Although the past decade has seen huge changes and consolidation in this industry (especially in North America and Europe), it is still worth quoting, as it covers all the main issues involved in the successful handling of engineering changes.

Strategies to cope with change include:
• prevention;
• front-loading;
• effectiveness;
• efficiency;
• learning.
(Fricke at al., 2000)

> *…the typical Japanese project has almost as many changes as its Western counterpart. The differences in approach lie not in numbers, but in patterns and content. Procedures are less bureaucratic and orientated more towards fast implementation than towards checks and balances. In effect this approach emphasises early versus late, meaningful versus unnecessary and fast versus slow. Engineers make changes earlier, when the cost of change and time pressure are still relatively low. They reduce the number of changes due to careless mistakes and poor communication so that changes that are made add value to the product.*
> (Clark and Fujimoto, 1991)

"The typical Japanese project has almost as many changes as its Western counterpart."
(Clark and Fujimoto, 1991)

Prevention

This strategy aims to reduce (or eliminate) the number of emergent changes that occur. Saeed *et al.* (1993) found that changes to correct errors accounted for 58% of engineering changes in the company they studied. However, examination of the sources of error in the design process in three aerospace companies found that it was difficult, if not impossible, to clearly identify the point of introduction of an error (Cooke *et al*., 2002). In all the cases examined:

> *the one common theme was the failure to correctly identify when the uncertainty in the design was becoming unacceptably large so that high levels of risk were introduced into the project.*
>
> *Ignorance of the limits of one's own knowledge is perhaps the most dangerous [factor] of all*
>
> (Cooke *et al*., 2002)

"Ignorance of the limits of one's own knowledge is perhaps the most dangerous [factor] of all."
(Cooke *et al*., 2002)

Initiated changes, which enhance the product or its production, are important and "efforts to eliminate them entirely are both undesirable and unrealistic" (Clark and Fujimoto, 1991). Smith and Reinerstein (1998) state that early freezing of the design specification is a 'foolhardy' method of reducing errors, as this does not fit with reality; the initial specification is rarely accurate and the market may alter during development.

A more sensible approach would be to reduce unnecessary specifications and focus on the core customer requirements. Techniques such as quality function deployment (Otto and Wood, 2001) and the separation of technology development from product development (as proposed by Clausing (1994)) are recommended to achieve this (Fricke *et al*., 2000).

Front loading

This strategy is proposed by a number of other authors (e.g. Nichols, 1990; Lindemann and Reichwald, 1998; Terwiesch and Loch, 1999). Early detection of required changes will result in a lower overall impact and cost, as discussed above (*i.e.* with the 'Rule of 10'). Good concurrent engineering practice, such as early involvement of suppliers and customers, coupled with techniques such as "failure mode and effects analysis" and "design for manufacture and assembly" will help bring changes forward in the design process.

Fricke *et al*. (2000) discuss in detail the front loading strategy. Although much literature promotes it, certain markets are changing so fast that following this strategy dogmatically could lead to companies losing out to their competitors by not reacting to customer wishes. Fricke *et al*. (2000)

conclude that the 'Rule of 10' must be broken and they propose Design For Changeability as a means to do this by moving away from 'single-point design'. At the heart of their proposal are the concepts of flexibility, agility, robustness and adaptability.

10.10 Effective change can contribute to commercial success
© AgustaWestland

Effectiveness

This strategy emphasises the making of effective 'effort versus benefit' analysis for each proposed change. Not all engineering changes are immediate or mandatory, as described above; in the study of Fricke *et al.* (2000) only 40–60% of changes were technically necessary. It is essential for engineers and managers to differentiate between the meaningful and meaningless, but the study showed that assessments of "possible effects of changes and the evaluation of change requests are mostly based on the experience and knowledge of the employees" (Fricke *et al.*, 2000).

Avoiding unnecessary changes, by getting the initial release right, is one of Terwiesh and Loch's (1999) four principles of change management. Analysing the effects of historic changes could be used as a method to support current change evaluation, but none of the companies surveyed by Fricke *et al.* (2000) did this.

Efficiency

Essential changes should be implemented as efficiently as possible by making best use of resources such as time and money. Essential changes should be communicated as soon as possible to all affected people and sections. Although change processes may be standardised (due to ISO 9000, *etc.*), this is not optimal for all kinds of changes; flexibility is needed. The reality of the situation is that people will often go out of process in order to improve the speed of implementation (Fricke *et al.*, 2000). They also highlight the impact of architecture on efficiency:

> *the design of the product, requirements and process, or the design of the entire project, should be of a kind that changes can be realised easily. Unfortunately, most companies focus only, if at all, on improving the administrative change process*
>
> (Fricke *et al.*, 2000)

Ways of speeding up the change process have been proposed by several authors. For example, Loch and Terwiesch (1999) examined and proposed methods of removing bottlenecks in the process.

"The design of the product, requirements and process, or the design of the entire project, should be of a kind that changes can be realised easily. Unfortunately, most companies focus only, if at all, on improving the administrative change process."
(Fricke *et al.*, 2000)

Reviewing and critiquing engineering changes offers a chance to improve the design of a product, the product design process and the engineering change process.

Learning

Reviewing and critiquing engineering changes offers a chance to improve the design of a product, the product design process and the engineering change process. However, few companies actually carry out consistent, continuous analysis (Fricke *et al.*, 2000). Another aspect of such a review process is increased awareness of the importance of engineering change and the issues amongst employees that affect it. A review and critiquing process, in a company studied by Fricke *et al.* (2000), led to a significant reduction in the average number of changes per item. Linked to this, the visibility of the engineering change process and employees' understanding of it are vital for success. However, Saeed *et al.* (1993) found that the process was very complex and few people understood it well.

Conclusions

Engineering changes allow companies to enhance and adapt their products, and to remove errors from them. Changes are a fact of life for all companies that design and manufacture products and they are a topic that is growing in importance as product lifecycles shorten and markets fragment. The engineering change process is a vital part of any product's life and it links into all the major business functions, such as manufacturing, purchasing, marketing and aftersales support.

The impacts of making changes to products can be surprising; occasionally, dramatic propagation from the initially affected component or system can occur. A key factor in whether propagation takes place is the product architecture and the interactions between components and systems. Careful design of the architecture can help minimise the negative effects of change and also allow for more product flexibility, which can be used to follow a business strategy such as mass customisation.

This chapter has highlighted five strategies to improve the handling of engineering changes. By both appreciating the importance of change and efficiently and effectively managing the process of making alterations to products, companies can gain a significant advantage over their rivals.

References

Anderson DM (1997) Agile product development for mass customisation. Irwin Professional Publishing

ANSI/EIA (1997) ANSI/EIA 649: national consensus standard for configuration management. American National Standards Institute

Baldwin CY, Clark KB (1997) Managing in an age of modularity. Harvard Business Review, 75(5): 84–93
Boznak RG (1993) Competitive product development: a quality approach to succeeding in the 90s and beyond. ASQC Quality Press
Bucciarelli LL (1994) Designing engineers. MIT Press
Burton M (2003) Design for rapid manufacture. Presentation given at Process/Design Improvement Workshop. Loughborough University
Clark KB, Fujimoto T (1991) Product development performance: strategy, organization and management in the world auto industry. Harvard Business School Press
Clausing D (1994) Total quality development. ASME Press
Cooke JA, McMahon C, North MR (2002) Sources of error in the design process. IDMME'02, Clermont-Ferrand, France
Coughlan PD (1992) Engineering change and manufacturing engineering deployment. In: Integrating design and manufacturing for competitive advantage. Oxford University Press
Cross N (1989) Engineering design methods. John Wiley
Dale BG (1982) The management of engineering change procedure. Engineering Management International, 1(3): 201–208
DiPrima MR (1982) Engineering change control and implementation considerations. Production and Inventory Management, 23(1): 81–87
Eckert CM, Zanker W, Clarkson PJ (2001) Aspects of a better understanding of changes. ICED'01, Glasgow, UK
Eckert CM, Clarkson PJ, Zanker W (2004) Change and customisation in complex engineering domains. Research in Engineering Design, 15(1): 1–21.(Pages 13, 17 and Figures 13,17)
Fricke E, Gebhard B, Negele H, Igenbergs E (2000) Coping with changes: causes, findings and strategies. Systems Engineering, 3(4): 169–179
Huang GQ, Johnstone G (1995) CMCEA: change mode, cause and effects analysis – a concurrent engineering approach to cost-effective management of product design changes. ICED'95, Praha, Czech Republic
Huang GQ, Mak KL (1998) Computer aids for engineering change control. Journal of Materials Processing Technology, 76: 187–191
Huang GQ, Mak KL (1999) Current practices of engineering change management in UK manufacturing industries. International Journal of Operations and Production Management, 19(1): 21–37

Inness J (1994) Achieving successful product change. Financial Times/ Pitman Publishing
ISO (1995) ISO 10007 quality management – guidelines for configuration management. International Organisation for Standardisation
ISO (2000) ISO 9001 quality management systems – requirements. International Organisation for Standardisation
Jarratt T, Eckert CM, Clarkson PJ (2003) A taxonomy of change. Technical Report CUED/C-EDC/TR123, University of Cambridge
Kettinger WJ, Teng JTC, Guha S (1997) Business process change: a study of methodologies, techniques and tools. MIS Quarterly, 21(1): 55–80
Lee HL, Tang CS (1997) Modelling the costs and benefits of delayed product differentiation. Management Science, 43(1): 40–53
Leech DJ, Turner BT (1985) Engineering design for profit. Chichester
Lindemann U, Reichwald R (1998) Integriertes Änderungsmanagement. Springer
Lindemann U, Kleedorfer R, Gerst M (1998) The development department and engineering change management. In: Designers: the key to successful product development. Springer
Loch CH, Terwiesch C (1999) Accelerating the process of engineering change orders: capacity and congestion effects. Journal of Product Innovation Management, 16(2): 145–159
Lyon DD (2001) Practical CM – best configuration management practices. Butterworth-Heinemann
Martin MV, Ishii K (2002) Design for variety: developing standardised and modularised product platform architectures. Research in Engineering Design, 13(4): 213–235
Maull R, Hughes D, Bennett J (1992) The role of the bill-of-materials as a CAD/CAPM interface and the key importance of engineering change control. Computing and Control Engineering Journal, 3(2): 63–70
Monahan RE (1995) Engineering documentation control practices and procedures. Marcel Dekker
Muffatto M (1999) Platform strategies in international new product development. International Journal of Operations and Production Management, 19(5/6): 449–459
Nichols K (1990) Getting engineering changes under control. Journal of Engineering Design, 1(1): 5–15
Ollinger GA, Stahovich TF (2001) Redesign IT – a constraint-based tool for managing design changes. ASME DETC'01, Pittsburgh, PA, USA

Otto K, Wood K (2001) Product design – techniques in reverse engineering and new product development. Prentice Hall

Pikosz P, Malmqvist J (1998) A comparative study of engineering change management in three Swedish engineering companies. ASME DETC'98, Atlanta, GA, USA

Pine BJ (1992) Mass customization: the new frontier in business competition. Harvard Business School Press

Rivière A, Dacunha C, Tollenaere M (2002) Performances in engineering change management. IDMME'02, Clermont-Ferrand, France

Saeed BI, Bowen DM, Sohoni VS (1993) Avoiding engineering changes through focused manufacturing knowledge. IEEE Transactions on Engineering Management, 40(1): 54–59

Smith PG, Reinersten DG (1998) Developing products in half the time. John Wiley

Terwiesch C, Loch CH (1999) Managing the process of engineering change orders: the case of the climate control system in automobile development. Journal of Product Innovation Management, 16(2): 160–172

Ulrich KT (1995) The role of product architecture in the manufacturing firm. Research Policy, 24: 419–440

Ulrich KT, Eppinger SD (2003) Product design and development. McGraw-Hill

Ulrich KT, Seering WP (1990) Functional sharing in mechanical design. Design Studies, 11(4): 223–234

Wright IC (1997) A review of research into engineering change management: implications for product design. Design Studies, 18: 33–42