INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

ENGINEERING CHANGE DURING A PRODUCT'S LIFECYCLE

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ABSTRACT

This paper describes a case study investigating the changes made to a complex product, namely an aero-engine through its product lifecycle. Document analysis of over 1500 reports covering eight years of the aero-engine lifecycle has been carried out. The research investigated how changes occur at different phases of a product lifecycle and how the causes of the changes differ during the different stages. The majority of changes were found to occur during the manufacturing and build phase. It was found that changes to the engineering specification together with meeting design criteria are the major causes during the prototype testing and development phase. The main cause of engineering change was found to be linked to its lifecycle phase.

Keywords: Engineering change, product redesign, product life-cycle and document analysis

1 INTRODUCTION

An engineering change can be triggered at any point in the product lifecycle, including manufacturing, prototype development and testing and during its service phase. For the purpose of this paper an engineering change is defined as a change that occurs after the original design task has been completed, therefore an engineering change can occur at any of the further stages of a products lifecycle. The research aims to understand how changes occur at different phases of a product lifecycle and to understand how the causes of the changes may differ during the different stages.

Huang *et al* survey of a 100 UK manufacturing companies identified that guidelines for managing engineering change are required for the majority of companies that were involved in the study [1].One of the key strategies identified for managing engineering change was to encourage early changes, the main reason for this is the extra cost incurred as a change is made in the later stages of a product's lifecycle. The cost of changing a design increases as the product's lifecycle progresses. Fricke *et al* state that the cost increases by an estimated additional factor of 10 as each stage of the product's lifecycle is surpassed, the main stages being development, prototype testing, manufacturing, production and lifecycle [2]. Figure 1 illustrates the mains stages as defined by Ulrich and Eppinger, from development until production [3]. In the case study employed during this paper, engineering changes that occur once the product is released and in service are also taken into consideration.

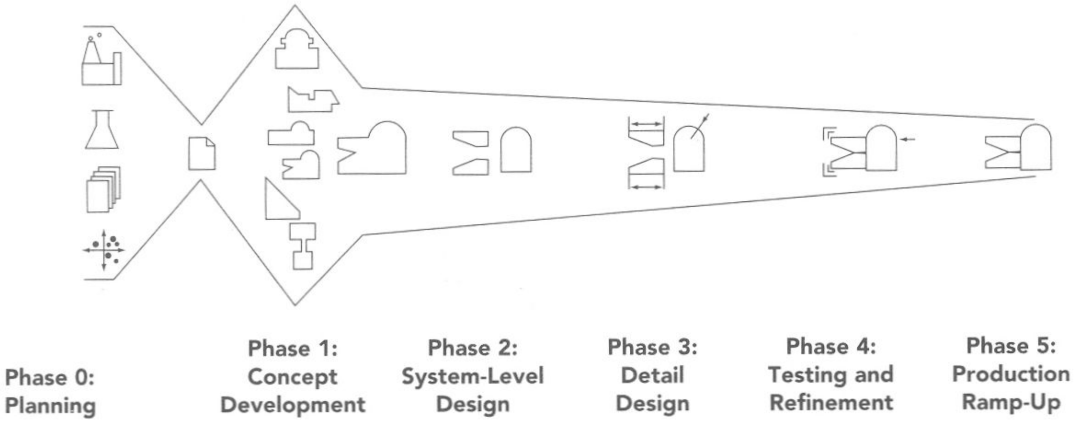

Figure 1 Generic Design Process [3]

Around 60% of the companies surveyed by Huang *et al* viewed engineering changes as unavoidable [1]. The number of changes a product needs to undertake varies, researchers have attempted to place a number on this, however these are difficult to compare. A number of factors contribute to this, including the complexity of the product, the portfolio of the company and number of projects handled and of course the quality of the company itself.

The reasons for changing a product can be categorised into two fundamental reasons, either 1): to remove/avoid errors or 2) to improve/enhance product [4]. Changes are often described as being either an 'emergent changes' (e.g. through correction of error, safety, etc.) or being initiated from outside (e.g. through customer, legislation, production etc.) described as 'initiated change' [4]. Engineering failure is often associated with engineering change, and a number of classifications of failure exist, however this is only one type of change and falls within the first category of emergent change [5].

Classifications of change focus primarily on the companies' response to the change, a common classification the purpose, origin, urgency, and timing of when the report was raised [4]. In this paper classification of change is examined to better understand engineering change throughout a product, including consideration of the nature of the change rather than focusing on the company's response to the change.

3 RESEARCH METHODOLOGY

Document analysis has been carried out for an aero-engine through all phases of its lifecycle, investigating over 1510 reports documenting the changes occurred to the product. Therefore, the product has undergone 1510 request for changing at the time of the data analysis. This figure should be taken within context:

- The product in question is complex, with several hundreds of components and interactions between components.
- The reports span an eight year period, including two years of service.
- The aero-engine is largely recognised as a success, with over 2.3 million flying hours.
- The aero-engine analysed is a variant design and succeeds two previous designs.

Each of the reports is indexed against 38 criteria, these describe the reason for the change, such as manufacture or a change to specification and the type of problem, implications for the change and suggested actions. The reports varied in length from 25 to 250 words and are the first reports raised to report the need of a change on a product. A change is only documented after the original design task has been completed; hence these reports are originated during the: development and testing phase; manufacture and build testing phase and; the service phase (whilst the product is operating in service). The reports are created by different people involved in the product lifecycle and are not limited to engineering designers; those involved in manufacturing and the service phase of a product are also originators of the reports.

Due to the large number of reports, the initial analysis focused upon determining the phase of the product lifecycle to which the report belonged to, through a quantitative analysis of the criteria that the report were indexed against. Once a quantitative analysis was completed a deeper more qualitative analysis through reading the reports was also undertaken.

[1] Results

The findings presented in this paper are primarily the quantitative and initial qualitative analysis and have focused upon:

- Identifying the most dominant phase during the product's lifecycle in which changes occur.
- Identifying the most dominant reasons from change during the product's lifecycle.

Out of 1510 reports, 1133 reports were identified as changes that belong to 39 different subsystem of product. The remaining 377 reports were not identified against the subsystem to which they belong since this was not clearly identifiable from the data. The number of reports for each of the different subsystem of product was an average of 29 reports per subsystem. However the range of reports for each subsystem varied between 4 and 101. As the complexity of the subsystems also varies it is difficult to interpret the variation of the number of reports.

1.1 Changes related to the phase of a product's life-cycle

The reports were analysed to understand the number of changes that occur during the three different phases of the product lifecycle. The initial analysis found that around 8% percentage (118 reports) of changes occur during development/prototype phase, 76% (1147 reports) of the reports have been identified as changes that were made during Manufacture/build and testing phase, and the remaining 16% (245 reports) of the reports during the products service phase as shown in below Table 1. The reports during the product's service phase represent around two years of its service phase, however, the number of reports in this phase may increase as the product's service is not completed.

Lifecycle phase	Nr. of reports	Percentage (%)
Development & prototype phase	118	8
Manufacture/build & testing phase	1147	76
Service phase	245	16

Table 1 Number of change reports at different stages of product lifecycle

The above table reveals that the majority of changes arise during the manufacture, build and testing phase. This finding was slightly surprising as it was expected that changes would be greatest at the early stage (i.e. development & prototype phase) and decrease with the progression of the product's lifecycle. Although this study focuses on all the changes made for *one* product, the finding is also consisted with a survey carried out with 171 companies within the German Manufacturing Industry. The survey aimed to understand how and when companies identify design flaws. The survey found that the only 4.6% of design flaws were identified during the development phase [6]. The majority of design flaws are reported by customers or users (around 36.4%), followed by flaws detected during manufacture and assembly, and flaws detected as a result of warranty claims (around 25% each). A design flaw is not the only type of design changes that occurs, however this is still relevant to understand. In addition a survey based research approach does not capture all the design flaws.

The reports were also analysed to understand the motivation for changes. The motivation of change was based upon the following, and the categorisation of the motivation was limited by the criteria employed to index the reports:

- Product Improvement: Changes that are made to improve the product, a solution may exits but an improved solution may be offered.

- Satisfaction: Changes made to increase satisfaction of a solution, including customer satisfaction and to avoid suspected failures based on the previous experience
- Cost reduction: Changes made as a result of an opportunity to reduce costs.
- Performance, Reliability: Changes to increase the performance or long-life reliability
- Durability/life, Warranty, Guarantee: Changes to enhance the product's durability; the length of warranty and guarantee.
- Maintainability Changes made to improve the maintainability of a product or attempts to design for ease of maintenance.

No significance difference was found between the motivation of the change during the different phases. A deeper qualitative analysis may reveal differences, but this was not carried out due to the large data set. The primary motivations of the engineering change, during all the phases, were product improvement and satisfaction.

1.2 Cause of changes related to the product lifecycle phase

The reports were analysed to identify the primary cause of change with respect to each of the three lifecycle phases. Table 2 shows the four most dominant causes for each of the phase, the reports are indexed against multi-criteria, therefore they can have more than one cause, and only the top four are shown, hence these values do not add up to 100%.

	Lifecycle phase		
	Development & prototype phase	**Manufacture/build & testing phase**	**Service phase**
Main Causes of Change	Weight (49%)	Manufacture/assembly (31%)	Manufacture/assembly (19%)
	Change to Specification (40,7%)	Reliability (28%)	Cost reduction (17%)
	Certification (32%)	Durability/Life (24%)	Operational Experience (15%)
	Manufacture/ assembly (28%)	Buildability (19%)	Buildability (15%)

Table 2 Dominant causes for changes at different phases of product lifecycle

The pattern that can be observed is that issues that are related to each of the phases are the primary cause during that phase. For example Table 2 shows that the weight, changes to specification are two of the dominant reasons of changes during the development and prototype phase. Weight is one of the criteria that the engine is designed for during development phase and this highlights changes made as a result of focusing upon attempting to meet a particular design criteria and to improve solutions. Manufacture and assembly and buildability are amongst the four dominant causes for the manufacture and build phase (also in the service phase), i.e. these are issues. In the service phase, operational experience is one of the main factors, operational experience does not occur until the product is in operation (i.e. only during the service phase). The causes identified highlight the difficulty in designing for considering the later stages of the product lifecycle, i.e. designing to consider manufacture and build and designing to consider the service phase of a product.

In addition, it was found that *changes to a specification* are more likely to occur during the development and prototype phase (and more than likely during the actual design phase, which is before a change is documented). Change to specification during the development testing phase is the second highest cause whereas this decreases to the 11th cause during the manufacture and to the 7th in the service phase of the product's lifecycle. Interestingly, one of the strategies adopted by experienced designers is to design solutions whilst keeping their design options open, hence allowing for the possibility of a change to specification [7].

Change propagation is often cited as a reason for engineering change, i.e. an engineering change arising due to the result of an earlier engine change. One of the criteria against which the reports can be indexed includes recording if the failure of the component has an effect onto another component. This is interpreted as the change *may cause* propagation rather than the change is a result of propagation. A total of 22% of the reports were indexed as likely to cause propagation, whether these did or did not occur was not traceable form the data set. As this analysis focuses upon document analysis it is difficult to establish how many of the changes may have been caused by earlier changes, one of the reasons for this is that the reports analysed are not necessarily aware of the root cause of the change, and there is no connectivity between the reports. A Design Structure Matrix (DSM) approach as adopted by amongst others 8] may highlight the connectivity between different components of the product, however the connections between actual changes is not traceable through the DSM approach.

1.3 Initiation of changes related to the product lifecycle phase

The reports were analysed to understand whether the change was initiated internally or externally. It was found that during the development and testing phase the main changes are external, during the manufacture and service phases this shifts to be internally driven. However, what it is internal or external is very much dependant upon the companies. The categorisation of what is considered to be internal or external may differ based on any individual company and the industry business model. As the company in question operates open a service model of selling hours of service as opposed to a product, operational experience was considered as internal. External initiation was considered if the originator of the change was:

- Customer
- supplier
- contractual.

Internal initiation was considered if the originator of the change was:

- operational experience
- manufacture/assembly
- production
- build.

Figure 2 shows the initiation of change for the three different phases. During the prototype development and testing phase the initiation of change is split almost evenly between internal and external. However, during the other two phases internal initiation (around 75%) is much more dominant. One of the reasons for this is related to the causes of the change, during the prototype development and testing phase many changes are a result of changes to specification. In the later two stages, manufacture, build and operational experience are amongst the major causes for engineering changes and for this particular company and business model, are viewed as internal.

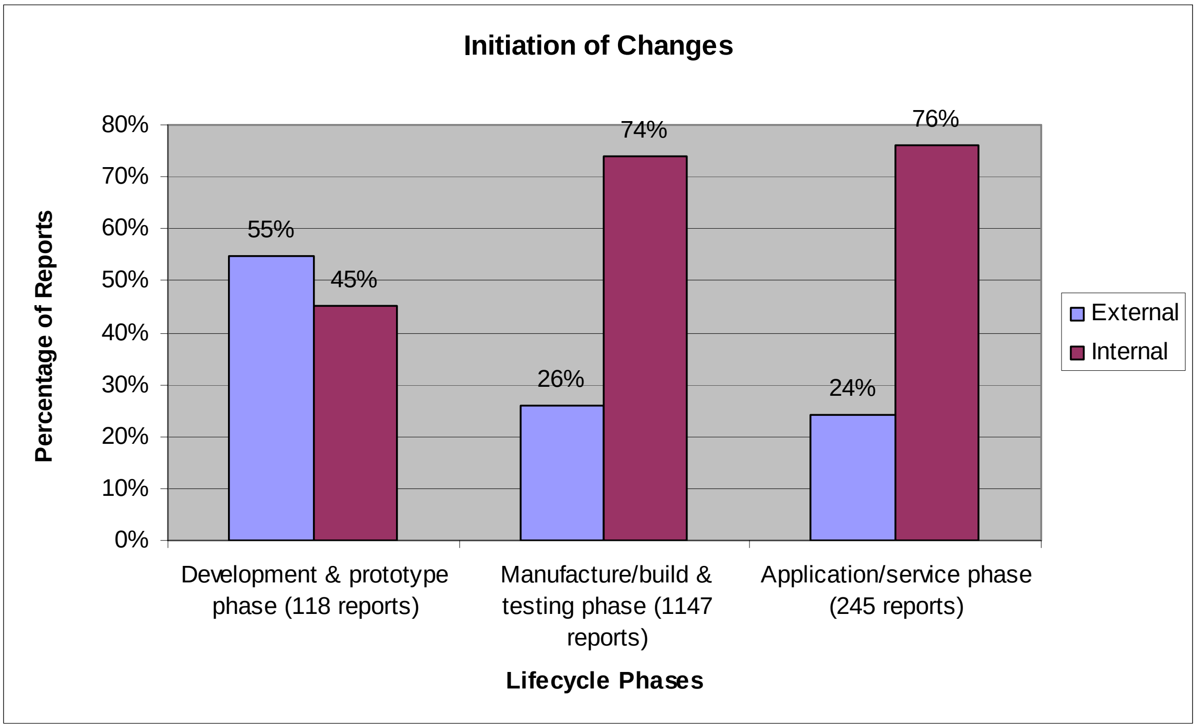

Figure 2 External or Internal initiation of change

4.4 Documentation of change

Documentation of engineering change is recognised as an important strategy when managing engineering change and is discussed briefly here [1]. Each of the reports were indexed with up to 38 criteria, these criteria can be classified as including:

- Motivation of change
- Initiation of change
- Suggestion of Change
- Type of problem (non-recurring, recurring, disruptive, etc.)
- Other criteria.

In addition, the cause of the problem is also recorded, however this may come under the type of problem (for example, functionality) or the motivation of change (for example, a product improvement). It was expected that all reports would be indexed with a motivation and initiation change. However this was not found to be the case, Figure 3 shows the category of criteria against which the reports are indexed during the different phases of product lifecycle. In Figure 3, in can be seen that the motivation and initiation of changes are not equally indexed, i.e. the number of reports are not the same for each of these categories. This suggests a need for clearer documentation of change reports.

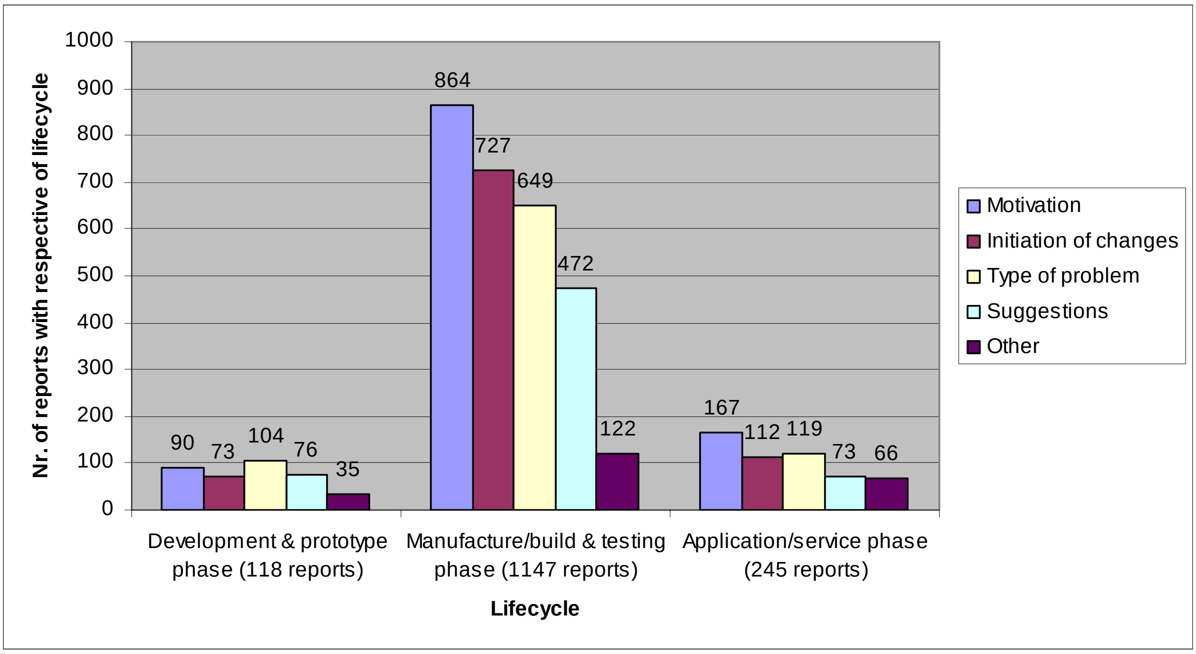

Figure 3 Indexing of Documentation of Change

In the quantitative analysis of the reports, it became clear that different users did not necessarily have the same understanding of a few of the criteria. For example, if we consider the criteria *satisfaction*, according to one user *satisfaction* means to avoid suspected problems based on a previous engine experience. According to another user satisfaction are the considerations of changes made to avoid failure from the results of testing. Some other users considered satisfaction as customer or supplier satisfaction. All these views were included for interpretation of the criteria for this analysis. However, this highlights that there is no unique definitions of criteria's for all users, one factor maybe that the users are not all from the same background and operate in different phases of the product lifecycle. The use of clearer definitions and guidelines to documentation procedure may assist in overcoming this ambiguity.

5 CONCLUSION

A study has been carried out to analyse a complex product's lifecycle with over 1500 changes spanning over an eight year period, and including two years of the product in service. The approach adopted was to conduct a deep analysis of one case, to understand how the number of engineering changes and causes for changes differ with the phases of the product lifecycle. Literature investigating in less depth, a broader set of case studies was consulted to assist in generalising the findings. From the document analysis, it was found that the majority of changes, over 75%, occur during the manufacturing and build and testing phase. It was found that the dominant causes for changes are related to their phase, for example operational experience is one of the main reasons for change during their operational (i.e. service) phase of the product, and manufacturing and build are the main causes during the manufacture and build phase. This highlights the difficulty for engineering designers to understand the later phases of the product lifecycle before the product enters that phase.

The research has highlighted the dominant cause for change for each of the lifecycle phases, and through identifying those that are most likely to occur and when, engineering designers can focus their efforts on these particular causes. In addition, it was found that externally initiated changes are more likely to take place in the earlier phases of the product lifecycle. Hence, engineering designers need to ensure that this is taken into account i.e. that their design solutions address the likelihood that changes will occur, such as changes to the specification.

The research also highlighted the need for clear and structured documentation of changes, and guideline in the reporting of changes, including definitions for the criteria against reports may be indexed.

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