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ENGINEERING CHANGE: DRIVERS, SOURCES, AND APPROACHES IN INDUSTRY

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ABSTRACT
Engineering change is a fundamental part of all design activities at all stages of design; complex products are designed by modification from existing ones; requirements change during long development projects; or problems through the design process or product use require rework. Yet engineering change has only recently become the topic of academic research and only few specific tools exist to manage engineering change. This paper reports on two workshops held in 2008, one in the UK and one in the US, where practising engineers reported on the challenges their organisations face with engineering changes and what approaches they take to deal with the effects of change. An analysis of 12 presentations shows that the causes for engineering change are very similar between different industries. However the approaches taken by companies to assess, manage and potentially take advantage of engineering changes are very different and in the absence of specific tools for managing engineering change companies used general process improvement and systems engineering tools, ranging from virtual design and QFD to high-level system simulation.

Keywords: Engineering change, customer needs, change prediction, change propagation

1 INTRODUCTION
Engineering change is a fundamental part of all design activities in all stages of design. New products are designed by modification from existing ones and designs are changed throughout the design process. After a core product has been released, often different variants are generated for slightly different markets or bespoke versions are produced for individual customers. During the life of a product performance and reliability issues require rework and long life products need to meet new needs or comply with new technology. Companies are now beginning to see engineering change as a recurring phenomenon at different stages of the process. In the last few years researchers have become interested in engineering change and began to study the phenomenon. Empirical studies ([1] [2] highlighted the potentially detrimental effect of changes propagating unexpectedly through a product. When changes snowball or avalanche causing many more changes to other parts, development projects can be severely delayed and over budget. At the same time, change processes, almost by definition, are not specifically planned at the beginning of process planning cycles and thereby escape the scrutiny of process evaluation. Process improvement initiates, and methods often focus on, the processes that are planned and intended rather than on change processes and the 'fire-fighting' mode in which they are often carried out. Change is conceptualised as an emergency, even if this particular emergency is more likely to be the rule rather than the exception.
As industry and academia are becoming more aware of change as a coherent phenomenon and early tools are reaching a point of maturity, it seems timely to investigate further how industry is conceptualising and handling change in complex engineering products. Moreover, there is a need to understand the need for (further) tools and establish new research questions. This paper summarises the reports that twelve engineers from ten different companies gave on the causes of engineering change and approaches taken to handle change during two workshops conducted by the authors to build up a community of practice around the handling of engineering change. Rather than providing a discussion of the issues based on the academic literature on engineering change, this paper will report on the perspectives of individual experts in industry and their discussions. During the workshops, which will be described in more detail in section 2, it became clear that engineers, from companies, whose fundamental business models require different types of changes (see section 3) and operate under considerable uncertainty, which leads to change (see section 4) see engineering change as a

coherent phenomenon, with similar causes as characterised in section 5. However, the approaches different companies take to avoid, manage or mitigate against engineering change and its effects, were very different, as illustrated in section 6. Only a minority of participants viewed change as an opportunity.

2 METHODOLOGY

The authors have been studying engineering change for many years, through a variety of different case studies based on interviews through which tools for handling change and in particular change prediction can be carried out. Initial work concentrated on change prediction [3] for customisation of complex products, in this case a helicopter [2] Work then analysed the different linkages between components to aid the elicitation of change prediction DSMs [4] and the impact change has on the organisation at large and vice versa [5] This led to the development of the CPM tool to visualise and predict change [6] through different phases of the design process [7] In collaborative work the authors analysed a company change database and elicited the patterns through which change propagated in the modification of a mature product [8] Further work on design for flexibility focused on designing products and platforms with flexibility such that future changes could be made more easily in those components of a product platform that were deemed most likely to change due to variant customization [9].

As part of on-going collaboration the authors received funding from the Cambridge MIT Institute (CMI) for two workshops in 2008 to bring together practitioners to talk about engineering change and to develop a community of practice. The participants where asked before the workshop to reflect on causes of change and to report on the approach that they took in their organisation to manage change, and to prepare a 30 minute presentation. This paper will summarise the presentations, as a reflection of the current state of change management in industry rather than present the authors' personal views.

Most of the participants were collaborators of the authors and people that the authors had previously had contact with, but not necessarily through their interest in engineering change. The participants are summarised in Table 1. To anonymise the participants they are listed by the type of products they spoke about and their role in the organisation. These generic classes will be used to refer to them in this paper. The presentations were video recorded. The analysis draws primarily on the presentation slides from each participant, but also on the follow up questions and discussions.

Table 1 Participants of the workshop

Country		Key product	Role of Representative
UK	1	Diesel engines*	Product and process integration expert
	2	Jet engines	Research liaison
	3	Cars (Germany)	Component team leader
	4	Military vehicles	Design Manager
	5	Trucks*	Product planning
	6	Automotive parts	Early product development
	7	Defence aerospace	System Engineering
US	8	Printing equipment	Vice president for production systems
	9	Oil and gas production	Team leader information technology
	10	Cars (US)	Senior research engineer
	11	Construction projects*	Senior vice president
	12	Fire engines	Chief engineer

* did not provide causes of change

The sample of companies attending the workshops was opportunistic through the contacts of the researchers. There is a bias towards large organisations and complex products, which increases the emphasis placed on the organisational challenges in handling change. In smaller businesses informal communication and a better overview over the products might avoid errors and lead to less formal responses to problems with change. However, even for a smaller business or a simpler product the approaches taken by large corporations are worth considering.

3 BUSINESS CONDITIONS LEADING TO CHANGE

The companies represented at the workshop were confronted with three fundamental drivers for change: *product proliferation*; *changes in legislation and regulations*; *infusion of new technologies* due to competition, and changes to *customer needs* throughout the development process. For each company one of these factors seemed to be dominant. The other drivers still existed, but did not drive the companies' selection of approaches to mediate against change as outlined in section 5. This might not be a fair reflection of the entire companies' approaches, rather than the individual, who represented it. All engineers attending the workshop came from companies who produced very complex products and perceived this complexity as one of the major conditions for change.

3.1 Complexity

All participants had a sense of the almost overwhelming complexity of their products and product ranges. This was not expressed in terms of a specific view of complexity as it would be held by complexity theories (see [10] for a review of complexity in the context of engineering change), but as an expression of the sense that they had to consider a very large number of interconnected factors, beyond the direct control of the individual or their organisation.

Complexity was also discussed explicitly by the representative from the defence sector talking about military vehicles. Each of their systems was a bespoke system for a particular customer, meeting their military needs and fitting in with their already existing military equipment. In addition, each product had multiple subsystems, which in their own right were complex products, for example a weapon system or a control system. They had a large number of suppliers and for many systems there needed to be dual sources, i.e. two suppliers needed to be able to provide the same component. Products were created by experts from different engineering disciplines, which brought challenges in managing the design process. Military equipment generally (or can) has a very long life, and will need to be changed and upgraded throughout its lifetime [11]

Each product had its own challenges in terms of product complexity, such as: needing to offer a number of product variants as for the fire engines; needing to cover a wide range of price points for the printing equipment; or needing to advance very mature and therefore optimised technology for the diesel engines and trucks. Several participants were publicly wondering whether their own product was more complex then anybody else's because of these specific factors. Several participants mentioned that globalization, i.e. the international footprint of their customer and supplier base as well as the geographic dispersion of their product development organizations significantly contribute to complexity.

3.2 Product proliferation

Product proliferation was a main concern in the design of fire engines and printing equipment, where the companies offered a very wide range of products within a huge price range and many different options. For example the fire engine company offered 60 different basic models for a variety of applications and 25,000 optional features on all their products. They built about 600 fire engines a year and they are all different. Fire engines for urban environments, where they need to deal with high rise buildings, but can rely on water hydrants, are very different from rural fire engines which require huge water tanks to extinguish fires in isolated, often wooden, buildings. Even if there are water hydrants, the water pressures will be different and might need to be augmented. The height of the buildings that need to be dealt with varies enormously, requiring different ladders and lifting mechanisms. But specific needs might be driven by more mundane issues, such as the size and configuration of the fire engine house. Some options are driven by customer preferences, for example, the type of pumping mechanisms or the desire to impress in a parade. Fire engines are specified by the fire department while they are waiting to be sent on missions. They want and need their fire engines to be just right and have the time to work out exactly what they would like. Vehicles are adapted to the fire-fighter's well trained processes, rather than the other way around. However, they purchase them sufficiently rarely, that they don't have an understanding of how much particular features would cost, so that they rarely systematically question their assumptions of their own needs. While this is an extreme example, automotive companies and their suppliers also offer large option packages around a large number of different basic models.

3.3 Legislation and regulations

Complex engineering products are heavily regulated by national and international legislation, regulations and codes of practice (standards), which are regularly updated. These updates set a type of clock speed for the development of these products. The aviation industry needs to meet complex airworthiness requirements while meeting stringent emissions and noise targets. The automotive industry is driven by emissions, fuel efficiency and safety targets, for example, pedestrian safety considerations have driven a redevelopment of the front and side of cars over the last decade. In some industries the regulatory requirements vary between countries, but in all cases, if a company does not have a product that complies with the regulations at a required date, they do not have a product they can sell in this market [12] . Some American automakers are currently redesigning fuel efficient European models for the U.S. market.

While legislation states very clearly what is required, changes in public demands often require swift changes to products, or the balance of sales within a product offering. As one of the automotive representatives pointed out, five years ago the business for Sports Utility Vehicles (SUVs) in the US was sound, and the company made substantial revenue from them. Now the fuel prices have risen and public awareness of climate impact has increased, so that the demand for SUVs has fallen significantly. While that particular company does offer many more fuel efficient cars, they have to improve public awareness of this fact. Product planning experts, such as the representative from the truck company, have to identify these long term trends and plan a sequence of changes to their products to enable the company to reach the required point in the market in an incremental way.

3.4 Technology infusion

In a number of markets there are competitive pressures that call for continuous innovation. This leads to the development of new technologies that are then infused (integrated) into existing products during major product upgrades. The printing equipment company for example attempts to stay ahead of competitors by simultaneously improving image quality and machine productivity, while decreasing operating costs [13]. New technologies such as automatic image correction require the integration of new sensors, software algorithms, and concomitant changes to power supplies and structural frames. Some of these changes are directly associated with the new technology, while others are knock-on changes that are necessary to accommodate the new equipment.

3.5 Changing customer needs

For mass produced products like cars or trucks the planning time horizons are sufficiently long that changes in customer demands are incorporated into new generations rather than changes to on-going development projects. This is very different for one-off or bespoke products such as construction projects or oil platforms. These projects are long and involve a large number of stakeholders. They also face many technical and cultural uncertainties during development.

Oil platforms are possibly an extreme case of this, where the oil companies send geologists to survey the land or seabed and identify potential oil reserves. However, despite improvements in prospecting such as seismic surveys and exploration drilling, substantial uncertainty remains about the quantity and quality of hydrocarbons during the entire design process. Only when they start operating the oil and gas platforms do they get a clearer picture of how much oil and gas there is and how difficult it is to extract, which in turn affects the scope of the project. This makes supplier management very challenging. As oil and gas are often found in politically volatile parts of the world the environment for building platforms and producing oil and gas can change very quickly. With fluctuating hydrocarbon prices the business case for a particular oil field can also change very quickly.

While the general circumstances of a construction project are usually more certain, customers often change their minds when they see a building emerge, as they are becoming aware of the potential of the building and as their own circumstances are changing. Cost saving exercises in particular, often lead to frequent changes. The construction company presenting at the workshop had identified through a survey that “Project changes represent the single largest source of project productivity impact” and pointed out that “Waiting to address change impacts via a dispute process is risky, expensive, and precludes impact mitigation”. They were very aware of the need to identify fully the impact of secondary changes, in terms of the disruption to the project, the loss to productivity and the knock-on effects to other parts of the product. How drastic these effects can be is illustrated in Short et al.’s [14] description of projected prices in theatre projects. Changing customer demands also affect military projects, due to the long development times and rapidly changing military needs.

3.6 Competitors

For many complex products, such as cars or engines, the markets have consolidated so that only a few 'big players' are offering products. Typically these companies offer a range of different products. For example the car companies offer a range of products from small economical cars to large luxurious vehicles. The diesel engine company offer engines from 4 – 2000kW. In these competitive markets it is critical that the companies position themselves appropriately towards their competitors. To keep up or exceed their competitors they need to make changes to their product. One form of change is to be a technology leader and continuously develop and integrate new technologies as described above in section 3.4. Another approach that was presented was to offer a larger variety of customization choices compared to other vendors who focus on few standardized configurations. The fire engine company in particular made it clear that the ability to change and customize rapidly was at the heart of their value proposition. Their entire process starting with order placement and pricing, assembly of the bill of materials and production planning is geared towards change. While companies of course try to predict what their customers will do, they might still be forced into late and unplanned, but substantial changes because of competitor product improvements.

3.7 Change throughout the development process

Changes occur throughout the development process, as illustrated in Figure 1, from the preplanning phase to the disposal of the product. Product planners endeavour to work out a trajectory of changes over many years of development. In an incremental product development climate many changes are planned into the new requirements for a new generation of products, as for those driven by legislation and public demands. Companies try to keep a certain amount of flexibility throughout the development process to cope with future needs for change, as the companies understanding of their customers needs evolve. However, the later in the process, the harder it is to change the product and the scope for changes will be limited to certain features. Generally, most firms seemed to take a rather passive approach to change, letting it happen and reacting to it, rather than proactively designing products with future changes in mind.

Coping with an enormous variety of products requires significant planning at the beginning of the development of a core product, as well as with later versions and for specific changes for specific customers. Suppliers and supply chain requirements are one of the causes of freeze in engineering design, when frozen components are those that can no longer be changed. They deflect change to other components of a product, thus increasing the proliferation of change, or in extreme cases they themselves have to be unfrozen, incurring additional cost. Errors also occur during the process, but often only manifest themselves during the detail design and integration phase.

Once a core product has been launched, companies often work on additional versions for specific markets or generate bespoke products for particular customers. While they might anticipate some of the requirements of those versions early and design them into the product, the implementation of versions often requires changes. Long life products are also sometimes upgraded to incorporate new technology when the product is already in operation (retrofits). Through the entire life-cycle of a product engineers gather insights for the design of future products.

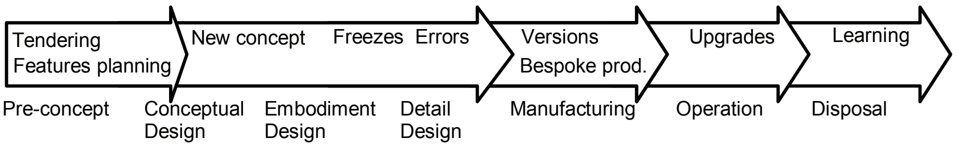

Figure 1 Changes through the design process

3.8 Large scale Uncertainties

Factors, which increase the uncertainty in the development process and the likelihood for mistakes in the development process, leading to changes late in the design process, are prevalent in all design companies. Only the oil production company has explicitly drawn attention to these general uncertainties. Their presentation highlighted a general skill shortage in their industry, in particular of

engineers of similar standard and training across the world. Exacerbated by general engineering skill shortages, there is competition for skilled contracting resources, forcing companies to work with non-preferred suppliers or to commit early to projects and contracts to assure availability of the contracting resource.
Yet, to gain an economy of scale there is a need to standardise the means of oil production. The oil companies put considerable effort into understanding how they can apply principles of standardisation, to oil production [15]. In the oil industry there is also considerable uncertainty over the supplier and product prices as global political factors and global demand drive the price of oil rather than the cost of production.
While the oil industry might be an extreme example, other industries are similarly affected by fluctuations in available resources and changes in price beyond their control. This is illustrated by the example of the SUVs, which for a long time were regarded as very precious products, for which customers paid a premium, thus increasing the profit margins of their manufacturers, but now have become extremely difficult to sell due to their actual or perceived inefficiencies.
Products, such as cars are not designed for particular customers, but for market segments within which the customer requirements cluster. The value that individual customers place on particular products is different and the membership of market segments constantly shifts. Particular features can make products targeted at different market segments suddenly more (or less) attractive. This is driven often by subtle socio-economic shifts, which are hard to quantify and to place into explicit metrics. As many companies cover a broad range of market segments, this only becomes a problem, as in the case of the SUVs, when customers move away from lucrative market segments.

4 SPECIFIC SCOURCES OF CHANGE

Section 3 has discussed the business conditions under which companies operate, which are more or less conducive to change. These were mainly given as background, this section looks at the specific causes, which are explicitly mentioned as such by participants. Not all presentations provided a comprehensive discussion of sources for changes, but those who did echoed many of the same issues.
Table 2 summarises the causes of change mentioned by 9 of the 12 companies who presented their perspective on change. The remaining presentations focused solely on the approaches that the organisations took to counteract change. The list (left-hand column of Table 2) has been generated as an abstraction of the factors that the participants have mentioned. Different industry terminology was summarised under one label, for example, the automotive representative talked about changes to use whereas the aeroengines representative described the same issue as change of duty. The number of issues mentioned depended on the role and insight that the presenter has, as well as the narrative they chose to tell. However, certain factors clearly emerged as prevalent in all industry sectors.

Table 2 Summary of the causes of change

Changes in:	Cars (US)	Cars (D)	Automotive parts	Aero engine	Defence aero	Defence vehicle	Fire engines	Printers	Oil
Requirements	✓	✓	✓	✓		✓	✓		
Regulations	✓	✓		✓	✓	✓	✓	✓	
Competition / market opportunities	✓						✓	✓	✓
Technology	✓		✓	✓	✓		✓	✓	✓
Quality, cost, capability	✓	✓			✓		✓	✓	
Sustainability					✓			✓	
Errors / problems / system integration		✓	✓	✓		✓		✓	
Project management		✓		✓	✓	✓	✓		✓
Change to use of product	✓			✓					
Design for service / upgrades / technology obsolescence	✓			✓	✓	✓	✓		

The oil production projects are to some extent a special case, because platforms are – for the most part - bespoke designs and only the solution principles and some components (such as power generation gas turbines) typically can be reused. Despite this there is a strong drive towards partial standardisation in this industry. The representatives of the oil company are not directly involved in the design of the platforms, which detail is mainly done by contractors, but in advising on the management of individual projects, which gives them a unique insight in the recurring management problems, in particular, in terms of resources, interfaces and alignment between partners. However, different project management issues were identified by many participants as causes for change.

Design for service has become a particular consideration in the aerospace industry, as the manufacturers of the equipment are increasingly taking over the service and maintenance of the product in civil and non-combat situations [16] . It is therefore not surprising that they picked up on these issues explicitly. In particular the aeroengine representative pointed out that as products are modified in service the number of product variants proliferates. Customers carry out different modifications and repairs and some buy third party spare parts. As many aerospace products are in service for 20 or more years, the knowledge of design intent gets lost within an organisation. As the manufacturers become responsible for the service, they are increasingly modifying their products to have synchronised service intervals for all major parts. This requires wide reaching modification to increase or potentially decrease the target life of key components. This issue is also reflected in the comments of the automotive company, i.e. that products deteriorate over time and components might need to be modified.

Only one participant explicitly talked at length about errors as drivers for engineering change. This discussion pointed out that the challenge with errors is finding the root causes of the problems. For example, a hardware failure might occur, so that the company needs to analyse whether this is due to a design error, in which case a change order would have to be raised, or an implementation or manufacturing error. In some cases failures occur because products are used outside of their intended operating range which can lead to redesigns and costly warranty claims. In the latter case a root cause analysis might need to look further back to establish whether a simple mistake has been made or whether the component has been designed in a way that makes it difficult to manufacture, in which case it again needs to be considered whether engineering change is worth undertaking. In some cases, designers have not considered all the parameters relevant to a component. Occasionally this also shows up when companies change their suppliers and a component no longer works as well as it did before the change. Errors are very closely linked to process management issues which most participants brought up, mentioning the challenges of coordinating design teams across expertise and company boundaries. Operational improvements and supply chain management issues were also mentioned repeatedly as sources of change. Closely related to error correction, cost and quality improvements are also mentioned several times as motivation for change. This is particularly an issue for companies whose products are extremely price critical in very competitive markets. Errors were also a topic highlighted when discussing process management challenges.

Competition and market opportunities are related to cost and quality improvements, but have an external rather than an internal view on the changes that need to be carried out. In competitive markets it is critical to both keep up with competitors and to find opportunities that they have not taken. Competition was primarily mentioned as a driver in the hard fought automotive market and for printers, products which are purchased from a catalogue offering rather than produced in small batches or as one-offs for specific customers.

Regulation was mentioned as a driver for change in all the presentations apart from the construction projects. For oil platforms and construction individual projects are carried out to current local regulations. However, in all other industries, safety, efficiency and emission standards played a major role. This might be a biased view, as eight of the represented products are engines or use highly complex engines, which are subject to emission, safety, fuel efficiency and noise legislation. All products that are subject to regulations have to be changed to meet new versions of the legislations. These changes are time critical and not optional, therefore they drive design and production processes. Two companies explicitly mentioned changes being driven by sustainability issues. Other companies have conceptualised similar issues as changes to customer requirements. For example, whether reduced fuel consumption is seen as an important customer requirement, as the automotive companies presented it, or as an environmental issue, is a matter not only of personal presentation, but also of the image a company presents of itself. Increasingly fuel efficiency limits are also being introduced to off-road applications.

5 APPROACHES

Change is a universal issue with very similar causes in all of the companies that contributed to the workshops. While particular engineers stressed one aspect of change above another, because of their own issues, none of the descriptions of causes or challenges associated with change were surprising to other participants. However, the approaches companies chose to handing change were very different. Fundamentally the different approaches fell into three categories: *trying to avoid change* in the first place through better requirements handling, well planned configuration systems and avoiding mistakes; *making the business agile* in responding to change through flexible business processes and virtual engineering; and introducing specific processes for *effective change handling* This is again to some extent a function of the role that the representatives play in their own organisation, but also how the organisation at large conceptualises change. Some see change essentially as a problem, that needs to be mitigated against from the beginning, others see it as an opportunity to improve the product. Some companies have approaches specifically targeted at handling change; others used general process improvement techniques. Every company chose to present a different approach, which we will present here briefly. Some of the approaches which were presented here as specially targeting change are established practice in other companies.

5.1 Avoiding change

For all the companies developing incremental products change is an integral part of their development processes, but many problems arise from late and unexpected changes due to errors or problems in the development process or requirements changing throughout the project. What appears as a requirement change, are often requirements that the company did not understand well in the first place, rather than customers requiring something different. These changes can to some extent be avoided, if problems in processes are avoided and the requirements of current and potential customers are elicited properly.
How to avoid change has also been the topic of academic research taking mainly two approaches: increasing the effort at the beginning of the design process to anticipate of the need for change [17] ; or by predicting the impact of change [3]

5.1.1 Managing requirements through QFD

A very well worked out approach of handling and avoiding change was developed by the diesel engine company. As with the fire engine example in section 2, diesel engines are produced as a variety of basic products and there are a large number of options for particular customers. Changes are required if customer requirements are not anticipated in the initial option planning. As many of their customers are producers of very specialised off highway equipment, it is the responsibility of the diesel engine makers to educate their customers about new legislation and lead them to adopt appropriate solutions.

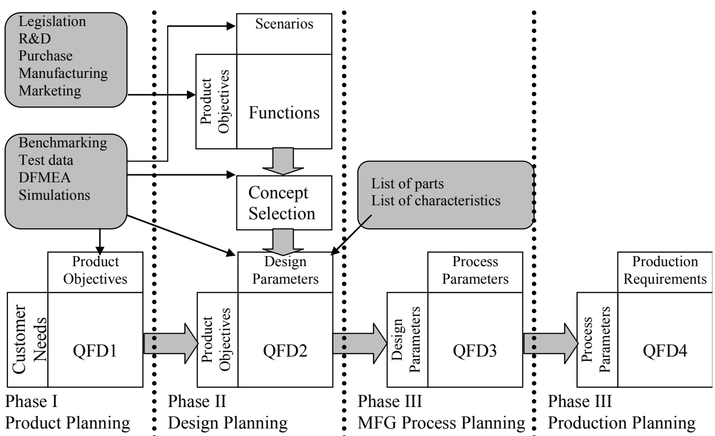

Figure 3 QFD approach for change minimisation

They apply a QFD approach to try to understand their customers' requirements and needs, as illustrated in Figure 3. They invite representatives of many of their key customers to their headquarters and gather from them the “Voice Of the Customer” (VOC). This is analysed internally and translated into a common language and format to gain the “true” voice of the customer. This enables them to distinguish between “Basics” and “Delighters”, i.e. essential and non-essential requirements. This also allowed them to reduce the number of changes that they need to carry out, because it allows them to negotiate with their customers those requirements or needs that they really had. Knowing exactly what was required, they were able to make key decisions early and therefore prioritise trade-offs.

Following a standard QFD approach [18] the company introduced a process to systematically cascade requirements throughout the design process, as illustrated in Figure 3. Through this process they gain a good understanding of the requirements at different stages of the process and use past experience and information about existing products in the translation of needs to product objectives and product objectives to design parameters. This also enabled them to manage the risk within the development processes. Amendments to existing features can be assessed through Failure Mode and Effects Analysis and identified ‘newness’ (new solution principles and substantially changed use of existing solutions) can be tested in as localised a way as possible.

While none of the techniques, tools and methods applied in this company were themselves new or specifically developed for change, they were outstanding in the consistent way they had applied them to manage change in engineering design.

5.1.2 Configuration systems

Many companies, who offer a great variety of product configurations allow the designers or sales personnel to see which options are available for which basic product and whether different options clash. The automotive companies and the diesel engine company also have configurators, but it was the fire engine company, which chose to highlight these as a means to manage change. They produced a web-base system for their engineers and sales force to increase the accuracy of the sales order and produce reliable cost estimates. The system gives them product data security and serves as a communication tool with the dealers. They incorporated 80 years of experience into rules and guidelines to establish viable product configurations, which allows them to generate a Bill of Materials from specific product requirements. This is linked to an automatic drawing system, which generates plans for the specific truck and generates an electronic workflow model for the ordering and delivering process. This enables the sales force to give their customers cost and time estimates for the delivery of a new truck. The orders are still checked manually and conflicts are resolved by in-house engineering experts.

5.1.3 Tailoring methods to the causes

While the processes of resolving a change are similar regardless of the cause of a change [2] the ways to avoid needing to make changes needs to be tailored to the cause of the change. The automotive suppliers apply a number of established techniques to avoid changes according to their causes. The company has invested heavily in 6 Sigma [19] training to have a number of methodology experts who can aid with selecting and applying suitable methods. To avoid errors as causes of change the company carries out root cause analysis of errors and carries out Design Review Based on Failure Modes, which has made FMEAs an integral part of their design process, rather than only being associated with quality management. To handle and visualise the complexity of their products the company uses Design Structure Matrices (DSM) and multiple domain mapping matrices [20] and cause and effect networks. To handle changing requirements they also employ a QFD approach, as explained in the previous section, but less rigorously. The jet engine company also uses DSMs which they generate as part of their regular design activities to map out the connectivity and functions within their product to access the potential impact of changes. These are then put together to map components and functions.

5. 2 Running the Business in a Suitable way

Several presentations highlighted the importance to run a business in such a way that it can handle change efficiently.

5.2.1 Dynamic businesses

The truck business representative, who was part of a product planning team, took a positive view of change as an opportunity and means for the business to improve its product. To make use of the opportunities that change affords it is vital for a business to be dynamic to handle change. At the same time it has to be able to manage the tools and methods, processes, and people and organisation. This is extremely difficult in a static process organisation, where people are encouraged to follow strict rules and which codifies best practices in rules which then become immutable. Instead the organisation needs to be dynamic and articulate best practice as guidelines that are able to be changed. This requires both dynamic leadership and the ability to pursue new opportunities. In particular, the presenter felt that functional organisation structures were too inflexible and that project teams need to be organised in a more flexible manner.

5.2.2 Virtual design in integrated system engineering

The representative from the military aerospace company presented their approach to virtual design as their approach to mediate against adverse effects of change. The approach is taken by many other companies, for example, in both engine design companies, but was only singled out by the aerospace defence company.

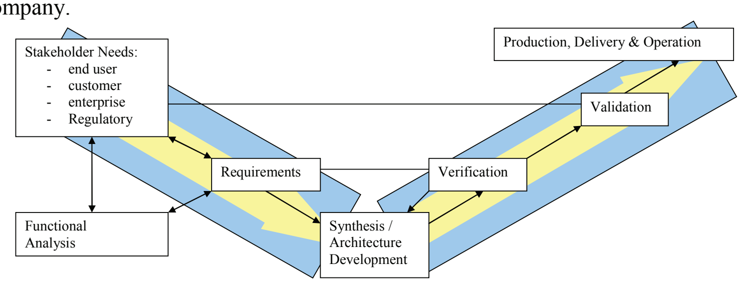

Figure 4 System engineering Context for Virtualisation

The organisation is moving towards virtual engineering, designers use integrated models and virtual simulations throughout the process. This is done in order to verify that physical components fit together as intended and that appropriate clearances are maintained in addition to predicting product performance. The supply chain is integrated into the design process and shares similar tools, built up in a modular way. The company applies a classical systems engineering V-model (as illustrated in Figure 4) to the design of components and systems as well as the entire system.
At present about only 15 % of the effort is expended on the left-hand side of the V, a large fraction of the remaining effort is expended in a “integrate – verify – correct” loop on the right side of the V. The long term goal of the organisation is to develop a heavily front-loaded process with the 60 % effort at the beginning, allowing them to verify and validate all responses to needs in a virtual design. This approach makes change an integral part of the product development process (Figure 5), rather than a corrective activity in later stages of the process.

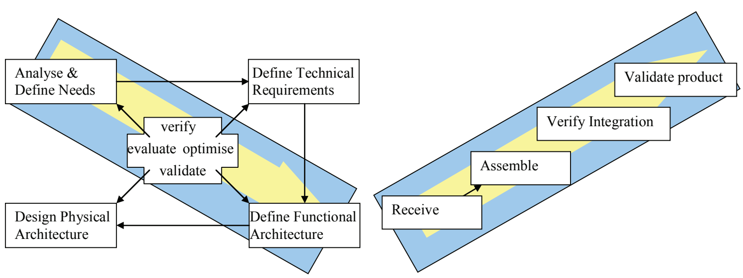

Figure 5 True Integration of Virtual Engineering

5.2.3 Risk management

The printer makers discussed another general process management technique which is used by a variety of the participants of the workshop: risk management. Printer manufacturers offer an enormously wide range of different products from small domestic printers to large industrial printers,

from very specialised printers, for example, for labels to standard office work horses. Their challenge is managing a sensible portfolio of products to allow them to cover a wide section of the market at a sensible profit margin, while maximising reuse of components and platform products. The company used DSM and score-card approaches to assess the technical risks and managed the risk using PSP/CMO, Management-By-Fact and Find/Fix tracking. They also placed huge importance on avoiding change, applying a 6 Sigma approach and iterative development to make the designs robust.
The construction company also employed a risk assessment approach to handling change. In their case, it was important to assess the cost of changes and thereby to decide whether a change would be carried out or not. They employed high-level system dynamics models and run-cost simulation to gain insights into the dynamic effects. This enabled them to assess costs and staffing levels as well as to pre-negotiate contractual changes and modifications with their customers.

5.3 Formal change processes

All the companies presenting at the workshop have formal change management processes. The representative from the German automotive company concentrated on change processes in his presentations. The company follows standard processes to handle change, as depicted in Figure 6, where each step of this process is itself supported by tools and methods. The company has a change database, which records a description of the problem and a description of the solution. It includes a description of the causes and details of the expected costs and benefits of the change and leaves space for remarks, where considerable effort is invested in the evaluation of significant changes.

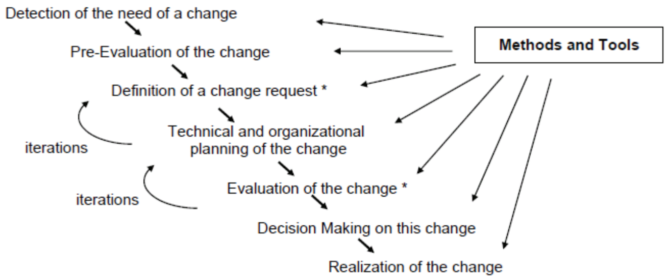

Figure 6 Standard Change Process

6 CONCLUSIONS

Engineering change is an important issue for all the companies who presented at the workshop, affecting them in all stages of their design processes. There was a wide consensus about the causes of changes regardless of the type of product or the role the representative of each company within their organisation. However, each company presented a different approach to handling change. All of the companies applied general design process improvement approaches to managing engineering change, but focused on different aspects of it. In many cases reduction of changes or their impact was a by-product of other improvement activities. As engineering change is becoming better recognised as a driving force in all engineering processes there is a need to develop specific tools, methods and processes to support engineering change. While there might never be a common approach to handling engineering change a better understanding of how different approaches can enhance each other and be supported by tools, will be very beneficial to companies. Some of the main dimensions along which future change management tools and approaches are likely to differ are the production volume (on-offs versus mass production), the degree of customer involvement in customization, the degree of internal and external uncertainty as well as the inherent product complexity. Future research will include the development of engineering change principles, methods and tools that take such factors explicitly into account.

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REFERENCES

[1] Terwiesch C. and Loch, C.H. Managing the process of engineering change orders: the case of the climate control system in automobile development. *Journal of Product Innovation Management*, 1999, 16(2), 160-172.

[2] Eckert C.M., Clarkson P.J. and Zanker W., Change and customisation in complex engineering domains, *Research in Engineering Design*, 2004, 15(1), 1-21.

[3] Clarkson P.J., Simons C. and Eckert C.M. , Predicting change propagation in complex design, *Proceedings of ASME Design Engineering Technical Conferences*, Pittsburgh, USA, CD-ROM, paper no. DETC2001/DTM-21698, 2004.

[4] Jarratt, T.A.W., Eckert, C.M. and Clarkson, P.J., Development of a product model to support engineering change management', *5th International Symposium on Tools and Methods of Competitive Engineering (TMCE 2004) Lausanne, Switzerland*, *, 2004,* 1, 331-342

[5] Ariyo, O.O., Eckert, C.M. and Clarkson, P.J. ,Unpleasant surprises in the design of complex products: why do changes propagate?', in *2006 ASME International Design Engineering Technical Conferences (IDETC/CIE2006), Philadelphia, USA*, 2006, 1057-1064

[6] Keller, R., Eckert, C.M. and Clarkson, P.J. 'Using an engineering change methodology to support conceptual design' in *Journal of Engineering Design*, in press

[7] Keller, R., Eckert, C.M. and Clarkson, P.J., 'Through-Life Change Prediction and Management' in *International Conference on Product Lifecycle Management, Seoul, Korea,* 2008.

[8] Giffin, M.L., de Weck, O.L., Buonova, G., Keller, R., Eckert, C.M. and Clarkson, P.J., 'Change propagation analysis in complex technical systems' in *Journal of Mechanical Design* (in press).

[9] Suh E.S., de Weck O.L., and Chang D., "Flexible product platforms: framework and case study", *Research in Engineering Design*, 18 (2), 67-89, 2007

[10] Earl, C.F., Eckert, C.M. and Johnson, J., Complexity models in design, *8th International Design Conference (Design 2004), Dubrovnik, Croatia*, 2004, 163-168

[11] Eckert, C.M., Jowers, I. and Clarkson, P.J. 'Knowledge requirements over long product lifecycles' in *16th International Conference on Engineering Design (ICED'07), Paris, France*, 2007, 913-914

[12] Jarrat, T.A.W., Eckert, C.M., Weeks, R. and Clarkson, P.J. ,Environmental legislation as a driver of design, in *14th International Conference on Engineering Design (ICED'03), Stockholm, Sweden*, 2003, 231-232.

[13] Suh E.S., Furst M.R., Mihalyov K.J., de Weck O.L., "Technology Infusion: An Assessment Framework and Case Study", DETC2008-49860, Proceedings of IDETC/CIE 2008, ASME 2008 International Design Engineering Technical Conference & Computers and Information in Engineering Conference, New York, New York, USA, August 3-6, 2008

[14] Short, C.A., Barrett, P., Dye, A., and Sutrisna, M., The Impact of Value Engineering on Five Capital Arts Projects, *Building Research & Information*, 2007, 35(3), 287-315.

[15] Kalligeros K., de Weck O., de Neufville R., Luckins A., "Platform Identification using Design Structure Matrices", *Sixteenth Annual International Symposium of the International Council On Systems Engineering* (INCOSE), Orlando, Florida, 8 - 14 July 2006

[16] Harrison, A. for service - Harmonising product design with a service strategy, *GT2006 ASME Turbo Expo 2006: Power for Land, Sea and Air, Barcelona, Spain*, 2006.

[17] Fricke E., Gebhard B., Negele H. and Igenbergs E., Coping with changes: causes, findings and strategies, *Systems Engineering*, 2000, 3(4), 169-179.

[18] Akao, Y. and Mazur, G. H., The leading edge in QFD: past, present and future, *International Journal of Quality & Reliability Management*, , 2003.,20 (1), 20-35

[19] Creveling, C.M., Slutski, J, Antis, D. *Design for Six Sigma*, Prentice Hall, 2003

[20] Browing, T. Applying the Design Structure Matrix to System Decomposition and Integration Problems: A review and new directions, *IEEE Transactions on Engineering Management*, 48 (3), 292-306.

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