

INVESTIGATION OF CHANGE IN SPECIFICATIONS DURING A PRODUCT'S LIFECYCLE

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ABSTRACT

Engineering changes (ECs) constitutes a normal part of a product's lifecycle. This paper aims to understand why changes are made to a product's specification during a product's lifecycle including understanding: the distribution of changes; the drivers for changes; how changes are discovered; which design attributes likely be changed; the initiation of change and how change in specifications are described. For this purpose, document analysis for a complex product has been carried out. In total, 271 reports of change request of an aero-engine that were associated to change in specifications were examined qualitatively and quantitatively. Several patterns in change in specifications were quantified and observed. The findings showed that the majority of changes were found in the manufacture/build and testing phase and most of these changes were described in terms of need and solution regardless of how the request was initiated. The study showed that experience plays a vital role in discovering the need to change a complex product.

Keywords: Change in specifications, engineering change, change request, product's lifecycle

1 INTRODUCTION

Engineering changes (ECs) constitutes a normal part of a product's lifecycle. Engineering changes are viewed in a number of ways, a brief overview of these perspectives is presented. Huang and Mak define ECs as the modifications of a product or component associated to forms, fits, materials, dimensions or functions. In their point of view, it can be as simple as documentary amendments, or as complicated as the entire redesign of products and manufacturing processes [1]. Whereas, Wright tackles the problems of ECs from the production perspective [2]. Wright defines engineering change as modification to the component of a product that normally takes place after the product enters the production phase [2]. Terwiesch and Loch define ECs in a general context which includes changes to software in the definition in addition to modification to physical components or products [3]. To differentiate ECs, Lindermann and Reichwald classify change by distinguishing them into problem or innovation oriented i.e if the change is error rectification or aimed to improve the product [4 in [5]]. Eckert *et al.* on the other hand, extend this classification by also considering the origin of the changes, i.e if it is initiated change and emerging change. Initiated change is the change arising from external sources (i.e. customers and legislation) and emergent changes are the changes arises from the product itself due to error during design process. In this respect, innovation is considered as a part of an initiated change for product improvement [5]. ECs are generally perceived as problems rather than opportunities. Thus, the facilitation of engineering change management (ECM) was not focused upon until the mid nineties [2]. Consequences of ECs have been reported in numbers of studies. ECM consumes 30 to 50%, and sometimes up to 70% of production capacity [4] and represents 20 to 50% of tool costs [6]. Clark and Fujimoto report that 20 to 40% of die development costs in vehicle development are caused by ECs [7]. Thus, the company has to ensure ECs are implemented efficiently to reduce lead-times and costs. This highlights the significance of devising supports (techniques, tools, etc.) to manage ECs. However, in order to provide such support, it is crucial to understand the company difficulties in dealing with ECs.

Several studies have been conducted in industries to understand ECs thoroughly. Huang and Mak, examine several aspects of industrial practices in managing ECs. Their study included the systems, organizations, activities, influential factors, strategies, techniques, and computer aids in 100 UK manufacturing companies. The major contribution of this study was guidelines for good ECM

practices [1]. Huang *et al.* also draw upon the findings from the interviews that were conducted within four Hong Kong manufacturing companies in 1999 to investigate the state of ECs problem and the industrial practice in managing ECs. They have examined the ECs in the aspects of volume, sources, and effects whereas the present industrial practice in managing ECs have focused their investigation in terms of documentation, organization, and activities. Two general findings from this study were that 1) EC is a noticeable problem that cannot be underestimated and 2) the management of ECs was unsatisfactory in the companies surveyed [6]. This indicates the need for a good ECM system including guidelines, methodologies, and/or techniques so that ECs can be dealt in a more effective manner within the product development process. Eckert *et al.* comprehensively analyze the problems and processes associated with product change. They specifically looked at the potential causes and effects of changes. They also analyse the formal and informal processes that are used to handle changes [5]. This descriptive study has led to the development of a computer support tool that gives an indication of the risk of a change affecting other systems [8]. This study has provided designers and design managers with a greater overview over the product. Veldman and Alblas carried out a multiple case studies to uncover the effects of engineering changes on companies' standard products and processes. The study found that companies were struggling with the amount of standardization required in their EC decision processes. There are conflicting needs emerging from several parts of the development lifecycle [9].

Ahmed and Kanike link the causes of changes to its lifecycle phase based on document analysis of 1500 reports of an aero-engine lifecycle. They found that most of the changes occur during the manufacturing and build phase. Moreover, they concluded that changes to the engineering specification together with meeting design criteria are the major causes during the prototype testing and development phase [10]. This study was the motivation for this research to further investigate change in specification. To understand the characteristic of change that is emerged in service phase Vianello and Ahmed analyze 250 documents of change request for the first two years service of an aero-engine. The aim of their study was to investigate the causes of changes in the service phase, where changes are most expensive [11], the study emphasised the need for a clear understanding of service phase issues at the earlier phases of product's lifecycle.

1.1 Research aims

This paper aims to understand the factors that contribute to change in specifications, its relation to the change initiator and its distribution during lifecycle phase of an aero-engine. The study also examines how the change requests were described.

There are three main research questions for this study:

- 1) How is change in specifications distributed during the phases of product lifecycle?
- 2) How the changes are initiated; by whom?
- 3) How change requests were described?

2 METHODOLOGY

The analysis of 1500 reports of change requests during an aero-engine development was carried out. This reports covering eight years of an aero-engine lifecycle including two years of the product in service. Each report is indexed to 38 true/false statements that describe the reason for change, implication of change and suggested solution. These reports originated during the; development & prototype phase, manufacture/build and testing phase and service phase of the engine's lifecycle [11]. This study focused on the changes that are associated to change in specifications, a total of 271 reports were identified that were associated with changes in specifications, and hence this subset of 271 reports were used for all the analysis. A report that is indexed with a false statement to the change in specifications was excluded from this study.

In order to quantify several aspects of change in specifications, the following codes were employed and of each 271 reports were indexed against these codes.

- Initiator for change:
 - Supplier: if the change is initiated by the company which supplies components to the producer.

Internal customer: if the company name is not mention in the text but the change has relation to the activities undertaken in the company.

External customer: if the external customer is clearly mentioned in the text and the name of the airline company is mentioned.

- Drivers for changes:
Error correction: if the change request has a clear relation to product deficiency.
Product improvement: if the change request has no relation to product deficiency.
- Change request description: detail explanation of the categorisation of description of change request is in the section 3.6.
- Change discovery methods:
Observation: by means of knowledge and expertise of stakeholders.
Assessment: through systematic approach by the means of instrument, software, calculation, etc.

3 RESULTS

The findings presented in this paper are primarily quantitative and also an initial qualitative analysis. The focus of the analysis was on the followings, which are presented in the next sections:

- Understanding of the distribution of changes that are associated to change in specifications during three different phases of the product's lifecycle.
- Understanding of the primary driver for change in specifications during the product's lifecycle.
- Understanding of the discovery of change in specifications during the three different phases of the product lifecycle.
- Understanding of which design attributes are requested to be changed?
- Understanding of the initiation of change in specifications and the primary contributor for the initiation.
- Understanding how changes in specifications requests are described.

3.1 Distribution of changes in specification during the product's lifecycle

The reports were analyzed to understand the distribution of changes that are associated to change in specifications during the three different phases of the product's lifecycle. Initial analysis found that around 17% (47 reports) of change in specifications occur during the development phase, 71% (192 reports) of change in specifications have been identified as changes that were made during the manufacture/build and testing phase, and the remaining 12% (32 reports) of change in specifications occur during the service phase. This is shown in Table 1. The analysis also reveals that the majority of changes in specifications arise during the manufacture/build and testing phase. This result is in agreement with the report by Ahmed and Kanike about changes distribution in the product's lifecycle, and also the work of Gries *et al.* [10][13], and hence shows that change in specifications follows a similar distribution all changes.

Table 1. Number of change in specifications reports at different stages of the product's lifecycle

Lifecycle phase	No. of reports	Percentage (%)
Development phase	47	17
Manufacture/build and testing phase	192	71
Service phase	32	12
Total	271	100

3.2 Change in specifications drivers during the product's lifecycle

The reports were analyzed to understand the primary driver for change in specifications in the product's lifecycle. The analysis found that there were two main drivers:

- Product improvement: changes that are made to improve product as to respond to external request due to external factors (i.e. innovation, regulation, etc.).
- Error correction: changes that are made to rectify product as to respond to the internal or external request due to product deficiency.

The analysis found that in the development phase: 77% (36 reports) of change in specifications were due to product improvement and 23% (11 reports) of change in specifications were due to error correction. Whereas during the manufacture/build and testing phase, and during the service phase, 44% (84 reports) of change in specifications were due to product improvement (e.g. change the material to gain cost benefit) and 56% (108 reports) of change in specifications were due to error correction (e.g. redesign of bracket because it could not be fitted to the gearbox), 31% (10 reports) of change in specifications were due to product improvement and 69% (22 reports) of change in specifications were due to error correction.

The reports were also analyzed to understand the primary driver for the change in specifications during each of the three different phases of the product's lifecycle. The result of the study, as shown in Table 2, reveals that product improvement is the primary driver during the development phase, whereas error correction and product improvement are drivers in the manufacture/build and testing phase and only error rectification is a driver during the service phase. In general, the result of the analysis reveals that the error correction is the primary driver of change in specifications in the product's lifecycle and improvement only justifies the cost associated with a change in the earlier phases. Figure 1 shows the trend of the change drivers in the product's lifecycle.

Table 2, Distribution of change in specifications drivers in the product's lifecycle

Change driver	Lifecycle phase			
	Development phase	Manufacture/build and testing phase	Service phase	All phases
Product improvement	36 reports (77%)	84 reports (44%)	10 reports (31%)	130 reports (48%)
Error correction	11 reports (23%)	108 reports (56%)	22 reports (69%)	141 reports (52%)

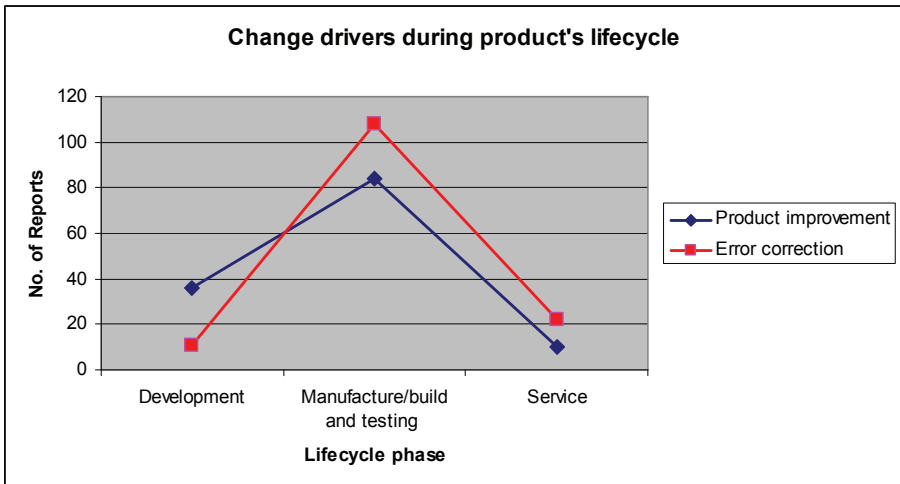


Figure 1 Change drivers during the product's lifecycle

3.3 Discovery of change in specifications during the product's lifecycle

The reports were analyzed to understand how change in specifications is discovered during the three different phases of the product's lifecycle. The analysis found that there are two methods of change in specifications discovery:

- 1) Observation: by means of knowledge and expertise of the stakeholders
- 2) Assessment: through systematic approach by the means of instrument, software, calculation, etc.

Table 3 summaries the discovery methods for change in specifications during the three different phases of the product's lifecycle. The analysis found that in: the development phase 89% (42 reports) of change in specifications were discovered through observation and 11% (5 reports) of change in specifications were discovered through assessment (e.g. the need to change IPC stub shaft for FBO was discovered through analysis of the whole engine model), in the manufacture/build and testing phase: 71% (136 reports) of change in specifications were discovered through observation and 29% (56 reports) of change in specifications were discovered through assessment and; in the service phase 69% (22 reports) of change in specifications were discovered through observation and 31% (10 reports) of change in specifications were discovered through assessment. In general the majority changes in specifications were discovered through observation during the product's lifecycle, although in the latter phase systematic approaches to discover changes are also significant. This finding highlights the significance and reliance of knowledge and experience of those who discover the need for change.

Table 3. Discovery methods of change in specifications during the product's lifecycle

Change discovery methods	Development phase		Manufacture/build and testing phase		Service phase	
	No. of reports	Percentage (%)	No. of reports	Percentage (%)	No. of reports	Percentage (%)
Observation	42	89%	136	71%	22	69%
Assessment	5	11%	56	29%	10	31%

3.4 Design attributes that are requested to be changed during the product's lifecycle.

The reports were analysed to understand which design attribute is most likely to be requested to be changed. The analysis found that ten design attributes were changed, namely; design parameter, component interface, component, configuration, contractual, document/drawing, device setting, software, procedure and protocol. Table 4 summaries the three design attributes that are most changed during each of the phases of the product's lifecycle. The reports are indexed against multi-criteria, therefore they can have more than one design attributes that is changed as a result of anyone report.

Table 4. The three design attributes that are most likely be changed

Development	Manufacture/build and testing	Service	All phases
Interface (24 reports)	Design parameter (58 reports)	Device setting (6 reports)	Design parameter (68 reports)
Component (18 reports)	Component (40 reports)	Software (4 reports)	Component (60 reports)
Design parameter (10 reports)	Document/drawing (19 reports)	Document/drawing (4 reports)	Document/drawing (24 reports)

3.5 Distribution of change in specifications initiation during the product's lifecycle

The reports were analyzed to understand: how changes in specifications are initiated; who the main contributor for the change in specifications initiation and; their relation to the three different phases of the lifecycle. The analysis found that the initiators during the product lifecycle phase were one of the following:

- Internal customers: the employees of the aero-engine company.
- External customers: the customers of the aero-engine company.
- Suppliers: the components/sub-systems suppliers of the aero-engine company.

Table 5 shows that the internal customers contributed 76% to initiate the change in specifications, the external customers contribute 15% and the suppliers contribute 9% to the initiation of the changes.

Table 5 also shows the relation between change initiators to the three different phases of the product's lifecycle. The result of the analysis as shown in Table 5 reveals that the internal customers are the major contributor for the change in specifications initiation during the product's lifecycle. The internal customers contribute around 43%, 89% and 53% to change in specifications during the development phase, the manufacture/build and testing phase and the service phase, respectively. Whereas, suppliers are likely to request for change in specifications during the development phase. The analysis also found that the suppliers do not request any changes in the service phase. However, the reports during the product's service phase represent around two years its service phase, hence suppliers may contribute to change initiation as the product's service of the investigated product is not completed.

Table 5. Initiation of change in specifications during the product's lifecycle

Initiator	Development phase		Manufacture/build and testing phase		Service phase		All phases	
	No. of reports	Percentage (%)	No. of reports	Percentage (%)	No. of reports	Percentage (%)	No. of reports	Percentage (%)
Internal customers	20	43	170	89	17	53	207	76
External customers	11	23	14	7	15	47	40	15
Suppliers	16	34	8	4	0	0	24	9

3.6 How change in specifications request are described during the product's lifecycle

The reports were analyzed to understand the description of the change in specifications requests. The analysis found that the changes in specifications requests were described in the four different statements:

- Need statement: The need is the statement of requirement a high level description of quality.
- Need & Solution: The need and solution statement is combination of the need which is typically stated as a high level description of product quality and the solution is a proposal by which the means for the need can be satisfied.
- Solution: A solution is stated as an idea to accommodate a certain need or is stated more precisely such as the statement of what component/part need to be changed.
- Solution & consequences: This statement states the solution beside the implication of change; the benefits if the change is implemented or the drawbacks if the change is ignored.

The analysis found that around 29% of the change requests were described in the need statements, 56% in the need and solution statements, 11% in the solution statements and 4% in the solution and consequences statements as shown in Table 6. The majority of change requests were described in terms of the need and solution statement. The low percentages of the reports which also describe consequences of a change (only 4%) highlight the difficulty in understanding the propagation of a change on one component to another.

The reports were also analysed to understand the distribution of the different types of change requests descriptions between the three different product's stakeholders. It was discovered that internal customers prefer to describe the change requests in the solution and need statements where both external customers and suppliers prefer to describe the change requests in the need statements. This is presented in Table 6.

Table 6. Description of change requests for the three different stakeholders

Description of change requests	Percentage of reports			
	Internal customers	External customers	Suppliers	All Stakeholders
Need statement	24%	52%	61%	29%
Need and solution statement	61%	40%	16%	56%
Solution statement	11%	8%	16%	11%
Solution and consequence statement	4%	0%	7%	4%
Total for each initiator	100%	100%	100%	100%

4 DISCUSSION

A study has been carried out to analyse over 1500 of the change reports of an aero-engine during its lifecycle phase spanning over eight years period, and including two years of the product in service. The approach was adopted to conduct a thorough analysis regarding change in specifications during

the product's lifecycle. This includes understanding the distribution of change in specifications, the drivers, discovery and the parameters that were requested to be changed; the initiation and how the requests are described.

The study found that the majority of change in specifications arises during the manufacture/build and testing phase. This result maybe related to the initiation of change in specifications which was likely be initiated by the internal customers. The study found that the internal customers contribute to around 76% to the initiation of change in specifications during the manufacture/build and testing phase. This finding also follows the previous study to understand the number of changes that occur during the three different phases of the product's lifecycle [10] where the study found that around 76% of changes occurred during the manufacture/build and testing phase. A similar pattern of changes distribution was also observed, in a comparative study between an aero-engine and oil rigs [11] and this highlights the generality of changes distribution pattern in a product's lifecycle.

As change requests are always concentrated at this phase of the product's lifecycle, further investigation of the relations between them (a change request to another change request) is needed to avoid conflicts, between requested changes. Further more it would help to avoid the repetition of work as the time progress. The study also found that two main methods were used for discovery of change in specifications: observation and assessment. However the majority of change in specifications was discovered through observation. To ensure ECs can be discovered as early possible, assigning the right person with the right task at the right time at the planning phase is vital. This finding also highlighted the importance of individual knowledge and expertise to discover the need of changes.

The need for change is usually discovered during the integration and testing of parts and systems [8]. In the manufacture/build and testing phase the components or sub-systems were subjected to physical testing, manufacture and assemblies. These activities may reveal the deficiency of the product leading to the change in specifications requests. The deficiency of the product is termed as an emergent change with need for correction [8]. The study found that the error correction is the primary driver for change in specifications in the manufacture/build and testing phase and during the product's lifecycle. Error correction contributes to around 56% of the change in specifications during the manufacture/build and testing phase. Changes for product improvement are likely earlier in the product's lifecycle.

During the product lifecycle phase the study found that change in specifications initiation is always described in terms of need and solution. However each of the change initiators have their own preference in describing change requests and the study reveals that the internal customers prefer to describe change request in the solution and need statement meanwhile the external customers and suppliers prefer to describe the change requests in the need statement. The internal customers are company employees who have their own specialty and function; hence, it is not surprising that they prefer to describe their change requests in the solution statement since they are most likely to know how to fix these problems. To satisfy a change request, engineering designers are required to find a low impact solution. However, if the solution from the initiator of change is always accepted then change process must be managed in a efficient way for cost and time minimization. Therefore, further investigation of changes due to design error and detail classification of them is essential to ensure proper production planning can be done prior to production. Proper planning of production enables companies to reduce the impact of a change to the whole production capacity.

The research reveals that the suppliers were most likely to request for the change during the development phase and they do not request for any changes in the service phase. This highlights the importance of involvement of suppliers in the earlier phases of the product's lifecycle to define specifications. The paper also highlights that changes are most likely to be discovered by internal customers. This result is in agreement with the finding of Ahmed and Kanike[10]. They have found that externally initiated changes are more likely to take place in the earlier phases of the product's lifecycle and they considered it is an external initiation if the originator of the change was; customer, supplier or contractual. The finding highlights the important of clients and suppliers need to modify specifications. Since the reports during the product's service phase represent around two years of its service phase, the suppliers may still request changes as the product service is not completed.

The results of the study also reveal that the three design attributes that are likely to be changed during the product's lifecycle are: the design parameter, component and document/drawing. This highlights the importance for engineers to consider interface, component and design parameter in designing a complex product such aero-engine and their relation. An understanding of the dependency and their

function, through approaches such as a Design Structure Matrix may help address knowledge of interfaces and may help to reduce the number of changes during the product's lifecycle [12].

5 CONCLUSION

A study has been carried out to analyze a complex product's lifecycle with over 1500 reports spanning over eight years period, and including two years of the product in service. The approach adopted was to conduct a deep analysis of one case to understand change in specifications. From the document analysis, it was found that the majority of change in specifications, around 71%, occurs during the manufacture/build and testing phase. It was also found that there are two drivers for change in specifications. That is error correction and product development. Further more, the analysis found that error correction is the primary driver for change in specifications during the product's lifecycle.

The research has highlighted the way the changes in specifications were described. The study found these changes were mostly described in terms of need and solution statement. Two methods for change in specifications discovery were identified: observation and assessment. The observation method is the dominant method to discover change in specifications during the product's lifecycle. This highlights the importance of experience and expertise of individual in carrying out the design tasks.

The research also highlighted that the three design attributes that is most likely be changed are; design parameter, component and document/drawing. Finally the research has found that the internal customers are the primary change initiator at each stage of a product's lifecycle and the suppliers are likely to request for change in specifications during the development phase.

Several issues have to be considered while designing a specification i.e. the technical content, the role of specification during the design process, etc. This is to ensure change in specifications leading to engineering changes due to specification deficiency would not likely to occur particularly in the later phase of a product's lifecycle. Beside that, change in specifications would occur in the other way round which mean that change in the product leading to change in specifications. Thus it would be beneficial to design a specification with mind the change in specification is likely to occur.

ACKNOWLEDGEMENT

The authors would like to thank Rolls-Royce for their permission to access change reports of an aero-engine.

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