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Engineering change: an overview and perspective on the literature

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Abstract Engineering change has grown steadily in prominence both as an important issue for industry and as an active academic research area. This paper provides a categorised overview and perspective on the published academic literature on engineering change. The aim is to give new researchers an understanding of the field's breadth and depth, as well as pointers towards additional information, and established researchers a non-dogmatic summary perspective on the work accomplished in this area. Change is defined as an alteration made to parts, drawings or software that have already been released during the product design process and life cycle, regardless of the scale or the type of the change. A change may encompass any modification to the form, fit and/or function of the product as a whole or in part, and may alter the interactions and dependencies of the constituent elements of the product. Key aspects of the engineering change process are highlighted along with the tools and methods that are available to support the process. The nature of products (in terms of complexity, architecture and degree of innovation) and how that affects engineering change are covered. Important related areas such as organisational structure and employee attitudes are also highlighted. The paper concludes by discussing different strategies that have been proposed to cope with engineering change in today's manufacturing environment.

Keywords Engineering change · Product development · Design management

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1 Introduction

To reduce risk and cost in the design of engineering products, many, perhaps even most, companies design new products by adaptation from existing products [Cross 1989], making engineering change an extremely important topic in industry. However, academic design literature [e.g. Pahl and Beitz (1996); Otto and Wood (2001); Ulrich and Eppinger (2008) and most of Cross (1989)] for a long time placed a great emphasis on the design of novel products (Wright et al. 2000), with design reuse coming into its own around the turn of the millennium and appearing more frequently in the literature ever since. In recent years, the topic of engineering change has gained increasing popularity with the rise of concepts, such as concurrent engineering, simultaneous design, and product platform design, plus the influence of business disciplines such as configuration management.

This paper focuses specifically on *engineering change*, defined as changes to parts, drawings or software that have already been released during the product design process, regardless of the scale of the change. This can range from small changes to a single component to big changes, with knock-on effects across the entire product. Changes can occur throughout the design life cycle from when the first partial designs are released to later modification to products in service. This is a broad viewpoint on change, where the emphasis is on returning to revisit an aspect of a design or the whole design, which was previously considered finished regardless of when this happens. This contrasts change to many forms of iteration, where aspects of a design are worked on repeatedly and routinely, without designers assuming that they had finished with it (Wynn et al. 2007). This paper takes an engineering design perspective and concentrates upon change as a technical activity carried out by engineers, rather than the logistical aspects of change processes, which are more considered with achieving a smooth document workflow, or the product data management side of change. This paper is not concerned with issues of technology change (i.e. the invention and diffusion of new technologies or processes) nor with organisational change (i.e. structural and process alterations in organisations, frequently arising from mergers, downsizing, etc.) General principles of engineering design or design management are extremely important in the successful execution of a change, but will not be discussed explicitly in this paper.

As Boznak (1993) notes, engineering change and its management is inexorably linked to the concept of continuous product improvement. Engineering change is both an opportunity and a burden for companies, however. Acar et al.'s (1998) survey, which examined UK firms in the mid-1990s highlighted that over 50% of the companies investigated, which both designed and manufactured products, regarded engineering changes as a major source of problems in their product development process, yet more than 60% felt that "it was possible for a well-managed EC [engineering change] process to provide a framework for improved product innovation." A study by the Aberdeen-Group (Brown 2006) showed that the majority of changes—although necessary for innovation—cause "scrap, wasted inventory, and disruption to supply and manufacturing". Of the companies they studied, 82% put emphasis on increasing the product revenue, which leads to innovation and in turn to the introduction of changes to the product, yet only 11% of all companies were able to assess the impact of a change on a product properly and were able to "provide a precise list of items affected by a change", whilst only 12% were able to assess the consequences of changes on the life cycle of the product. A survey of 50 German manufacturing companies carried out by the Technical University of Munich (Deubzer et al. 2005), which supports these findings, point out that 56% of all changes made to a design happen after the initial design phase and of these, 39% are said to be avoidable. This shows a clear need for tools and techniques to manage and predict change, which is being recognised more and more in industry and academia.

When Wright (1997) conducted a survey on engineering change management literature published between 1980 and 1995, he initially found only 15 "core" papers (eight further articles were discovered after analysing the citations in the core group). Since Wright's review the amount of published work has risen steadily and significantly across the set of topics that form engineering change research. The purpose of this paper is to provide an up-to-date review of the field by highlighting the key engineering change articles and examining the key themes.

1.1 An overview of engineering change research

Engineering change was, historically, seen by the design community as the responsibility of manufacturing research groups and any changes made to a product during design were regarded as normal iterations of the design process. Early researchers in the field mainly focused on how engineering change affects specific business processes such as manufacturing (Coughlan 1992), Material Requirements Planning (MRP) systems (Ho 1994), Manufacturing Resource Planning (MRP II) systems, and logistics (Wänström et al. 2001). Often engineering change was at the heart of a piece of research, but the authors choose to focus on other aspects of the work, for example the "Design for Variety" research (Martin and Ishii 2002) or design for changeability (Fricke et al. 2000; Fricke and Schulz 2005).

Apart from journal or conference papers, engineering change has featured in a few book chapters (see Leech and Turner 1985; Boznak 1993; Huang and Mak 2003). However, hardly any complete books have been devoted to the topic. One of the most detailed studies was carried out by the Technical University of Munich (Lindemann and Reichwald 1998), but only a little of this work has been published in English (Lindemann et al. 1998). One of the few books in English on the subject of engineering change is by Inness (1994). It is thorough in most areas and covers many of the key engineering change topics such as change planning, but it is incredibly hard to locate and has been out of print for many years. Monahan (1995) is occasionally referred to by authors working on engineering change (e.g. by Huang and Mak 2003). This is a detailed book, but the focus is on document control and the bureaucracy of Configuration Management; product issues are ignored.

1.2 Categorising engineering change literature

Engineering change can be tackled and understood from a number of different perspectives, which are reflected in the literature. The main categories are a process perspective, a tool perspective and a product perspective. In practice, these perspectives are difficult to separate so that many papers contribute to the discussions in more than one area. Nevertheless, these perspectives provide the structure for this paper.

Some authors are concerned with a general characterisation of engineering change, defining engineering change, placing it in the context of other related activities such as configuration management and outlining generic processes for engineering change, which will be discussed in Sect. 2. Others consider the specific nature of change processes, such as discussions on the nature of change propagation, and the challenges that arise from these, as summarised in Sect. 3. These insights have led to a number of tools that were developed to address the needs of designers in change processes, which will be introduced in Sect. 4. Engineering change can also be tackled by making the product easier to change or more resistant to change. Product focused research in engineering change will be addressed in Sect. 5. Finally, some authors bridge the product or process focus by providing general strategies and methods to cope with engineering changes, as discussed in Sect. 6.

2 An overview of engineering change

Engineering change must be distinguished from the general concept of change in a business or organisational context. Change management is a term that is common in management and business literature, especially with regard to Business Process Re-engineering (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 refers to making alterations to a product and Engineering Change Management to the organising and controlling of this process. These latter two terms are often used interchangeably according to the focus of the researcher.

2.1 Defining engineering change

It is important to establish what is meant by an "engineering change" (the required redesign) or an "engineering change order" (the directive to make the required change). 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. Other authors use slightly differing terms such as a "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 examination of these articles indicates that all of the authors are referring to the same phenomenon. Throughout this paper, the term engineering change is used.

There are subtle differences in the definitions which have been made in the literature. Three definitions 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)

There are issues with the coverage of each of these definitions. Wright's (1997) definition restricts engineering change to the production stage, and so ignores the whole range of alterations that can occur during the design and development of a product. This approach creates an artificial division between engineering change and "normal" product design and development work. Huang and Mak (1999) define the scope of the change, but do not comment on the timing when a change occurs. The Terwiesch and Loch (1999) definition introduces software, which is a vital part of most modern complex products, into the scope of engineering change as well as the idea, that a change occurs once a part, drawing or software has been released and thus handed over. It indicates that a key difference between change and many other forms of iteration (Wynn et al. 2007) is that change is an active revisiting of a task that has been considered completed. A weakness of the Terwiesch and Loch (1999) definition is its conflation of the change and the directive to make the change.

None of the definitions 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. Based on Terwiesch and Loch (1999), Jarratt et al. (2004a) provide a more complete definition, which is adopted in this paper.

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

2.2 Engineering change in the product life cycle

Engineering change occurs throughout the entire product life cycle from the time a concept is selected to when a product finally goes out of service, even though activity varies significantly depending upon which phase of its life cycle a product is in. Change activities are also at the heart of maintaining, upgrading and ultimately replacing complex long-life products; however, this is not the focus of this paper.

Companies will often use different terminology to describe the change processes that occur at various points in the product life cycle and employ different teams to carry out the change. For example, one company uses the following terms through the engineering design process: Simultaneous Engineering Amendment, Prototype Alteration and Design Change (Jarratt 2004). These processes are similar, but the level of formality increases as more internal (other functions e.g. manufacturing) and external elements (e.g. suppliers) become involved in the product as the design progresses. Although different terminology is used, the basic engineering change process is the same. However, differences become apparent in the detail of each stage of the engineering change process depending upon when in the product life cycle the change process is triggered.

2.3 The engineering change process

Most authors refer to the engineering change process, but only a few actually outline the elements or phases within it. Perhaps the clearest overview 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".

There are two types of change process in existence in companies: official and unofficial. The majority of the engineering change processes suggested in literature and used in industry can be seen as official or formal ones. They contain the same ideas/themes irrespective of the company or product involved, and this is because the proposed processes are similar at the macro level. Pikosz and Malmqvist (1998) investigated the engineering change processes in three Swedish engineering companies. They discovered that whilst similar tasks may be performed at a high level, organisational, market and product issues lead to significant differences when the processes are investigated at greater detail. For example, if the company produces a safety–critical product, the engineering change process is much more focused on quality than on speed or low costs.

Unofficial processes have been highlighted. Eckert et al. (2004) observed design in the aerospace industry and identified a "backwards patching/debugging redesign" change process (in the pre-certification phases of design), where designers attempted to fix a problem quickly. This was a semi-formal rather than a formal change process. Administrative and paperwork issues were usually cleared up towards the end of the process. Engineers at another company visited by the first author have discussed leaving the formal change process in order to be able to implement a required change within a tight time frame (Jarratt 2004). As Chinn and Madey (2000) point out one challenge of carrying out engineering change processes in the right time frame is to organise the workflow of multiple changes coming through.

2.3.1 A generic engineering change process

Different authors have proposed distinct engineering change processes. They split the process into different numbers of elements or phases. For example, Dale (1982) proposed a formal process split into two phases, whereas Maull et al. (1992) suggested a process made up of five parts. A comprehensive six-step process has been suggested by Jarratt et al. (2004a). This is shown in Fig. 1.

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 into 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 due to 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: e.g. 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 potential for disruption there is.
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

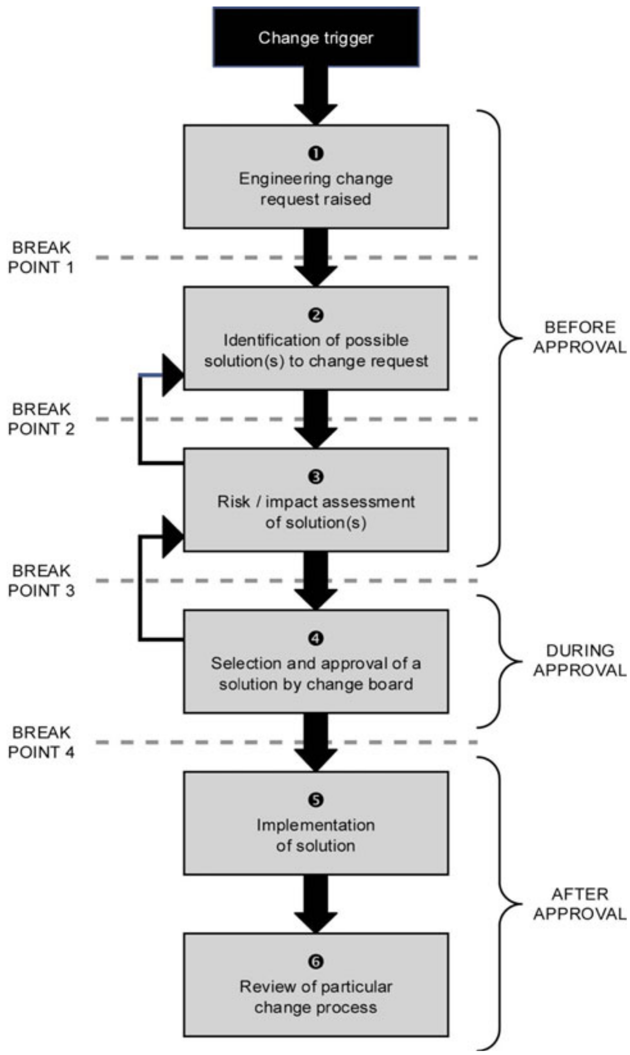

Fig. 1 A model of a generic change process from Jarratt et al. (2004a)

each change, making a cost benefit analysis for the company as a whole and then grants 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: e.g. 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 change can either occur immediately or be phased in. Which option is followed will depend upon various factors such as the nature of the change (e.g. if it is a safety issue, then immediate implementation must occur) and when during the product life cycle the change is occurring. Paper work must also be updated. “One of the major problems frequently associated with EC 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 learned for future change process. This aspect is emphasised by DiPrima (1982). The review should examine whether the product and associated processes (e.g. manufacturing) are functioning as expected. Often surprises can be discovered, for example, more obsolete stock than originally accounted for. Not all companies carry out such a review process properly.

There are possible iterations within the process, two of which are marked by arrows in Fig. 1. For example, a particular solution may be too risky for the company to implement and so the process will return to Phase 2 so that other possible solutions can be identified. At the approval stage, the Engineering Change Board may feel that more risk analysis is required (maybe in the form of more testing) and so the process will return to Phase 3. There are other possible iterative loops, but they are not marked for sake of clarity. The most extreme loop would be when, if during the review phase, it was realised that the implemented solution had been ineffectual or made matters worse. In such a circumstance, the process would return to the start with a new change request being raised.

There are four break points in the engineering change process shown in Fig. 1. 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. Break point 4 is typically the juncture where an Engineering Change Order will be issued if the Engineering Change Board has approved a change and an appropriate higher authority in the organization has authorised the Board’s decision. In some companies, it is possible for a senior executive to overrule the Board at this point.

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 learned. Only those changes that actually provide an overall benefit to the business should be allowed to proceed to the end of the process. The benefit cannot always be measured in terms of money, for example, a change might have to be implemented to maintain the goodwill of a key customer. Sometimes, there is no choice if the change is 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. It is vitally important to differentiate between meaningful and meaningless changes (Clark and Fujimoto 1991).

2.3.2 *Engineering change process documentation terminology*

Several terms are used by different authors and companies to describe the documentation (paper and electronic) that accompanies the engineering change process. These documents have titles such as Engineering Change Request (ECR), Engineering Change Notice (ECN), Engineering Change Order (ECO) and Engineering Change Proposal (ECP). As with the definitions and processes discussed earlier, there is some discrepancy 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; Loch and Terwiesch (1999) do not make this distinction. Definitions of these two groups are (taken from Monahan 1995):

- Engineering Change Request form—"a form available to any employee used to describe a proposed change or problem which may exist in a given product"
- Engineering Change Order form—"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"

Supporting the administration of the paper flow of change management has attracted considerable interest from the information system community, e.g. Borgman et al. (2005).

2.4 Engineering change and configuration management

The close 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 2003) and ISO 9001 (ISO 2008), which demand clearly documented processes for all key business activities. According to the still current IEEE-Std-610.12-1990 (IEEE 1990), Configuration Management is "a discipline applying technical and administrative direction and surveillance to identify and document the functional and physical characteristics of a configuration item, control changes to those characteristics, record and report change processing and implementation status, and verify compliance with specified requirements", where the item may be software or more generally a system. In software design, the term configuration management is used to describe most change-related activities (Bersoff et al. 1980); however, in engineering design a narrower view is sometimes taken focusing on making sure that the different configurations offered by option packages are internally consistent (Jarratt 2004). 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).

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 inter-related, they are not the same. Firms producing products of low complexity do not require a procedure as complicated as Configuration Management.

3 The nature of the engineering change process

This section will discuss the key aspects of engineering design change processes. Many of these insights are based on empirical studies of design processes through surveys and case studies.

3.1 Reasons for triggering the engineering change process

A great many authors have put forward reasons for or causes of change (e.g. Pikosz and Malmqvist 1998; Dale 1982; Fricke et al. 2000; Saeed et al. 1993; Rivière et al. 2002; Hsu 1999). The most comprehensive (albeit unstructured) list is by Inness (1994).

At a fundamental level, there are only two reasons to change a product: (1) to remove mistakes or make it work properly or (2) improve or enhance or adapt it. Eckert et al. (2004) took this approach when examining the origins of change. They categorised instigating changes, i.e. those that start a chain of changes, as either *emergent* (coming from the product e.g. errors) or being *initiated* from outside the product (e.g. customer requests). As shall be discussed later, changes often arise from other changes—a recent study of one hundred consecutive engineering change requests identified "other design change" as the cause of 36% of the requests (Rowell et al. 2009).

3.1.1 Emergent changes

Emergent changes arise from the properties of the product itself.

- *Error correction*: mistakes made during design can be identified at any point during the development life cycle by any party involved with the product. Mistakes can range from minor drawing errors to issues that effect the fundamental operation of the product. Many problems occur during product integration.
- *Safety*: this is an issue "which respects no commercial boundary" (Inness 1994). Products must be changed if they do not meet safety requirements or are expected to kill, injure, damage property or cause commercial damage. Producers must also be aware of and take actions to limit unintended uses of their products, which may be hazardous.
- *Change of function*: this is required when the design does not satisfy its original functional requirements, for example, if the operating environment (altitude, humidity, etc.) was not accurately assessed or was expanded during the design process.
- *Product quality problems*: problems with rework and scrap can often be traced back to poor design or incorrect manufacture and assembly instructions.

Engineering changes can be raised to remove these emergent changes.

3.1.2 Initiated changes

Improvements, enhancements or adaptations of a product can take on various forms. For example, a change may be initiated to reduce the cost of the product (e.g. by component standardisation) or it may be initiated to make the product comply with the standards and laws of the territories (e.g. the European Union) into which they wish to sell. Rather than list possible reasons why such changes may be instigated, it is easier to examine the different stakeholders that might initiate change to a product.

- *Customers*: customers typically request increases in range and magnitude of performance after they have experienced the product. However, sometimes it may be more economic to postpone performance improvements to the next generation of products (Fricke et al. 2000).
- *Sales and marketing*: as well as liaising with current and potential customers, the marketing department must keep abreast of market trends and developments in rival products (e.g. fashion and styling issues). Marketing can sometimes demand that product specifications be changed to meet a particular market window of opportunity, for example, sell a slightly lower specification product to capture market share (Fricke et al. 2000) or to adapt a product designed for a specific customer for the general market, for example, the alteration of military radios for civilian uses (Inness 1994).
- *Product support*: maintenance or repair problems may require parts of a product to be altered. This is a very complex commercial issue as there are major implications. For example, with spare parts, should two sets of parts be retained or should all products in the field be altered?
- *Production*: Concurrent Engineering best practice should ensure that manufacturability is a key issue during product design, but once production starts changes can still be initiated to speed up assembly operations, clarify build instructions or remove the likelihood of mistakes such as a component being wrongly oriented.
- *Suppliers*: this issue is becoming more common as companies concentrate on their core technology and leave the development of components to other firms. Suppliers suggest changes to comply with technical standards, standardise components or alter material specifications. Problems can occur when suppliers themselves run into problems, for example, when they go out of business or have problems with their own supply chain. These are amplified by communication between purchasing and suppliers. See Rouibah and Caskey (2003) for a review of supply chain issues in change management.
- *Product engineering*: designers may identify ways (e.g. new technologies) in which the product can be enhanced to the advantage of the customer and/or the company. They can also initiate changes to make up for earlier sub-optimal design, for example, in the initial design a component may be too heavy due to bad planning of the design process leaving too little time or too little resource for that particular component. A later, initiated change can rectify the situation.
- *Company management*: often companies will have policies that initiate change, for example, firms will try to pick certain suppliers in order to reduce overall business costs. This can lead to product changes in order to comply with the initiative.
- *Legislators*: products often need to be adapted to meet new legislation or certification requirements. This can drive major product redevelopment (Jarratt et al. 2003).

Changes may also be initiated for political reasons. This is apparent in the defence industry where governments demand "offsets", that is, where portions of the product need to be produced and/or assembled in the purchasing country, when buying military equipment (Eckert et al. 2004). A series of recent studies by Ahmed and co-workers have considered the quantity and drivers of change across product life cycles for aeroengines and drilling machinery, with the findings showing a non-uniform distribution with changes in early life cycle phases being mainly driven by product improvement issues, whilst later changes mainly arise from error correction (Ahmed and Kanike 2007; Vianello and Ahmed 2008; Sudin and Ahmed 2009).

3.2 Classifying engineering change to order change execution

There are many different ways of classifying change: by purpose or origin as discussed in the previous section, or by urgency of the change or its timing in the product life cycle.

3.2.1 By urgency

DiPrima (1982) categorises engineering changes by when they should be implemented (several other authors, suggest similar classifications e.g. Maull et al. 1992):

1. *Immediate*—these must be done immediately and are typically safety or defect-related modifications, but could also include changes that must be made to maintain the goodwill of a particular customer;
2. *Mandatory*—these are required as soon as is feasible, but there is some flexibility on the timing;
3. *Convenience*—these improve the product, but are not essential and so should be incorporated whenever practicable, i.e. to upset production as little as possible.

Legislative changes are an area of growing importance. DiPrima (1982) regards them as *Immediate*, but given the relatively slow nature of legal discussion and the introduction of laws, it is probably more accurate to regard them as *Mandatory*.

3.2.2 By timing

Reidelbach (1991), in his work on long-lead time products, suggests the following engineering change (EC) classes based upon the timing of the change within the product development process:

1. *Early, low impact ECs*—generally have a low impact because the issue is addressed before release of procurement orders or design freeze;
2. *Mid-production ECs*—occur after approval of procurement orders and start of manufacturing. They can have tremendous impact to long-lead production, but if well managed these can easily be contained;
3. *Late, expedited ECs*—depending upon which subsystem is affected, these can be very damaging to the efficient delivery of the project. If the change is non-critical, the change could be made after delivery.

3.3 Effects and impacts of engineering change

The effect of making a change is one area 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. This rule has its origin in an examination of software design and development (Boehm 1981), but it is also a useful "rule-of-thumb" for engineering design (Fricke et al. 2000). Terwiesch and Loch (1999) break down the costs of engineering changes into three categories: (1) design, (2) changes in prototype tools and (3) changes in production tools. One change that they tracked in an automotive company affected production tooling and cost 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 that must be notified of a change increases dramatically. If a change is required after a product has entered service (e.g. due to the emergence of a fault), then the manufacturer may have to recall the product in order to make the necessary alteration. This is an expensive process and can have a very negative effect on a company's image and brand.

Engineering changes during the design process result in "*information deficiencies*" for other development teams so decisions are made about the product without up-to-date data (Fricke et al. 2000; Rouibah and Caskey 2003). This situation is increasingly common with the compressed development schedules that are now required in most markets.

As stated above, changes can propagate. Thus, 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 (e.g. other family members) due to common platforms, processes (e.g. manufacturing) and businesses (e.g. suppliers, partners, etc.). These problems can be amplified by difficulties in the supply chain, which can cause time delays in the delivery of component specifications or components, thus compressing already tight schedules or compromising the quality of the product.

As Williams et al. (1995) point out, the sheer number of changes and the (resulting) delay in decision-making can seriously jeopardise the success of projects.

Three key couplings have been identified that can lead to propagation (Terwiesch and Loch 1999): (1) between components and manufacturing; (2) between components within the same subsystem; and (3) components in different subsystems. Two other authors (Fricke et al. 2000; Clarkson et al. 2001) have identified propagation as a key potential impact of implementing an engineering change. Eckert et al. (2004) have identified two different types of propagation, which are illustrated in Fig. 2:

- Ending change propagation—consists 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 an expected time frame (marked by a “t” in Fig. 2);
- 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 in time. Fricke et al. (2000) also talk of an avalanche of engineering change, whilst Terwiesch and Loch (1999) refer to “a snowball effect”. As the right-hand side of Fig. 2 indicates sometimes additional resource can be put to the problem after the expected time frame so that the change can be brought to a conclusion; however, in other cases, this might not be possible at a reasonable cost and the project has to be terminated.

3.4 Efficiency of the engineering change process

There are three ways of measuring the current state of engineering change practice in a company (Huang et al. 2003): (1) number of active ECs; (2) calendar time taken to deal with an EC; (3) cost or effort (person hours) needed to process an engineering change.

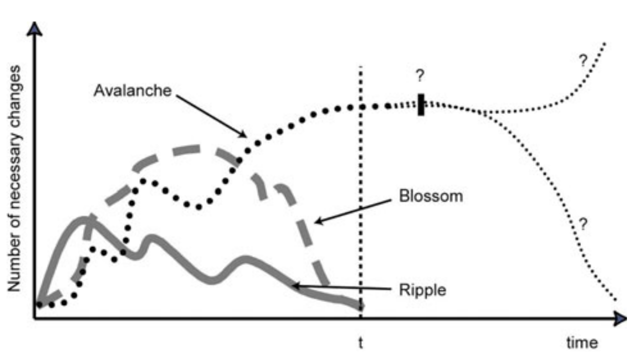

Fig. 2 Different patterns of change propagation from Eckert et al. (2004)

3.4.1 Engineering change volumes

The volume of engineering changes occurring in companies can vary significantly, depending on the product and the stage in the development process, authors have commented on companies experiencing between five and “too many to count” (Huang et al. 2003). Comment is rarely made on the severity of the changes observed and, the products involved, if mentioned, are only briefly described, doubtless for corporate confidentiality reasons. The significant differences in volumes depend upon several factors in addition to the efficiency of the company’s change process, for example, the definition of engineering change used, the point in the life cycle or design process that is examined and the complexity of the product involved, which will be discussed later in this paper.

One of the problems with having many “live” engineering changes is that engineers constantly have to switch from one to another and individuals may well be responsible for tens of changes at the same time. Loch and Terwiesch (1999) note that there is a “mental setup” time associated with each switch as the person reacquaints himself or herself with the details. The amount of set-up time will depend upon the type and size of change involved.

3.4.2 Iteration time for the engineering change process

As with change volumes, the calendar time to go through the engineering change process varies significantly. Huang et al. (2003) noted that processing time varied between 2 days and the whole life of the product (i.e. the change was never implemented). Despite strong time pressures, changes can take several months or even over a year to implement (Terwiesch and Loch 1999); for each day of processing, there were on average 2 weeks of non-value added time. Sometimes, this can lead to a situation where approved changes can fail on implementation because the system/product has altered during the time whilst the change was being resolved. This is an important issue and one that was also highlighted by Eckert et al. (2004) in their investigation of aerospace design.

The engineering change process can be extremely bureaucratic. Watts (1984) investigated and improved the process in a large electronics/IT firm. Originally, the process took 120 working days on average, of which 40 were for paperwork processing. This was reduced to 5 days. However, bureaucracy is still blamed for poor change performance, for example, over 70% of UK firms have stated that it is a key issue (Huang and Mak 1999). Because of this, a number of companies implement more rapid change processes during product development and prototype testing, for example, the company investigated by Saeed et al. (1993).

3.4.3 Cost of the engineering change process

The cost of the engineering change process can be split into tangible and intangible elements. Hours invested in a change or its financial cost can be estimated, but there are also factors that are hard to assess such as missed opportunities and customer annoyance.

In terms of effort, changes can consume a considerable amount of product engineering resource. The company examined by Saeed et al. (1993) invested approximately 4,600 person-days of effort each year in the engineering change process. Huang et al. (2003) found that the time invested in an engineering change varies from two person-days to three dozen. The financial costs can also be significant. An automotive firm investigated by Boznak (1993) spent \$41 million per year on the administrative processing of engineering changes, which averaged out to \$1,400 per change. It must be noted that none of these figures are given in context (e.g. size of company, number of products, etc.), and thus it is hard to draw absolute conclusions from them. However, they do give an indication of the significant costs of the engineering change process.

3.5 Personnel and organisational issues

Effective and efficient management of engineering change is not just a matter of technique and technology; as Inness (1994) states: "Organisational attitude to product change is the key to success."

3.5.1 Company structure and culture

One of the reasons that is often advanced to explain badly operating change processes is communication and co-ordination between design teams or groups (Fricke et al. 2000). Clark and Fujimoto (1991) state that up to two-thirds of all technical changes could be prevented by better communication and discipline (i.e. fewer errors being made). Communication failures can result in a large number of changes and also lead to increased change impacts because out-of-date data is being used by other groups as a basis for decision-making. In over 80% of UK firms, "poor communications" is seen as a barrier to effective engineering change management, whilst over 70% perceive "people indifference" and "internal departments not [being] cooperative" to be major factors too (Huang and Mak 1999).

The current promotion of flexible organisational structures within design, as seen with the concept of Concurrent Engineering, promotes improved communication, but this is not always mirrored in the operation of the engineering change process. In many companies, changes are carried out by the development team. Lindemann et al. (1998) proposed the concept of "Integrated Engineering Change Management" to improve this situation. The concept advocates the formation of "matrix teams" to overcome the interfaces between design groups in large project teams. Members of the various Concurrent Engineering product development teams are seconded to the matrix team to ensure that knowledge is much more widely shared. In this environment, engineering changes are "moderated" rather than centrally controlled. Change to products in service is mainly carried out in dedicated in-service teams. Matrix management has its own weaknesses in terms of problems arising from dual responsibility, additional time required for conflict resolution, the need for a shared understanding and collegial relationships, and the maintenance of organizational power balances (see Daft 2007). In addition, line team members can struggle to obtain resources, when they are not line managers.

Decision discipline is a key area highlighted as a cause of changes and a reason for change propagation (Fricke et al. 2000). This issue is fundamentally linked to the culture of the company or business unit. Poor decision discipline occurs when decisions are made without basis or when necessary decisions are postponed. Often decisions are made under conditions of high uncertainty; (further) engineering changes are a "logical consequence when the missing information is finally available" (Fricke et al. 2000). Three reasons have been proposed as to why necessary decisions are postponed in companies (Fricke et al. 2000):

1. People see initiating changes as unpleasant (draws attention to the initiator);
2. People waiting for other changes to occur as a cover/screen (shifting responsibility); and
3. People wanting to be seen as heroes by rescuing the project.

3.5.2 Attitudes towards engineering change

Attitudes within industry to engineering change can vary widely both between companies and within different units of the same firm. Overall, employees regard managing engineering changes as difficult, in general, "the focus of [change] thinking is on damage control rather than product improvement" (Acar et al. 1998). Inness (1994) highlighted the attitudes and drivers of several key business functions towards engineering change. The key issue is the cause or reason for the change. For example, the design team is often focused on "new" products and does not regard the implementation of engineering changes as a positive activity, especially if it is error correction. This view is supported by Pikosz and Malmqvist (1998) who noted that in the companies they surveyed, engineering change (EC) had "a lower status than… creative 'first time' design and [this] results in a negative attitude towards the EC process." Studies into helicopter design found that engineers often resented changes arising from mistakes, but quite welcomed changes that led to enhancement or adaptation, even when the tasks involved in realising those changes were very similar (Eckert et al. 2004).

From the perspective of manufacturing, inventory and production control engineering change causes delays in task completion (Hegde et al. 1992) with schedules slipping (due to machine down time, the need to redesign tooling, etc.). Obviously in this situation, alterations are regarded as disruptive to the smooth running of business processes. They are a "necessary evil" that must be addressed in order to deliver products on time (Balcerak and Dale 1992). "No matter where the request for a [change] may originate and no matter what beneficial effects may result from its incorporation, it will be disruptive to the routine process and to the normal flow of production work" (Dale 1982).

4 Engineering change and the nature of products

The previous section addressed the nature of the change process, which is deeply influenced by the product that is changed and its characteristics. The impact a change has on a product is governed by three factors: (1) the complexity of the product, (2) the architecture of the product and (3) the degree of innovation within the product.

4.1 Product complexity

It is important to establish or qualify what is meant by complexity, as it is a word that has many connotations and uses. There are multiple views on the subject, which Eckert et al. bring together in the context of change (Eckert et al. 2005). Product complexity is conceptualised in different ways. Some authors (e.g. Suh 1990; Jaynes 1957) judge the complexity of a system or entity by the amount of information inherent within it, e.g. using queuing theory (Frizelle and Suhov 2001) or in terms of the number of tasks (Eppinger et al. 1994). Other authors focus on the potentially chaotic and non-linear properties of the product, which can give some changes huge effects across the product in often hard to predict ways (see (Alligood et al. 2001) for a general introduction or Carlson and Doyle (2002) for an application to engineering). The key type of complexity from an engineering change perspective is connectivity; many authors (e.g. Johnson 1995; Sosa et al. 2007) give the linkages between elements and their interaction within a system as a measure of complexity. This is a function of the relation between the product and its description (i.e. how it is decomposed into constituent elements).

An important area of complexity research that affects design is the issue of how the description of products is broken down. Many design support tools and methodologies make the assumption that products can be decomposed into individual parts or subsystems, which in turn, can be designed or sourced in isolation. As Ariyo et al. (2007) point out, this can be very problematic. For example, an automobile can be decomposed into engine, suspension, wheels, bodywork, etc. These, in turn, can be split hierarchically into their constituent parts, for example, the engine can be broken down into the cylinder block, sump, etc. Such decomposition is possible under certain conditions and specific tasks can be undertaken on these systems or parts, pretty much in isolation. However, this is only one part of the issue as the tree structures of such breakdowns offer only a partial view of a product. Simon (1996) states that design is inherently complex, because design systems are only almost decomposable, but never fully decomposable. Whilst a hierarchical breakdown of a system provides a useful structure to conceptualise a complex problem, it hides many vital dependencies between parts and systems, and biases the design that is generated by using a certain hierarchical breakdown. This is an underlying problem with using many PDM/PLM packages to support change processes. The structure of the information is mainly constructed for the benefit of particular users or view points, when change predication needs to consider the whole spectrum.

Changes to highly coupled products (that is products with many dependencies and interactions amongst constituent elements) are much more likely to propagate than changes to relatively simple devices. With a complex product, it is much harder to control all the relevant parameters and their impacts upon each other (Fricke et al. 2000). Rouibah and Caskey (2005) focused on parameters as a means of supporting information sharing and data validity between companies for improved concurrent engineering and change management, including the capture of change propagation. As the complexity of a product rises so too do various factors such as the number of parts, cost of development and the size of the design team. For example, the number of unique parts in a screwdriver is 3, whereas the same figure for a passenger aeroplane is around 130,000 (Ulrich and Eppinger 2008).

Highly complex products go through a large number of changes between the first prototype and launch: the number for a jet engine is in the region of 3,000 (Leech and Turner 1985). The majority of complex products have long-lead-times for production and long operational lives. A consequence of this is that the manufacturer has to form a close long-term relationship with the customer (Reidelbach 1991). As stated before, changes can occur throughout a product's life cycle and as such, the problem for the firm is how to plan for engineering changes that may affect the product many years into the future. At the extreme end of the spectrum are Large Made to Order (LMTO) products (which many would consider as projects) such as oilrigs, factories and power stations, which have useful lives in the region of 30 years. When undertaking such a design project, a clear decision has to be made about how the product will be designed for the future. Three options present themselves (Barber et al. 1999):

1. Design to meet current requirements only;
2. Design to meet predicted requirements at the end of the product's life span; and
3. Design so that the product can be updated to meet future needs.

Whereas option 1 leaves no room for manoeuver, the second case is very dependent on predictions of life well into the future. Over designing a product to meet future expectations that never arise could be a costly mistake. The third option is the most attractive, but is very hard to implement successfully. Following such a route leads to an increase in the modularity of the product architecture, which may well lead to an increase in production costs due to a lessening of function sharing amongst and by components.

4.2 Product architecture

How change affects a product is fundamentally linked to the make-up 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 amongst the interacting physical components" (Ulrich 1995). There are two main types of product architecture: modular and integrated. 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.

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. By sharing components across many high volume products, an economy of scale can be achieved; and new products can be generated fast as many parts can be drawn from the platform. A review of the concepts and challenges of product platforms can be found in Simpson (2004) and Simpson et al. (2001). Whilst platforms can reduce the cost of design and production significantly, they also increase the problems with changing them. Many components are frozen and can only be changed at great cost (Eger et al. 2005) and there is a risk that changes can propagate across multiple products. A theoretical analysis by Ho and Li (1997) suggests that there may be an optimum level of component standardization, although the greatest risk of change propagation between parent and immediate child components. There is a growing recognition that product platforms themselves need to be designed by changeability in mind (de Weck and Suh 2006).

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 constituent elements. Wyatt et al. (2009) discovered that reuse requirements from the previous product generation were included as constraints into the mathematical performance models that drove the next generation of design. In their case study on automotive engines, system architecture was the emergent result of meeting performance and reuse requirements, rather than being a distinct task.

Another categorisation groups components or sub-systems into three approximate types with regards to their effect on change propagation (Eckert et al. 2004). Note that these properties change throughout the design process, as tolerance margins are used up. These categories are illustrated in Fig. 3.

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.

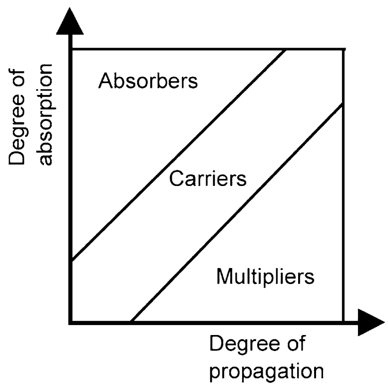

Fig. 3 Representation of the change propagation characteristics of components from Eckert et al. (2004)

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 cause an "avalanche" of changes.

An example of a helicopter subsystem that can be both an absorber and a multiplier of change is the fuselage. Many other subsystems are physically directly connected to the fuselage, and changes to these subsystems that increase their mass increase the load placed on the fuselage. Within a certain design tolerance, the fuselage is able to accommodate this increase and so acts as a change absorber. Once the increases exceed the design tolerance, then the fuselage itself must be changed with the strengthening typically increasing its weight, which has knock-on effects on the power requirements of the engine and the rotor design, probably increasing their mass, etc. Thus, the fuselage has transformed from an absorber into a change multiplier.

4.3 Degree of innovation

Changes are much more likely to occur and propagate in products that are highly innovative. This is because there is a low degree of information and knowledge with such products. A good illustration of this comes from the wrong cost estimations that are made for highly technical, innovative systems (Fricke et al. 2000).

How innovation affects product design depends upon how companies carry out research and development work, and how they manage their product portfolios (Otto and Wood 2001). Several authors (e.g. Clausing 1994) recommend decoupling innovation from product design. This policy enables components and systems to be thoroughly tested before they are transferred into commercial products. At the most extreme end of this approach are "Technology Demonstrators". For example, the Eurofighter Typhoon combat aircraft was preceded by an Experimental Aircraft Programme, which brought together in a single airframe technologies previously partially developed in isolation (Eurofighter 2004). These technologies included new lightweight materials, a co-bonded wing and an advanced cockpit. This is now being adopted in organisations under Business Process Excellence initiatives (Kirchmer 2008), where new technologies are being developed at dedicated R&D facilities or universities and only introduced into products when they have been successfully tested. However, problems can still occur when multiple new technologies are employed, which can lead to late changes in the design process (Eckert et al. 2009a).

5 Tools to support the engineering change process

Tools and methods to support the engineering change process can be divided into two groups:

(1) Those that help manage the work flow or documentation of the process and (2) those which support engineers in making decisions at a particular point in the engineering change process (e.g. the risk/impact analysis phase). Some small companies consider word-processing and spreadsheet packages as support tools (Huang and Mak 1998). Whilst these generic software tools are of some use (e.g. for the creation of change request forms or change case registers), they will not be considered further; the focus for this paper is on tools and techniques specifically developed to support engineering change management.

5.1 Work flow/documentation support

A number of authors agree that computer-based tools are essential to support engineering change management within firms (e.g. Huang and Mak 1999; Huang and Mak 2003; Lindemann et al. 1998; Kidd and Thompson 2000). Paper-based engineering change management systems are generally inefficient as only one person or group can access the data and document file at any one time; such systems become worse as the volume of engineering changes rises for a product, especially if multiple changes are being carried out simultaneously on a particular component or system (Kidd and Thompson 2000).

Computer-based systems generate electronic change request and change notice forms. Users are able to initiate a change request and have it approved electronically. Huang and Mak (1998) provide a thorough early review of the area, but as Rivière et al. (2003) note, this work needs updating to take account of the major advances in product data management (PDM) and product life-cycle management (PLM) software packages over the last decade.

Huang and Mak (1998) break computer-based tools into four categories. The first is decision support tools, which will be discussed in a later section. The other three categories relate to work flow.

1. Dedicated systems focused on engineering change management. These contain databases of engineering change activities and generate electronic change request and notification forms. Often, such systems are developed in house.
2. Computer aided Configuration Management systems. These take the form of software-based engineering change management systems and add extra functions such as product structuring and versioning. Recent developments in this area have been targeted at the software development industry (Huang and Mak 1998).
3. Product Data Management or Product Life-cycle Management systems have gained increasing prominence throughout the entire design and product life cycle [see Mesihovic et al. (2004) for a discussion of their potential]. They incorporate all of the above plus additional functions to encompass all stages of the product life cycle such as design planning. Due to the scope and size of these systems, they are almost all developed by large software houses such as Siemens (developer of the "Teamcenter" PLM suite). Such systems have many capabilities, and there is a potential to revolutionise the handling of engineering changes by incorporating elements such as decision support modules and Concurrent Engineering best practice, but as yet "the processes that have been implemented through workflow in PDM systems seem to be a copy of the old paper-based systems" (Rivière et al. 2003). Identifying potential change propagation is difficult in current PDM systems; there is a need for such systems to contain a product architecture model that is created from an engineering change perspective and can support the assessment of the impact of change (Rivière et al. 2003).

5.1.1 *Computer tool development in academic institutions*

Academic work into computer-based engineering change support tools has been published in the past few years. Chen et al. (2002) proposed a tool to support distributed engineering change management linking in with Concurrent Engineering. A standalone web-based tool for managing the engineering change process was described by the Department of Industrial and Manufacturing Systems Engineering of the University of Hong Kong (Huang and Mak 2003; Huang et al. 2001, 2000b). Ma et al. (2003) have proposed a framework for a "knowledge-supported change impact analysis system". Rivière et al. (2003) reported upon the development of an "Engineering Change Management Environment" for the better control of engineering changes in the aerospace industry. Lee et al. (2006) produced a prototype "Collaborative Environment for Engineering Change Management" combining ontology-based representations of engineering cases, case-based reasoning for retrieval, and a collaboration model, emerging from studies in an automotive factory. However, at the time of writing, none of the authors have yet described the testing, evaluation or use of these tools in a "live" industrial environment.

5.1.2 *Uptake of computer tools*

Many different packages are commercially available or developed in house, but few companies seem to be using or considering such systems. Various reasons have been proposed for this slow take up of computer-based tools (Huang and Mak 1998):

- Firms are unaware that such tools exist;
- Existing systems do not meet the user requirements;
- Available systems are too difficult and time-consuming to use;
- Systems require too much data; and
- The technology does not deliver as much as it promises.

Added to this list is the issue of companies having a general lack of understanding of how changes are connected; if the change situation is not really understood, a tool can only provide limited help.

Pikosz and Malmqvist (1998) comment that the potential benefits of computer support for engineering change processes were not fully realised by the three companies they examined. Volvo operated the most advanced system, but it was a legacy system first developed in the 1970s; new employees found it hard to use and required extensive training. At the time of publication of that article, all three companies were investing in new computer systems. The main issue they faced was whether to customise a system for their own company, which would be associated with a customising cost (potentially high) or to adapt to a standard process that may well not be optimal for their business. Kidd and Thompson (2000) reported that the Military Aircraft Division of British Aerospace (now BAE Systems) decided to write its own engineering change management software because the company felt that it would take longer to refine and adapt a commercially available package. They mention that another UK-based company, Pilkington plc., also chose to write their own software package rather than purchase a proprietary system.

5.2 Decision support

A wide variety of techniques are used by businesses to support decision-making during the engineering change process. These can be grouped as follows (Huang and Mak 1999):

- Hard technologies such as Computer Aided Design (CAD), Materials Requirements Planning (MRP) and academically developed tools;
- Soft techniques such as Failure Mode and Effect Analysis (FMEA), Design For Manufacture and Assembly (DFMA) and Value Analysis (VA).

5.2.1 Hard technologies

Decision support systems can include software such as CAD and MRP packages, which can be extended to incorporate simple engineering change management functions. MRP systems can support the phasing in of changes once they have been authorised. CAD software with error recognition can assist designers in making an initial assessment of many changes, but the drawback of such software is that it only covers the first stage of a change; propagation effects cannot be handled with such a tool. Modern CAD packages, such as CATIA, can predict the impact of changing a component by analysing the product geometry and calculating the mismatch to neighbouring components. The major drawbacks to such an approach are that they can generally only identify the immediate implications of a change rather than the consequences of change propagation and currently do not consider functional relationships. Modelling software such as Modelica (Modelica 2009) can describe the energy exchange between different subsystems in a dynamic fashion. Global behaviour can be predicted to a certain extent at the systems level, but not effects at the component level yet.

In the field of computing, a few models have been proposed to highlight change effects in evolutionary software development (e.g. Schach and Tomer 2000; Rajlich 2000). These approaches split a programme into pieces that are connected in a propagation graph, which can highlight where subsequent changes might be necessary during software redesign. Such methods cannot be easily transferred to mechanical design because the parametric links are less explicit and accurate predictions of change propagation beyond one step cannot be made.

There is currently no commercial package that helps predict the effect of a change although some work is being carried out in academic institutions. Specific tools have been proposed by researchers to help engineers with the risk/impact analysis phase of the engineering change process.

5.2.2 Academic tools and prototypes

Mokhtar and colleagues developed an information model for assisting design coordination across disciplines in the construction industry (Mokhtar et al. 1998). Their system used a central database modelling the individual components of the system as active elements which utilised linking rules to disseminate information concerning change propagation to affected components and their responsible engineers. Some of the rules were constructed in the early design phase, but the system provided the facility to dynamically generate new rules as needed by capturing them from designers following design decisions. The model was validated against a real-world case study example to prove concept. Akin to this is the work by Bouikni et al. to create a "Product Feature Evolution Validation" model to support the preservation of consistency across the product as changes occur to specific features and need to be disseminated across disciplines so that the positive or negative impact of a change can be identified—here the work focuses on mechanical engineering applications involving CAD systems (Bouikni et al. 2006, 2008).

Roser et al. (2003) have proposed an "economic design change method", which includes the effects of uncertainty in the evaluation of the economic benefits of various design change options. The method is thorough in its examination of costs, but would appear computationally complex; the only given example of its use is on redesign options for a simple fibre-reinforced I-beam.

A tool called "RedesignIT" has been reported upon by Ollinger and Stahovich (2001), which uses a product model consisting of the relevant physical quantities (e.g. oil pump power) and the causal relationships between them, to generate and evaluate proposals for redesign plans. This technique has been used to examine various redesign options for a turbocharged diesel engine. The plans generated by this technique are rather abstract in that "they specify which quantities should be changed and in which directions… [but] they do not specify numerical values for the quantities" (Ollinger and Stahovich 2001). However, by identifying the key parts of the product that will be affected, the designer can focus his or her effort.

C-FAR (Change FAvourable Representation) is a technique that has been proposed to facilitate change representation and propagation mechanisms (Cohen et al. 2000). The technique is built upon the EXPRESS information model, which is the formal information modelling language used to specify the information requirements of the STEP (Standard for the Exchange of Product) data model (Cohen and Fulton 1998). The STEP data model was created to define engineering products and support the management of engineering data. In the C-FAR technique, a product is split into its core elements that are then examined in terms of their attributes (e.g. the radius, colour and area of a plate); the interactions between the attributes are recorded in matrices, which are analysed to predict the effect ("high", "medium" or "low") of one attribute on another. A major drawback of this technique at the time of its development was its computational complexity, which made it more suitable for simple or small products, but even with modern processing power calculating the set of paths between source and target elements (which is a polynomial cost operation on the number of edges in a graph) still would impose limits on its applicability—the maximum number of edges ever used in the original work was twenty. The technique has been used to examine several industrial case studies, for example, a car bumper, a printed wiring board and an injection moulding (Cohen et al. 2000).

Another tool, called the Change Prediction Method (CPM), assists in the understanding of how changes spread through a product (Clarkson et al. 2001; Keller 2007). This approach uses a Design Structure Matrix (DSM) as the basis of the product model. The tool uses a simple model of risk, where the likelihood of a change propagating is differentiated from the impact of such an occurrence: risk is defined as the product of likelihood and impact. A product model consisting of two numerical DSMs is created, which show the likelihood and impact of change propagation occurring between directly connected components. A route counting algorithm is then used to calculate the combined risk of change propagation, which is the sum of the direct risk and indirect risk (change spreading via intermediate parts). To date, the technique has been used to examine helicopter redesign (Clarkson et al. 2001), the architecture of a railway valve (Jarratt et al. 2002), and diesel engine design (Jarratt et al. 2004b). The tool also supports the visualization of change connectivity, based on a database of historic changes (Giffin et al. 2007). The CPM approach has also been used to explore change absorbing architectures by other researchers (Oh et al. 2007) and to assist in discerning the value of change prediction in prioritizing activities in design workflows for future engineering environments (Wynn et al. 2010). Chen et al. 2007) advocate supporting redesign by using DSM analysis techniques to indentify decomposition patterns to control change propagation, in effect identifying a highly clustered part of the products within which a change requirement can be met. This approach has been refined in Li (2010). Recently, they have extended this work in Li and Chen (2010) to prepare these decompositions in advance to have them ready when a change request arrives.

Ouertani et al. (2004) suggested a distributed product model capturing product-product and product-manufacturing process interactions to encapsulate the direct dependencies. This was then linked to a constraint problem solver to extract the likely change propagation. As the authors note the approach has significant resource implications in terms of manually capturing the impacts and dependencies.

Rutka et al. (2006) reported a Change Propagation Analysis method utilizing a dependency model supporting multiple linkages between pairs of information items, where linkages varied by type and level of change at both initiator and target of change. The model is searched for matching triggers and propagation paths followed, enabling final impacts and likelihoods to be computed. The CPA approach requires even more information to populate its model and its assumptions on final change levels (use the worst case) and frozen items simply stopping a propagation path may not always hold true. The authors indicate that the method has been tested in aerospace case studies but results have yet to be reported.

Grantham-Lough et al. (2006) used prediction methods for change propagation and risk estimations based upon a functional decomposition of the product in early design stages. Their methods utilise knowledge about failures of designs in the past and assume that the behaviour of past products is sufficiently similar to current or new products to still be relevant. Their approach is based on function failures (Stone et al. 2004), which has been inspired by Failure Mode Effect Analysis (FMEA).

Reddi and Moon's (2009) approach is another dependency model technique, harvesting dependencies in the early phases of design for use in later stages of the life cycle. It captures the type of change at both initiator and target as well as the likeliness of the specific change propagating between the two in terms of discrete levels (low, medium, or high). Search algorithms iterate through the model to identify all possible propagation paths. The method requires a dynamically evolving ontology and model as it is unlikely that all dependencies and dependency types will be captured during early design.

Most recently, Kocar and Akgunduz (2010) have developed a hybrid engineering change management and virtual reality collaborative design system to create the ADVICE (Active Distributed Virtual Change Environment prototype. Engineers can raise, view and accept/reject proposed changes in a graphical visualization of the product, akin to a CAD or virtual reality view. This is coupled with a database of engineering changes, which is searched by data mining agents, both to identify prior attempts to raise the same or similar changes and to predict possible change propagation, by detecting patterns of repeated events in the change records. The tool has yet to be tested on a real-world case study and the authors suggest that they may need to adapt their algorithms to better reflect the non-ideal nature of actual change case records.

Most of the academic tools require the user to provide them with data in a suitable representation. This data preparation process can be time-consuming and deter users. The tools aim at supporting changes to a given design, but do not address the question to date of how changes would affect the design, once a previous change has been implemented. This begs the question of how long the given set of data remains valid; in some cases this can be addressed by modelling products on a suitable level of detail. For example, the CPM model of diesel engines (discussed in Jarratt et al. 2004b) is sufficiently abstract (a 20 $\times$ 20 matrix) that it covers most diesel engines; however, as changes are undertaken the probability of a change propagating would increase and the user would have to amend the model. The extent to which models, based upon generic data derived from multiple instances supplied by experts, can predict specific changes remains an open question. Some systems like C-FAR (Cohen et al. 2000) or Li and Chen's (2010) work expect the designer to anticipate changes during the design phase and feed potential change options into the system once the design is completed, but before a change is required. However, if the designers were able to anticipate changes during the design, they might also be able to make changes to the system architecture to make these changes easier. All of the systems to date deal with individual change requests, where one change is considered at a given time. In practice, often multiple changes occur at the same time, either because an Engineering Change Board bundles the changes as a result of how change processes are organised, or a customer wants multiple changes carried out at the same time. These multiple changes affect each other and can therefore amplify the effect of a change or possibly even cancel it out. Some initial work extending the CPM approach in this regard has been reported by Ahmad et al. (2010). The inability of products to accommodate new requirements through a lack of flexibility is the major source of problems in coping with engineering changes; adequate tools and techniques to assess and design appropriate flexibility in substantive components, products and platforms do not yet exist.

Although the academic tools show a diversity of approaches and potential promise, it would be equally fair to note the lack of sustained software development in most of them (most are reported once in the literature with no follow-up work appearing) and relative scarcity of industrial case studies to thoroughly test their usability and utility. This is an area where more work needs to be done to bridge the gap between academic demonstrator and industrial deployment.

5.2.3 Soft technologies

Huang and Mak (1999) found in their survey of UK manufacturing industries that 30–40% of respondents used methods such as Quality Function Deployment (QFD), Failure Mode and Effect Analysis (FMEA), Design For Manufacture and Assembly (DFMA) and Value Analysis (VA) to identify necessary engineering changes early in the process and reduce the number of emergent changes. These techniques are common and outlined in most modern engineering design textbooks (e.g. Otto and Wood 2001). Each of these techniques forces engineers and designers to think about key aspects of their products such as customer wants, manufacturability and potential failure modes. In an analysis of responses to engineering change based on two workshops on engineering change with 12 companies in Europe and the United States, Eckert et al. (2009b) reported that companies are integrating their customers early in their design processes and use QFD to build up a clear picture of their requirements to avoid late requirement changes leading to engineering change. Organisations are moving towards virtual engineering with designers using integrated models and virtual simulations throughout the process. Companies are applying a classical systems engineering V-model (as illustrated in Fig. 4) to the design of components and systems as well as the entire system, whereby components are tested virtually as soon as possible to reduce the overall risk.

In terms of soft technologies specifically aimed at assisting the evaluation of engineering changes, Huang et al. (2000a) have proposed a methodology for engineering change impact analysis. At the heart of this methodology is a worksheet that assists an engineer to assess the importance and severity of a proposed change. The methodology instructs users to investigate the impacts of any proposed change, but gives no guidance as to tools that should be used. It is not yet known whether this methodology has been evaluated in a "live" industrial setting.

6 Strategies and methods to cope with engineering change

Several authors suggest strategies to cope with or improve the handling of engineering change (Terwiesch and Loch 1999; Nichols 1990). However, before examining this area in detail, it is worth highlighting a passage from Clark and Fujimoto's examination of the World automotive industry (Clark and Fujimoto 1991). One aspect they identified that differentiated Japanese firms from their Western counterparts was how engineering changes were handled. Although the past decade and a half has seen huge changes and consolidation in this industry (especially in North America and Europe), it is still worth quoting as it clearly covers all the main issues involved with the successful handling of engineering changes.

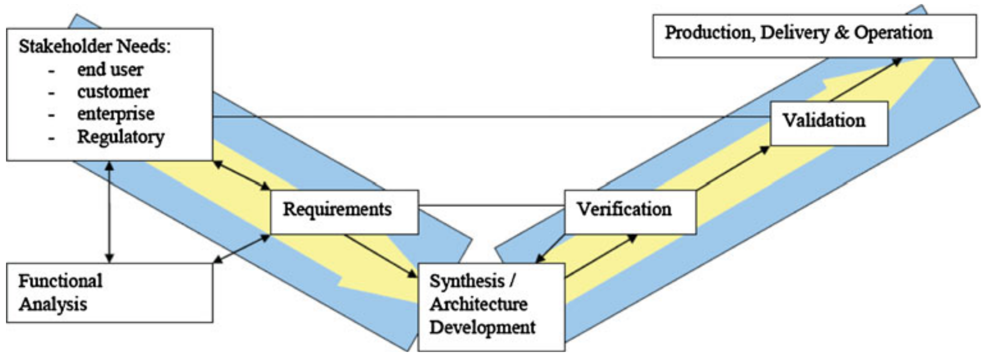

Fig. 4 Classical systems engineering V-model from Eckert et al. (2009b)

> …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 most comprehensive list of coping and improvement strategies is from Fricke et al. (2000) who suggest five.

1. Prevention aims to reduce (or eliminate) the number of emergent changes that occur in a product, which can often be the majority (e.g. Saeed et al. (1993) found that changes to correct errors accounted for 58% of all changes in the company they studied). However, avoiding errors is not a simple issue. Work examining the sources of error in the design process in three aerospace companies found that it was difficult, if not impossible to make a clear identification of the point of introduction of an error (Cooke et al. 2002). It must also be noted that not all design problems are linear so the existence of chaos in non-linear systems can mean that small changes can have a huge impact.
2. Front-loading is proposed by a number of other authors (e.g. Lindemann et al. 1998; Terwiesch and Loch 1999; Nichols 1990). Early detection of changes will result in a lower overall impact and cost as discussed earlier (i.e. with the "Rule of 10" that was discussed earlier). Good Concurrent Engineering practice, such as early involvement of suppliers and customers, 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 Ten" must be "broken" and they propose "Design For Changeability" as a means to do this by moving away from "single point design". Martin and Ishii (2002) have proposed a methodology called "Design for Variety", which could be used to reduce design effort and time-to-market for future generations of a product. By using this methodology during the conceptual design phase, a design team can identify a decoupled architecture, which will require less design effort for future generations of products. "Changeability" in terms of five quantifiable concepts of "flexibility, adaptability, scalability, modifiability, and robustness" is proposed by Ross et al. (2008) as a means of sustaining value over the life cycle of a product despite context changes. An augmented Change Modes and Effects Analysis tool has also been advanced as a means of quantifying the design flexibility of a product or a product family by identifying the number of functions in a product, mapping potential change modes to affected components, and calculating other factors such as the frequencies of changes (Keese et al. 2006)
3. Effectiveness emphasises the making of effective effort versus benefit analyses for each proposed change. Not all engineering changes are immediate or mandatory and it is essential for engineers and managers to differentiate between the meaningful and meaningless. The study of Fricke et al. (2000) showed that the assessment of "possible effects of changes and the evaluation of change requests are mostly based on the experience and knowledge of the employees". As Terwiesch and Loch (1999) note, many unnecessary changes can be avoided by getting the initial release of a product right. This is one of their four principles of change management.
4. Efficiency means that essential changes should be implemented as efficiently as possible by making best use of resources such as time and cost. 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 compliance, etc.), they are not optimal for all kinds of changes; flexibility is needed. In reality, often people will go out of process in order to improve the speed of implementation (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.

5. Learning and reviewing offers a chance to improve both the design of a product, the product design process and the engineering change process. A change is a chance to both improve the product and do things "better next time" (Fricke et al. 2000). However, few companies actually carry out consistent, continuous analysis (Fricke et al. 2000). Another aspect of this approach is the raising of awareness of the importance of engineering change and the issues that affect it amongst employees. Such an approach 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. Saeed et al. (1993) found that the process was very complex in their case study and few people understood the entire process well.

Tavčar and Duhovnik (2005) developed a questionnaire to discern the quality of an engineering change management process and in so doing enable an organization to improve their process. Their criteria included the proportion of active work in the process, the costs of the change process, and the duration of the change from initiation to close-out, as well as the tracking of changes, the opportunity to perform technical assessments and prototyping, frequency of decision points with input from affected parties to approve/reject changes, and the correctness and consistency of change implementation across production and documentation.

The results of the two change workshops, reported in Eckert et al. (2009b) show clearly that whilst there is remarkable consensus about the causes of change and the problems associated with change, the responses in how to deal with frequent changes are very diverse. Coping mechanisms ranged from agile businesses and virtual engineering to the use of QFD to avoid change and structured change processes. To date, there is no consensus on how engineering changes can be handled most effectively and efficiently. The literature overwhelmingly points to the need for such methods. Traditionally methodological frameworks in engineering design, such as Pahl and Beitz (1996) have been targeted to ab initio design, rather than design by modification. Additional methods for engineering change might require a collective shift in the academic community to recognise that change is the predominant paradigm of engineering rather than ab initio design. This might lead to a much increased effort in developing methods across the board, which could tackle change management effectively.

Despite the existence of these improvement strategies, engineering change remains a very real problem for organisations. Research is needed to discern what is the current state of industrial practice, whether companies have incorporated the study findings of a decade ago, and whether the strategies promulgated in the 1990s remain relevant in the changed business environments of the 2010s.

7 Summary

This paper has provided an overview of engineering change and described the nature of the engineering change process, which combines the procedural handling of design errors with the subtler and/or more substantial resolution of issues arising from uncertainties in designer, customer and market requirements. Various tools to support both workflow and decision-making in engineering change management have been described. In addition, how engineering change is connected to the makeup of the product in terms of architecture, complexity and degree of innovation has been discussed. Finally, management strategies to deal with the issue of engineering change were outlined.

Engineering change features in almost all design activity. Compared to other areas of engineering design, little literature has been published on engineering change, but what there is, demonstrates that engineering change is a topic of great importance to industry. Although there has been a recent increase in the amount of research carried out in the field, a great deal more academic effort is required to develop tools and knowledge to help companies understand and improve their engineering change processes.

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