Requirements and Use of In-service Information in an Engineering Redesign Task: Case Studies from the Aerospace Industry

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Abstract
This paper describes the research stimulated by a fundamental shift that is occurring in the manufacture and marketing of aero engines for commercial and defence purposes, away from the selling of products to the provision of services. This research was undertaken in an aerospace company, which designs and manufactures aero engines and also offers contracts, under which it remains responsible for the maintenance of engines. These contracts allow the company to collect far more data about the in-service performance of their engines than was previously available. This paper aims at identifying what parts of this in-service information are required when components or systems of existing engines need to be redesigned, because they have not performed as expected in service. In addition, this paper aims at understanding how designers use this in-service information in a redesign task. In an attempt to address these aims we analysed five case studies involving redesign of components or systems of an existing engine. The findings show that the in-service information accessed by the designers mainly contains the undesired physical actions (e.g. deterioration mechanisms, deterioration effects, etc.) and the causal chains of these undesired physical actions. We identified a pattern in the designers' actions regarding the use of these causal chains. The designers have generated several solutions that utilize these causal chains seen in the in-service information. The findings provide a sound basis for developing tools and methods to support designers in satisfying their in-service information requirements effectively in a redesign task.

Keywords: information types, in-service information, aerospace engineering, knowledge management, redesign, document analysis

Introduction

Recently, a shift in business models from selling of products to provision of services is becoming noticeable (Mont, Dalhammar, & Jacobsson, 2006). Such shifts in business models influence design of products (Jagtap, Johnson, Aurisicchio, & Wallace, 2006). Since design is an information-intensive activity, this has a subsequent impact on the types of information accessed by designers (Jagtap, 2009). In the field of engineering design research, several studies focusing on engineering information issues such as designers' information-seeking practices, and designers' access and retrieval of information from paper-manuals and electronic systems, have been undertaken in industrial environment (Aurisicchio, 2005; Court, 1995; del-Rey-Chamorro, 2004; Marsh, 1997). In the area of information science research, there are several studies that examine engineers' information behaviours such as: how engineers seek, process, and use information; distribution of their working time among activities associated with information seeking and use; their judgment regarding relevance of information; their e-learning behavior; their access to different types of information sources; and factors influencing their assessment of information sources (Allard, Levine, & Tenopir, 2009; Balatsoukas & Demian, 2010; Fidel & Green, 2004; Hertzum & Pejtersen, 2000; Kwasitsu, 2003; Ong, Lai, & Wang, 2004; Robinson, 2010). However, these studies do not focus on a specific type of information, such as in-service information.

In the global market of air transport, integration of products and services is now seen as being necessary for the long-term success of engine manufacturers. A fundamental shift is occurring in our collaborating company, away from the selling of products to the provision of services. The company now offers contracts, under which it leases engines to airlines while remaining responsible for their maintenance. Different services such as repair and overhaul, technical publications, inventory management, predictive support through engine health monitoring, etc. are designed for those contracts. These contracts thus transfer the technical and financial burden of engine maintenance and management to the manufacturer. This affects the design of new and existing engines, which now need to have low and predictable maintenance costs, in addition to the previous requirements of reliability and low specific fuel consumption. By incorporating in-service experience from existing engines in the (re)design of components in existing or new engines, it is hoped to tackle some of the current in-service issues through better design. In a *redesign* task, components or systems of an *existing* engine are redesigned when they do not perform as expected in service.

A flow of in-service information to designers is thus crucial for minimising in-service issues, and can also reduce the cost of both planned and unplanned maintenance (Jagtap, Johnson, Aurisicchio, &Wallace, 2007). In-service information is the information on product and support services such as repair, overhaul, etc., and is generated after the product's entry into service. In order to develop tools and methods required to capture, structure, store, and retrieve in-service information such that it can be used effectively by designers in a design task, it is important to understand their in-service information requirements and how they use this information in a design task. The work presented in this paper aims at:

- identifying in-service information required by designers in a design task, and specifically in the *redesign* of components or systems in an existing engine; and
- understanding pattern (if any) in different activities of designers when they use in-service information in a redesign task.

In an attempt to address these aims, five case studies involving the redesign of components or systems of existing engines are used.

Background literature

In-service information and product design

The reviewed literature confirms the importance of in-service experience, in improving the (re)design of existing and new products. Alonso-Rasgado, Thompson, and Elfström (2004), with reference to the design of functional (or 'total care') products, mention the importance of service data collection and storage. They define 'total care' products as "integrated systems comprising hardware and support services" (p. 515). The support systems maintain the hardware in working condition. Thompson (1999) describes the importance of information related to maintenance for design actions. Operating records are a vital source of information for designers. Periodic interviews with maintenance personnel, and the records kept by these personnel, also provide useful information for designers. Sander and Brombacher (2000), in connection with high volume consumer products, state that in order to improve future products, the entire relevant service experience from previous products should be evaluated, stored and used. A clear understanding of the causes behind the failures of existing products is important in the (re)design of existing and new products. Petkova (2003) describes the consumer electronics products' field feedback that companies require in order to make decisions regarding product quality. A recent study carried out by Vianello and Ahmed (2009) identified that the engineering designers require in-service information at a component level to improve next generation of products through design. Their study is based on the interviews with engineering designers and service engineers from oil industry. Those designers were interested in in-service information in a structured form so that it can be used in their different activities during a design process.

Engines that are leased to airlines require long service intervals, ease of maintenance and high reliability (Kirkland & Cave, 1999). Harrison (2006) has discussed the elements of the process, describing problems and successes in the deployment of 'Design for Service' for the Trent 1000 aero engine, used in the Boeing 787 aircraft. He has listed some of the significant operator cost drivers such as: range and payload, safety, schedule reliability, life cycle fuel burn and engine overhaul. He states that in-service information is useful to understand the following issues, which can address all of the above drivers positively:

- understanding the engine's deterioration mechanisms;
- controlling their rate of occurrence and their impact;
- ensuring effective and low-cost restoration of capability at overhaul.

Lannoy and Procaccia (1996) state that, for creating a database from operation feedback, it is necessary to identify the needs of its potential users. Data regarding reliability, maintenance, operations, service, market, management focus, etc. helps to improve the product. The data has to be stored in systems that make it easy to retrieve, analyze, and draw conclusions (Markeset & Kumar, 2003). Some of the aspects behind the design of information management systems are to identify the users and their requirements. Although the aforementioned literature suggests the importance and usefulness of in-service information in the design of products, and identifies the need to understand designers' in-service information requirements, it does not provide a detailed understanding of what in-service information is required by designers, or of how they use this information in a design task. Our research addresses these gaps in the reviewed literature.

Redesign case studies

Several case studies aimed at identifying causes behind the failures of various components, and describing the redesign of these components, are available in the reviewed literature (Gagg & Lewis, 2007; MacGregor, 2003; Sivaprasad, Narang, & Singh, 2006; Smith, Fisher, Romios, & Es-Said, 2007). For example, Gagg and Lewis (2007) have described seven case studies regarding wear of components in service; and in three of these case studies, design changes to avoid future failures in these components have been described. The causes behind the failures have clearly played an important role in directing the design changes. However, these case studies are not focused on the in-service information that might be considered by the designers in the redesign activity.

The reviewed literature does not report case studies that aim at understanding how designers use in-service information in executing design changes. Sander and Brombacher (2000), Brombacher, Steinz, and Volman (1998), Petkova (2003), and the aforementioned case studies highlight the importance of the root causes in the design changes. However, they do not examine the designers' activities or pattern in these activities when they use the information on root causes or causal chains in the in-service experience. Our work addresses the weaknesses and omissions in the above studies by identifying in-service information required by designers in a redesign task and understanding how they use this information in that task.

Functionality, causality, and side effects in a technical system

We present a brief review of literature on the theory of technical systems because we have used a model of causality (i.e. the SAPPhIRE model) found in this literature for analysing case studies to fulfil one of our aims of understanding how designers use in-service information in a redesign task.

A given function of a technical system is achieved by a *physical process*, which is realised by physical effects and the geometric and material characteristics of the system (Pahl & Beitz, 1996). Chakrabarti (1993) proposes *function* as a relation (or relations) between at least two situations which describe the measurable responses of an artefact to measurable external stimuli. He proposes *form* as structural descriptions of a solution, and could be described by one or a set of situations.

Pahl and Beitz (1996) define *side effect* as "functionally undesired and unintended effect of a technical system on a human or on the environment" (p. 43). Chakrabarti and Johnson (1999) discuss the issue for identifying side-effects in conceptual solutions. They define *side effects* as effects whose outputs influence the intended operations of a system. Side-effects can be identified by noticing the inputs and contexts that are available in the situation in which a system works. From these inputs and contexts, the possible physical effects that might get activated can be identified.

There are multiple meanings and representations of function, form, design problems and solutions (Chakrabarti, 1993). The SAPPhIRE model provides a rich causal explanation of a physical phenomenon and attempts "to reach a nonarbitrary degree of detail of behavioural explanation" (p. 118) (Chakrabarti, Sarkar, Leelavathamma, & Nataraju, 2005). The SAPPhIRE (*S*tate-*A*ction-*P*arts-physical *Ph*enomenon-*I*nputs-o*R*gan-physical *E*ffect) model explains the relationships between the following seven constructs (Chakrabarti et al., 2005):

- parts - "a set of physical components and interfaces constituting the system and its environment of interaction" (p. 117);
- state - "the attributes and values of attributes that define the properties of a given system at a given instant of time during its operation" (p. 117);
- organ - "the structural context necessary for a physical effect to be activated" (p. 117);
- physical effect - "the laws of nature governing change" (p. 117);
- input - "the energy, information or material requirements for a physical effect to be activated; interpretation of energy / material parameters of a change of state in the context of an organ" (p. 117);
- physical phenomenon - "a set of potential changes associated with a given physical effect for a given organ and inputs" (p. 117); and
- action - "an abstract description or high level interpretation of a change of state, a changed state, or creation of an input" (p. 117).

The relationships between these constructs are shown in Figure 1. The SAPPhIRE model thus provides a rich causal explanation of an action.

Figure 1. SAPPhIRE model of causality (Chakrabarti et al., 2005).

The SAPPhIRE model (see Figure 1) can be useful in tackling the confusion created by the multiple meanings and representations of the various concepts such as function, behaviour, structure, etc. We believe that this model has integrated the concepts, namely function, behaviour, and structure. The constructs 'parts' and 'organs' explain the structure of a device, and the construct regarding the changes in states describe the behaviour of a device. Regarding the function of a device, the authors state, "In our view, function is seen as specific, limited, intended aspects of the rich causal behaviour of artifacts embedded in and in conjunction with the environment in which it operates, and could be seen as

- State change
- Attained, final state
- Inputs
- I/O transformation
- Creation of the context for physical effects to appear, i.e., organs, etc" (p. 117).

Furthermore, this model is useful in explaining physical actions, such as corrosion or wear, that result from the operation of products in service, and which are subsequently seen in the in-service information. We have used the SAPPhIRE model in the analysis of case studies in order to understand pattern in different activities of designers when they use in-service information in a redesign task

Redesign case studies

Selection of research method

Five case studies involving the redesign of components in an existing aero engine, based on their in-service information, were carried out. Redesign case studies were selected because the redesign was mainly based on the in-service experience, and this helped us to examine a large amount of in-service information. These case studies were aimed at seeing what in-service information was accessed by the designers in those redesign tasks, and at understanding pattern in their activities when they used this in-service information in those redesign tasks.

Several studies (Cross, Christiaans, & Dorst, 1996; Khadilkar & Stauffer, 1996; Kuffner & Ullman, 1991; Restrepo & Christiaans, 2004), regarding designers' information requirements or their information-seeking activities, have been carried out in laboratory settings with experienced designers or students. As there are several limitations on a study carried out in a laboratory setting (e.g. number of participants, artificial nature of the design problem, etc.), these studies do not fully represent the actual working conditions of designers from a company. Therefore, the findings of these studies do not necessarily reflect the actual information requirements of professional designers working in a company which operates in a competitive environment.

An alternative way to identify all pieces of in-service information accessed and used by the designers is to observe them throughout the design process. This type of study is hard to conduct in an industrial environment for the following reasons:

- designers work on more than one project or task at different times in a day;
- it is difficult to anticipate when the designers will access and use in-service information on a given day;
- the time-spread of the redesign task can be several months, and gaining access to the designers for this period is difficult.

Therefore, we examined the Design Definition Reports (DDRs) from the aerospace group of a major power systems company involved in the delivery of products and services to four market sectors, namely civil aerospace, defence, marine, and energy. The aerospace group in this collaborating company is involved in the design, manufacture and provision of service support for aero engines. These DDRs summarise the design changes made during a redesign task, and are written retrospectively by the designers themselves. The number of designers that contribute towards writing a DDR ranges from two to four. The diary notes taken throughout the design process assist the designers in documenting a DDR. Designers take these diary notes on the daily basis, and the format of these notes is textual plus diagrammatic.

The following positive aspects of document analysis are also applicable to the analysis of DDRs:

- document analysis is a non-reactive method: that is, using documents does not have an effect on the object of study (Robson, 2002);
- it saves time on the part of the company employees;
- there is no transcription burden.

Two of the main limitations of the analysis of the DDRs are as follows. Firstly, they are written by the designers themselves. It is likely that they might forget to document some information in a DDR. However, the diary notes taken through the design process help the designers in documenting a DDR, and minimise the likelihood of omitting any important information. Secondly, a DDR is not written for the researcher's purpose. It was necessary to contact the designers and service engineers when we found any unfamiliar terms or concepts.

Data collection method

A DDR is structured in three main sections:

- Specification Requirements - this section describes the in-service experience of version-1 (the component before redesign) and the requirements for version-2 (the component after redesign);

- Alternative Solutions - describes the different alternative solutions and also mentions the final solution selected for further detailing;
- Solution Description - describes the various decisions made in the actual design changes, and the rationale behind these decisions.

In total, we analysed five DDRs. Each case study consisted of one DDR.

Semi-structured interviews were also conducted with service engineers and designers. The questions were directed towards understanding: the construction details of the components or systems before and after redesign; in-service experience of version-1; different alternative solutions generated; and the changes carried out on version-1 to achieve version-2. For each case study, the participants for these interviews consisted of two designers and two service engineers. These designers were involved in the redesign of the components or systems and in documenting the DDR. The service engineers provided the required in-service information to the designers during the redesign process. All participants were males.

In selecting the five case studies, attention was directed to cover different modules of an aero-engine (see Table 1). Two components were selected from combustors, and one from each of the other assemblies, namely turbines, compressors, and transmissions. Due to our confidentiality agreement with the collaborating company, the components' details such as their structure, the in-service experience of version-1, and the design changes, cannot be presented in detail. Appendix A1 presents some information on the component 'burner seal' from combustors, and also includes examples of sentences from the DDRs. The selected case studies were fairly recent, and the initial in-service experience of the redesigned components or systems from these case studies showed that their redesign was successful.

Table 1. Case study components and engine modules.

Method of analysis

The DDRs were analysed from two novel perspectives, namely *informational* analysis and *explanatory* analysis. We developed these two types of analysis-methods to fulfil our research aims. The informational analysis was aimed at understanding what in-service information is accessed by the designers in the redesign tasks. The explanatory analysis was aimed at understanding any patterns in using this information.

Informational analysis

Baya and Leifer (1996) employed the following criteria in segmenting the data gained through a design experiment:

- change in the designer's train of thought;
- changes in designer's attention from one concept to another;
- pauses in the audio recording (think aloud protocol);
- change in the informational activity;
- certain phrases in the data (e.g. o.k., umm, etc.).

Their research was aimed at identifying the different ways in which designers use information, and the amount of information handled by the designers.

Depending on the research aims, different criteria (e.g. meaningful piece of information, intentions and actions of designers, syntactic markers, etc.) have been used to segment the data collected through empirical research (Dwarakanath & Blessing, 1996; Gero & Tang, 2001; McAlpine, Hicks, Huet, & Culley, 2006).

The segments in the transcripts of a protocol experiment can be pauses, sentences, clauses, phrases, or words (Ericsson & Simon, 1993). In analysing the contents of a document, Robson (2002) uses the term 'recoding unit' in place of 'segment'. The words, paragraphs, etc. of a document can be regarded as recording units. Chi (1997) states that the non-content features of the data such as words, sentences, etc. can be used as segments, depending on the research questions posed.

In this research, individual sentences of the DDR were used as segments, for the following reasons.

- It seemed appropriate for a document that is created by the designers retrospectively, after completion of the design task.
- It fulfilled our aim of identifying the in-service information that was accessed by the designers.
- It helped to objectively maintain consistency in the segmentation process, and to compare the findings quantitatively. For example, the percentage of sentences under the different topics of in-service information helped to measure the relative frequencies of accessing information under these topics.
- It helped in interpreting the different activities of the designers (e.g. formulating requirements, analysing the problem, generating solutions, etc.), and in correlating the different sections of a DDR with the design process stages (e.g. task clarification, conceptual design, etc.).
- It helped in understanding the different activities of the designers regarding the in-service information that they used, and in seeing when they used this information in the design process. This is evident from the findings explained further in this paper.
- It helped to achieve the sufficient degree of detail in our analysis. This degree of detail, for example, would have been unlikely to attain by using paragraphs of the DDRs as segments.

The first author of this paper coded all the five DDRs. The coding scheme consisted of labelling each sentence with the relevant categories, as discussed later in this Section. For example, as the research focus is on the in-service information requirements of designers, 'in-service information' was one of the categories. Thus, whenever the designers appeared (based on our interpretation of a DDR's content) to be accessing the in-service information, the relevant sentence was marked with that category.

The context in which the sentence appeared played an important role in the coding process. The following items helped to establish the context:

- the paragraph in which the sentence was embedded;
- the previous and subsequent paragraphs;
- the section of the DDR;
- any additional explanations provided by the designers and service engineers during the semi-structured interviews.

As the coded data was concise, it was easy to handle for answering the research questions. In addition, the designers' in-service information requirements could be quantitatively observed. The findings are presented in terms of the different categories. Figure 2 explains the steps involved in the coding process and the outputs of these steps. In this figure, the bulleted lists show the outputs of the coding process. For each sentence of the DDR, designers' activity was interpreted. As shown in Figure 2, these activities are 'access information', 'analyse problem', 'formulate requirement', 'generate solution', 'evaluate solution', 'detail solution', and so on. All sentences under the 'access information' activity were selected, and for these sentences the information types were interpreted. Different topics (e.g. 'deterioration information', 'statistical information', etc.) were interpreted for the sentences that were classified under the in-service information type. The topic 'deterioration information' was further classified into different subtopics (e.g. 'deterioration mechanism', 'deterioration effect', etc.) because deterioration information plays an important role in redesign, and this is clear from the findings of the informational analysis. These findings are presented further in this paper.

The different categories, which are the outputs of the coding process, evolved during the analysis. The reviewed literature (Baya & Leifer, 1996; Davidson & Hunsley, 1994; Marsh, 1997; Motte, Andersson, & Bjärnemo, 2004; Nidamarthi, 1999; Pahl & Beitz, 1996; Peres et al., 2007; Pinna et al., 2005) helped to formulate the initial set of categories. This set evolved into the current set of categories while analyzing the DDRs' sentences. After reading a sentence and understanding the context, the sentence was categorized under the current categories if it was possible. Sometimes, the current categories required refinement or clarification of their meaning before a sentence could be categorised. New categories were created when the sentence could not be categorized under the existing set of categories.

In order to validate the data analysis method, 50 sentences from a randomly selected DDR were coded to identify designers' activities only (e.g. access information, analyze problem, etc.) by two people – the researcher (i.e. the first author of this paper) and one coder. Prior to this coding, we explained the coder the different activities of designers with examples. The coder read the complete DDR before coding the given 50 sentences. There was 92% agreement between the researcher and the coder.

Figure 2. Steps in the coding process. *Notes*: (1) The bulleted lists show the outputs of the coding process; (2) The underlined numbers in brackets show the number of sentences (e.g. for 234 sentences under the 'access information' activity, we interpreted information types).

The outputs of the coding process (i.e. designers' activities, information types, topics under the in-service information, and subtopics of the topic 'deterioration information') and the definitions used to interpret these outputs are explained with examples in Appendix A1.

Explanatory analysis

In order to understand any patterns in the process of using in-service information in a design task, it is necessary to know what in-service information was accessed by the designers in that design task. Therefore, the informational analysis was conducted before the explanatory analysis. This helped the researcher in understanding and remembering the accessed in-service information.

The researcher examined the DDR repeatedly asking himself questions such as 'is this designer's activity based on the in-service information he has accessed?', 'are designers making use of the issues seen in the in-service information?', 'what is the intention behind using the in-service information (e.g. to generate alternative solutions, evaluate solutions, etc.)?', etc.

This repeated examination revealed that the designers considered the different physical actions (e.g. deterioration mechanisms such as wear, corrosion, etc.; deterioration causes; and deterioration effects) seen in the in-service information, and they then generated solutions aimed at tackling those deterioration mechanisms. This is also evident from the findings of the informational analysis presented further in this paper.

In an attempt to model these physical actions and their chains, the SAPPhIRE model of causality (Chakrabarti et al., 2005) was considered. We define a causal chain as the sequence of physical actions in which one physical action contributes to the occurrence of the next physical action. The SAPPhIRE model is explained in Section on background literature. The SAPPhIRE model provides a rich causal explanation of a physical action, and is useful in explaining concepts such as deterioration mechanisms, deterioration causes, and deterioration effects.

We analyzed the DDRs to identify the constructs of the SAPPhIRE model, and to identify the following three aspects of each redesign:

- the chains of physical actions (e.g. deterioration mechanisms, deterioration causes, etc.) considered by the designers in the in-service information;
- the intentions behind the alternative solutions (a solution consists of a single change mentioned by the designers);
- the physical actions (side effects) and/or 'other' aspects due to a change suggested by a solution. ('Other' aspects are not physical actions but issues regarding manufacturing, time, cost, etc.)

The identification of the above three aspects is explained in Appendix A2 by providing examples from the burner seal case study.

In order to validate the data analysis method, one DDR was analyzed by two people – the researcher and one coder - to identify chains of physical actions, intentions behind alternative solutions, and physical actions and/or 'other' aspects due to a change suggested by a solution. Prior to the analysis, the coder was explained the SAPPhIRE model of causality and researcher's analysis method with examples drawn from the DDR regarding the burner seal. The coder analyzed the DDR related to the lockstrap. There was 89% agreement between the researcher and the coder regarding the above aspects (e.g. identified chains of physical actions, intentions behind alternative solutions, etc.).

Findings: Informational analysis

This section presents the findings of the informational analysis. There are two alternatives to present the findings of the five case studies: (1) calculating the results of the five case studies collectively; and (2) calculating the results of each of the five case studies, and then calculating the means and standard deviations across all these case studies. We selected the first alternative of presenting the collective findings of all the five case studies. The second alternative would have enabled us to carry out statistical significance test. However, we selected the first alternative (i.e. collective findings) because the sample size (i.e. number of case studies) is small for meaningful statistical significance test.

Activities

In total, 597 sentences were identified in the five DDRs. The average number of sentences per DDR is 119 with a standard deviation of 59 sentences. Figure 3 shows the distribution of these sentences under the three sections of the DDR. The Solution Description (SD) section includes slightly less than one half of the sentences. About one fourth of the sentences are identified in the Specification Requirements (SR) and Alternative Solutions (AS) sections of the DDR.

Figure 3. Percentage of 597 sentences for the different sections of the DDR.

Figure 4 shows the percentage of sentences classified into the different activities. In the case of some sentences, more than one activity was noticed. Figure 5 shows the percentage of sentences for different activities found in the three sections of the DDR.

Figure 4. Percentage of the 597 sentences classified into the different activities. *Note*: In the case of some sentences, more than one activity was noticed. Therefore, the total of all percentages (39+10+4+9+34+16+4) is greater than 100.

Figure 5. Activities identified in the different sections of the DDR (percentage of sentences based on 597 sentences in the DDRs).

Figure 5 shows that the main activities of the designers seen in the SR section are 'access information', 'analyse problem', and 'formulate requirement'. The prominent activities interpreted in the AS section of the DDR are ‘generate solutions’, and ‘evaluate solutions’. In the case of SD, the prominent activities are ‘evaluate solution’ and ‘detail solution’. The activity ‘detail solution’ encompasses defining the arrangement of components and specifying materials, geometrical shapes, dimensions, manufacturing processes, etc. Pahl and Beitz (1996) state that, in the task clarification phase, information on the problem is collected, the problem is analysed, and design specifications are formulated. In the conceptual design phase, broad solutions are generated and evaluated. In the embodiment phase the layout of the assemblies and components are outlined and in the detail design phase, dimensions, tolerances, materials, surface properties, etc. are fully specified. This suggests that the SR, AS, and SD sections of the DDR provide an insight into the task clarification phase, conceptual design phase, and embodiment and detail design phase respectively (see Figure 6). The designers have a similar view regarding the DDR. The designers expressed this view when we presented the findings of this paper in one of the monthly meetings of the project called Integrated Products and Services (IPAS). The work reported in this paper was part of the IPAS. In each of these monthly meetings, at least one designer and one service engineer were present.

Figure 6. DDR sections provide insight into the different design process phases proposed by Pahl and Beitz (1996).

The following points can be noted from Figures 4 and 5.

- The major share of the sentences is devoted to the activities ‘access information’ (39%) and ‘evaluate solution’ (34%).
- The ‘access information’ activity is identified in all the three sections of the DDR. The sentences that are classified under the ‘access information’ category are analysed in detail to identify the different information types. Therefore, this analysis covers the complete spectrum of the different phases of the design process.
- Sentences corresponding to the activities ‘analyse problem’ and ‘formulate requirements’ are identified in all the three sections of the DDR.
- All activities are seen in the SD section of the DDR. This may either be because this section consists of about one half of the total number of sentences, or because it is a characteristic of the embodiment and detail design phases.

Information types

In total, 234 sentences were identified under the ‘access information’ activity. In the case of some sentences, more than one type of information was noticed. This means that some sentences were classified into two or more types of information. The explanation of information type proposed by Court (1995), has been adopted in this work. He explains information type as what information is required to undertake a specific task (e.g. a material strength, why a particular design was used in past or how a design is to be installed in the working environment, etc.).

Figure 7 shows the percentage of sentences for the different information types. Most of these sentences refer to in-service information (50%) and design information (35%). Note that the sentences under the in-service information type include those that describe in-service information from components similar to the one being redesigned. Sentences under each of the information types are noted in all sections of the DDR (see Figure 8). Most of the sentences corresponding to in-service information appear in the SR section. In the case of the design information, the percentage of sentences gradually increases from the SR section to the SD section. This suggests that the use of this specific type of information increases gradually during the design process.

Figure 7. Distribution of the information types (percentage based on the 234 sentences under the ‘access information’ acti–vity). *Note:* In the case of some sentences, more than one type of information was noticed.

Figure 8. Types of the information in the different sections of the DDR (percentage based on the 234 sentences under the 'access information' activity).

From Figure 8 it is clear that, in the case of the SR section, the dominant information type is in-service information. In the same section, the activities 'access information', 'analyse problem' and 'formulate requirements' are seen (see Figure 5). It therefore seems that the in-service information has played a key role in the task clarification stage, i.e. in analysing the problem and formulating requirements.

In-service information

Figure 7 shows that one half of the sentences under the access information activity come under the in-service information type (i.e. total number of sentences classified under in-service information type was 116). 91% of these sentences are categorised into the 'deterioration information' topic, followed by 'maintenance information' (15%) (see Figure 9). This suggests that the information on the topic 'deterioration information' is frequently accessed by the designers in these redesign tasks. In the case of some sentences, more than one topic of in-service information was noticed.

Figure 9. Distribution of sentences under different topics of in-service information (percentage based on 116 sentences under the 'in-service' information type). *Note*: In the case of some sentences, more than one topic of in-service information was noticed.

Figure 10 shows distribution of the different subtopics under the topic 'deterioration information'. The subtopics, - deterioration mechanism (DM), deterioration cause, DM location, and deterioration effect account for over 80% of the sentences under the in-service information type. In the case of some sentences, more than one subtopic of the topic deterioration information was noticed.

Figure 10. Distribution of the different subtopics under the topic deterioration information (percentage is based on the 106 sentences that are classified as 'deterioration information'). *Note*: In the case of some sentences, more than one subtopic of the topic deterioration information was noticed.

These findings are consistent with the expectations of designers, and the experts who deal with the management of in-service information for the designers. The monthly IPAS meetings, where we presented the findings of this work, helped us to identify this consistency. In these meetings, designers and service engineers expressed that our findings were in congruence with their expectations. This increases our confidence in the method of analysis and the findings.

The sentences that are classified into in-service information type cover those that consider in-service information from components similar to one being re-designed. In total, 12 percent of the sentences under in-service information type take into account such information. It appears that designers have used the type of component as criterion to search for similar components.

Findings: Explanatory analysis

The collective findings of the five case studies are presented in Table 2. In total, 22 causal chains are identified in the in-service information.

Table 2. Number of causal chains identified in the in-service information, causal chains used in generating solutions, and number of solutions generated.

In total, 44 solutions are generated in the five case studies, and 37 solutions (84%) are generated by considering causal chains. Out of these 37 solutions, physical actions and / or ‘other’ aspects are identified or speculated on in the case of 29 solutions (78% of the 37 solutions). Out of these 29 solutions, physical actions are identified or speculated on in the case of 19 solutions, and ‘other’ aspects in 21 solutions.

Based on the above findings, an overall pattern can be seen, when designers use in-service information in a redesign task. This is shown in Figure 11.

Figure 11. The overall pattern when designers use in-service information in a redesign task.

Figure 11 is explained below.
<u>Understanding the causal chains:</u>
The in-service information that is considered by the designers mainly consists of causal chains of physical actions (e.g. deterioration mechanisms, deterioration effects, etc.). The requirements for the redesign are formulated based on these causal chains. Figure 13 (Appendix A2) shows an example of a causal chain leading to the action corrosion. These causal chains consist of the relevant parts, the structural conditions, and the inputs that are necessary to bring about the physical actions.

<u>Modifying the causal chains:</u>
The findings of the analysis show that the designers of components of an existing engine have generated several solutions that utilise the causal chains seen in the in-service information (see Table 2). The causal chains that lead to the undesired physical actions (e.g. deterioration mechanisms, deterioration effects, etc.) provide the understanding of the inputs and the structural conditions necessary for the physical actions to occur. The designers have generated several solutions that attempt to eliminate these conditions, whilst maintaining the conditions that are essential to achieve the desired functionality of the component. In order to identify the undesired physical actions, it is necessary to understand the functionality of the system. The undesired physical actions are those actions that obstruct the system’s functionality. Figure 14 (Appendix A2) shows an example of a causal chain considered by the designers in generating a solution. In this example, the designers changed the organ that is created by the ring’s failure to follow the liner’s profile, and which leads to the undesired action ‘leakage’.

<u>Identifying or speculating on the side effects and/or ‘other’ aspects:</u>
In the case of some solutions, the designers have modified the causal chains leading to the undesired physical actions. These changes can activate other actions that can be either desirable or undesirable. The designers have identified or speculated these actions and/or ‘other’ aspects from the proposed solutions or design changes. Figure 15 (Appendix A2) shows an example of the identification of an action due to a design change.

Discussion and Implications

The case studies reported in this paper looked at the redesign of components or systems from different engine-modules, which had experienced problems in service. The informational analysis helped to identify what in-service information designers accessed in the redesign of those components or systems. The findings of the informational analysis suggest that, in redesigning components or systems of an existing engine, designers mainly access deterioration information. This deterioration information consists of data on the deterioration mechanisms, causes, effects, and locations of deteriorations. In addition, the findings suggest that the type of information accessed depends on the phase of the design process; and that a substantial amount of in-service information is accessed during the task clarification phase. Designers use in-service information at the start of the design process in the activities, namely when analyzing the problem and formulating requirements.

The explanatory analysis was aimed at understanding patterns in designers' activities when they use in-service information in a redesign task. The findings of this analysis suggest that the designers first understand the causal chain of physical actions (e.g. deterioration mechanisms, deterioration effects, etc.) in the in-service information, they then generate solutions by using these causal chains, and finally they evaluate the generated solutions by identifying or speculating on the side effects or 'other' aspects from the generated solutions. Thus, the informational and explanatory analyses suggest that designers mainly use causal chains of physical actions (e.g. deterioration mechanisms, deterioration effects, etc.) from the in-service information, and they use these causal chains in the early phases of the design process. The SAPPhIRE model of causality can help designers in using in-service information and in particular deterioration information effectively in the early phases of the design process. This is explained as follows.

Designers can use in-service information effectively in a redesign task if this information is represented diagrammatically. The reviewed literature (Aurisicchio, Bracewell, & Wallace, 2007; Hoffman et al., 2002; Kokotovich, 2008; Salustri, Weerasinghe, Bracewell, & Eng, 2007) suggests that the diagrammatic representation of information during the early phases of the design process has the following advantages:

- it helps designers to comprehend design problems;
- it improves the effectiveness and efficiency of early engineering design, and facilitates human cognitive processes fostering innovation; and
- information can be analysed at a faster rate than in a text format.

This suggests that the diagrammatic representation of in-service information and in particular deterioration information (e.g. deterioration causes, deterioration mechanisms, deterioration effects, etc.) is useful for improved comprehension and effective use of in-service information in a design task. In addition, this diagrammatic representation can allow designers to understand which parts of the causal chains of deterioration information are (or are not) used for generating solutions, and this can help them in generating useful solutions. The SAPPhIRE model of causality is useful in presenting the deterioration information in a diagrammatic format. It would be useful to present the relevant in-service information to the designers in the form of rich and detailed causal chains of physical actions seen in deterioration information, and broader causal chains as well. These broader causal chains can allow the designers to gain a more holistic view, and prevent them from being overwhelmed by the detailed causal chains. We recommend that service engineers should record all the relevant in-service information in a diagrammatic format for designers. They can create the detailed diagrams using the SAPPhIRE model of causality (for example see Figure 14). Furthermore, they can attach the relevant in-service experience, for example, pictures of failed components, statistical information, etc. to these causal chains.

The findings of the explanatory analysis show that the designers involved in the redesign of components or systems have not used 41% of the total number of causal chains seen in the in-service information to generate solutions (see Table 2). For example, if the designers had been presented with the deterioration information as shown in Figure 14, they might have noticed which parts of the causal chains are (not) used to propose a solution, and they might then have proposed additional solutions. In this example (Figure 14), designers have proposed a solution, which targets the 'organs' in the lower part of the detailed causal chain shown. However, they have not proposed a solution which targets parts/organs or inputs in the upper part of this detailed causal chain. This is evident from the diagrammatic representation of the deterioration information. This would be less evident if the information was presented in a text format as the causal chains are not explicit in such a format.

Currently, in the collaborating company the in-service information is stored in various disparate and heterogeneous sources (e.g. documents, databases). The possible agents to consolidate/structure the in-service information for the designers are human and computer, and are explained as follows. The findings of our research can help these agents.

In the collaborating company the members of the Technical Services and Operations (TS & O) team provide in-service information to designers. The TS & O team lacks in-depth understanding of designers' in-service information requirements. The members (i.e. service engineers) of the TS & O team need to be aware of the in-depth understanding of designers' in-service information requirements as identified in this paper. This will help these members to structure the in-service information such that designers can use it effectively in their design tasks. Educating the TS & O team members regarding the in-service information requirements of designers would facilitate their task of consolidating and structuring the in-service information appropriately. This education can consist of the different findings of this paper (e.g. in-service information required by the designers and patterns in their activities when they use this in a redesign task). Furthermore, the TS & O team members can structure the deterioration information in a diagrammatic format so that designers can use it effectively in a redesign task.

Recently, the use of ontologies is increasing in the engineering domain, including information systems aimed at retrieving information stored in more than one document. Devaney, Ram, Qiu, and Lee (2005), Shin, Busby, Hibberd, and McMahon (2005) employ ontology for the prediction and diagnosis of machinery failures. Wong, Crowder, Wills, and Shadbolt (2007) use ontology to integrate disparate and heterogeneous sources of information. They use automated information extraction tools (Ireson et al., 2005) to extract information from different documents, and subsequently populate a database. Kim, Bracewell, and Wallace (2007) developed a software tool to extract causality chains from textual documents. Information extraction can effectively process a large number of documents, and has shown a considerable improvement in retrieving relevant information compared (for instance) to keyword searches. Evaluation of these software tools suggests improved access to the causal chains extracted from documents. Such tools based on ontologies and information extraction methods are useful to infer causal chains of deterioration mechanisms, effects, etc. from the in-service information stored in different documents. The findings of our paper (e.g. topics of in-service information, subtopics of deterioration information as identified in the informational analysis) can help in developing ontology of in-service information required by designers.

The case studies reported in this paper looked at the redesign of components from different engine-modules, which had experienced problems in service. The typical design task in the collaborating company can be categorized as variant design. According to Pahl and Beitz (1996), in the case of variant design sizes and/or arrangement of certain aspects of a selected system are changed, while the function of the system is unchanged. Therefore, the design of components or systems in a new engine and the redesign of components or systems of an existing engine are similar in terms of the design types proposed by Pahl and Beitz (1996). The method of analysis and findings of this paper, which involved the redesign of components or systems of an existing engine, were presented through the monthly IPAS meetings to the designers of components or systems in a new engine, and those designers believed that the findings were applicable to their work as well. These designers of components or systems in a new engine were from the collaborating company. This implies that the findings of this paper should also be applicable to the design of components or systems of a new engine.

The findings reported in this paper are based on the analysis of redesign case studies from one aerospace industry. These findings can be applicable to other industries (e.g. automobile, chemical plants, etc.) involved in similar redesign tasks. However, further research is required to test this assumption.

Conclusions

Analysis of the DDRs was found to be a pragmatic and useful way to identify the in-service information considered by the designers in the redesign of components or systems of an existing engine. The informational analysis helped to identify the topics and subtopics of the in-service information that is accessed by designers during redesign tasks. The data analysis method of the informational analysis is useful in the analysis of a DDR to identify topics and subtopics of any type of information used by designers in a design task. The important findings of our informational analysis are as follows.

- The SR, AS, and SD sections of the DDR provide an insight into the task clarification phase, conceptual design phase, and embodiment and detail design phases respectively. The activity 'access information' is seen throughout the DDR, and indicates that the analysis covers the complete spectrum of the design process phases.
- Half of the sentences under the 'access information' activity belong to the 'in-service information' type. This high usage of in-service information can be attributed to the type of design task studied here, namely redesign aimed at tackling an in-service issue.
- It is inferred that the prominent activities of the designers based on the in-service information are 'analyse problem', and 'formulate requirements'.
- The designers have mainly accessed in-service information from the topic 'deterioration information'. The subtopics of deterioration information, namely deterioration mechanism, deterioration cause, DM location, and deterioration effect cover the significant proportion of the sentences.
- The designers have considered in-service experience of components similar to the one being redesigned.

In the case of the explanatory analysis, the application of the SAPPhIRE model proved useful in understanding the causal chains considered by the designers. The in-service information accessed by the designers mainly contains the undesired physical actions (e.g. deterioration mechanisms, deterioration effects, etc.) and the causal chains of these undesired physical actions. A pattern has been identified in the designers' actions regarding the use of these causal chains. The designers have generated several solutions that utilize these causal chains seen in the in-service information. It would be useful to present the relevant in-service information to the designers in the form of rich and detailed causal chains of the physical actions seen in the in-service experience. These broader causal chains might allow the designers to gain a more holistic view, and prevent them from being overwhelmed by the detailed causal chains. Further research involves identifying the effect of representation of in-service information and in particular deterioration information in different formats (i.e. textual vs. diagrammatic) on the designers' comprehension and use of that information in a redesign task. One of the alternatives to identify this effect is to carry out controlled experiments involving two groups of designers (i.e. textual vs. diagrammatic). After generating the solutions by using the causal chains seen in the in-service information, the designers have identified or speculated on side effects and/or 'other' aspects from these generated solutions.

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Appendix A1: Examples of the outputs of the coding process (case studies)

The outputs of the coding process, namely designers' activities, information types, topics under the in-service information, and subtopics of the topic deterioration information, are explained with examples. Unless otherwise stated, these examples are drawn from the burner seal case study, and are taken from the DDRs as direct quotes. The burner seal has three main parts, namely, liner, rings, and carrier (see Figure 12). All three parts experience wear in service. This leads to leakage of hot air into a zone that houses the control system's wiring. There is a potential risk of engine malfunction when the temperature of this zone reaches a particular value. In addition, the following issues have been noted.

- Due to thermal effects, the shape of liner changes when the engine is at cruise. Although this shape change is very small, it increases the air leakage.
- The rings experienced a deterioration mechanism, namely corrosion.

Table 3 shows the actual design changes to the three parts of the burner seal. The liner is not changed.

Figure 12. Illustration of burner seal.

Table 3. Actual design changes in the case of the burner seal.

Designers' activities

The activities of the designers, interpreted from the content of the DDRs, are divided as follows:

- access information;
- analyse problem;
- formulate requirement;
- generate solution;
- evaluate solution;
- detail solution;
- other.

Access information

This activity was coded when a designer appeared to be referring to a piece of information or describing information such as in-service information, design information, etc. The following are the examples of this activity.

(1) *Some wear was seen on the outer piston ring grooves, and some wear on the inner ring grooves too.*

(2) *JDS686.01 recommends that the ratio of outer diameter to radial thickness should be* <u>*a:b*</u> *as a minimum.*

The first sentence accesses in-service information, whereas the second sentence accesses design information. In the second sentence, we have not provided the actual ratio mentioned in the DDR for confidentiality reasons. Henceforth, we use underlined words in the sentences from the DDRs where we have changed some words for these reasons.

Analyse problem

This activity was coded when a designer appeared to be examining or speculating on the nature of the problem. In addition, this activity includes information on the analysis procedure (e.g. rig-test set up). The following are the examples of this activity.

(1) *This* (forward motion of the CSC) *would transmit high loads from the CSC through to the COC via the burner bolts.*

(2) *The sealing ring end gap, unless chocked, will always cause a certain level of leakage area throughout the flight cycle.*

The first sentence examines the problem of forward motion of the CSC, and the second sentence speculates on the issue of the sealing ring's end-gap.

Formulate requirement

This activity was coded when a designer appeared to infer a requirement or constraint for the redesign. The following are the examples of this activity.

(1) *A solution is required to improve the life of the burner seal carrier arrangement and stem the HP3 leakage, in time for service introduction in July 2004.*

(2) *In order to aid overhaul/repair, the liner could be revised for inserting in to the COC from outside the casing, such that it can be assembled and stripped on wing.*

In the first sentence, requirements to improve the life of the burner seal and stem the HP3 air leakage are inferred. In the second sentence, a requirement for the ease of overhaul/repair is inferred.

Generate solution

This activity was coded when a designer appeared to generate or propose a solution. Two examples of this activity are as follows.

(1) *A bellows seal could replace the carrier and sealing rings as a conduit between the CSC and COC.*

(2) *The diameter of the liner bore could be reduced so that the overall leakage periphery/area is reduced.*

In the first sentence, the designers propose a solution that involves a bellow seal to replace the existing burner seal. The second sentence proposes an alternative solution by reducing the diameter of the liner bore to minimise the leakage of HP3 air.

Evaluate solution

This activity was coded when a designer appeared to assess or select a solution. Additionally, it was coded when the final selected solution was evaluated (e.g. by assessing it, providing reasons behind its detailing, or analysing it for the purpose of its evaluation). Some examples of this activity are as follows.

(1) *This* (alternative of one ring per carrier) *would allow the assembly more freedom to rock within the liner whilst maintaining a seal.*

(2) *This* (thermal match between carrier material and liner material) *helps the piston rings maintain seating even with their smaller radial thickness.*

In the first example, the designer evaluates a solution that incorporates only one ring per carrier. In this evaluation, a positive aspect of the solution is identified. In the second example, the designer evaluates a solution which changes the carrier material to abc, to allow the carrier grooves to expand at a rate similar to that of the liner. This thermal match helps the rings to maintain their seating inside the carrier grooves. In this case too, a positive aspect of the solution is identified.

Detail solution

This activity was coded when a designer appeared to describe or specify the implemented solution (e.g. describing arrangement of components, specifying materials, geometrical shapes, dimensions, manufacturing processes, assembly procedure, etc.) Two examples of this activity are as follows.

(1) *If the existing liner diameter is maintained, this results in a radial thickness for the sealing rings of xyz mm.*

(2) *The piston ring split lines are to be positioned diametrically opposite each other and orientated circumferentially with respect to the engine centre line.*

In the first example, the radial thickness of the sealing rings is calculated. In the second example, the designer specifies the assembly procedure for the sealing rings.

Other

Sentences were classified under this category when they could not be categorised into any of the above activities. Some examples of this activity are:

(1) *It has been shown in the earlier concepts that it was difficult to produce a lockstrap that could be supported in the centre and still be likely to stay intact for the duration of it use.*

(2) *These potential changes are described in the rest of this* (Alternative Solutions) *section.*

These sentences are drawn from the lockstrap case study. The first sentence was classified as an 'other' activity because it was noted earlier in the DDR and was thus repeated. The second sentence refers to a section of the DDR.

In some sentences, more than one activity was identified. The following sentence was classified into two activities, namely 'generate solution', and 'evaluate solution'. In this sentence, an alternative of using a ring without end gaps (i.e. a 'solid ring') has been devised, and then evaluated by identifying a negative aspect.

(1) *Using a solid ring has been considered to remove the end gap, but this prevents the ring from expanding and contracting within the liner, so compromising sealing on the ring's periphery.*

Information types

For the sentences that were classified into the 'access information' category, the following information types were identified:

- in-service information;
- design information;
- cross-project information;
- testing and analysis findings.

In-service information

This source of information was interpreted when the sentence described or referred to in-service experience, or to the findings of root cause analysis (RCA). This category includes the in-service information of the component being redesigned, as well as that of similar components on the same engine type or on different engine types. Two examples of the in-service information type are given. The in-service experience of the COC and the rings is accessed in these two sentences.

(1) *Inspection of the combustion outer casing (COC) also found some wear and galling to the burner seal liner.*

(2) *Some wear was seen on the outer piston ring grooves, and some wear on the inner ring grooves too.*

The in-service information was further divided into the following topics:

- deterioration information;
- maintenance information;
- statistical information;
- operating information.

<u>Deterioration information</u>

This topic is further classified under the following subtopics.

- Deterioration mechanism (DM): Information regarding deterioration mechanisms such as wear, corrosion, etc. and the immediate observable effects of these deterioration mechanisms (e.g. material loss due to wear) was included under the subtopic DM.
- Deterioration cause: The causes behind a DM or deterioration were classified under this subtopic.
- DM location: The information regarding the location of a DM on a component was noted under the subtopic DM location.

- Deterioration effect: The effects of a DM or deteriorations were included in this subtopic (e.g. leakage due to wear of a component, in-flight shut downs, aborted take off, etc.). The context of a sentence was important in discriminating between the subtopics DM, deterioration cause, and deterioration effect.
- DM measure-qualitative: This subtopic covers information on qualitative measures of DM (e.g. 'high' wear, 'excessive' corrosion, etc.).
- DM attribute: This subtopic considers a characteristic of a DM (e.g. attribute 'depth' of wear).
- DM measure-quantitative: This subtopic covers information on quantitative measures of the DM (e.g. wear depth is 1 mm).
- DM rate: The growth rate of a DM was considered under this subtopic.
- Acceptance limit: This provides criteria for making decision on repair or replacement of a component.

Some examples of these subtopics are shown in Table 4. The DM 'wear' and its qualitative measure 'some' can be seen in the first sentences of this table. The second sentence exemplifies the subtopics DM 'corrosion', DM measure-qualitative 'to some extent', and deterioration effect 'sticking of rings within the carrier'. The DM 'corrosion' and the deterioration cause 'temperature and environment' were noted in the third sentence. The fourth sentence considers the deterioration mode 'material loss', which is an observable effect of the DM 'wear'. In addition, this sentence includes the DM attribute 'depth' of the 'material loss', its quantitative measure (0.1 mm), and the location of the DM on the liner. The fifth sentence has been selected from the LPT blade damper case study, and considers DM rate. The final sentence is drawn from the lockstrap case study, and considers the acceptance limit for the loss of blade height and the deterioration effect, which is loss of blade height due to material release from the lockstrap.

Table 4. Examples of deterioration information subtopics.

<u>Maintenance information</u>

This topic was coded when the sentence described information regarding the maintenance aspects such as maintenance type, maintenance procedure, etc. Two examples are given under this category. The first sentence considers the maintenance type and the second mentions a maintenance procedure, namely inspection.

(1) *<u>'abc'</u> fleet leader engine <u>xyz</u> was removed from wing after <u>def hours</u> (<u>lmn cycles</u>) as part of an unrelated rollover programme.*[1]

(2) *Inspection of the combustion outer casing (COC) also found some wear and galling to the burner seal liner.*

([1] This sentence has been categorized into more than one topic of in-service information. For example, this sentence is categorized under the topics, namely 'maintenance information' and 'operating information'.)

<u>Statistical information</u>

This topic covers statistical information such as the percentage of failures, or the number of failures for different airlines, regions, etc. Two examples of sentences classified into this topic are as follows.

(1) *<u>xyz%</u> of burner seal liners exhibited such wear, which opens up additional leakage paths.*

(2) *Typically <u>abc%</u> of blades are rejected at overhaul due to the extent of sulphidation attack.*

<u>Operating information</u>

This topic covers information regarding operating variables (e.g. temperature, pressure, etc.) and the number of cycles/hrs. Two examples of this topic are as given. The first sentence specifies a number of cycle/hrs, and the second sentence discusses the operating variable temperature.

(1) *<u>'abc'</u> fleet leader engine <u>xyz</u> was removed from wing after <u>def hours</u> (<u>lmn cycles</u>) as part of an unrelated rollover programme.*

(2) *The existing carrier material in Jethete is only capable of a maximum operating temperature of <u>xyz°C</u>.*

The first sentence provides information regarding the percentage of burner seal liners that are responsible for leakage due to wear. The second sentence is selected from the LPT blade damper case study, and presents some statistical information regarding the rejection of blades due to the deterioration mechanism sulphidation.

Design information

This source of information was coded when a sentence described or referred to design information, for example, information regarding precedent designs, previous design modifications, design standards, materials data, etc.

The following list provides examples of the design information type. The first sentence describes the information provided by a design standard, regarding the dimensions of a ring. The second sentence provides information about the application of dry film lubricant on nickel alloys. The last sentence refers to the assembly procedure of the existing design, and explains how the liner is inserted into COC bore.

(1) *Note that radial thickness as defined by the JDS, relates to the difference between the inner and outer radius of the rings; it does not refer to the radial direction with respect to the engine.*
(2) *Dry film lubricant is also not recommended for nickel alloys as there is a risk of sulphidation corrosion above xyz°C.*
(3) (In the case of the version-1 of the burner seal) *The liner is inserted by shrink fitting to the COC bore from the inner face of the casing and then swaged open on the outer surface.*

Testing and analysis findings

This source of information is interpreted when a sentence describes or refers to the findings of testing or analysis (except for the findings of RCA, which are categorised under the in-service information type). In addition, this information type includes information on the methods and tools used for testing and analysis. The first example accesses information on the forward movement of the combustion support casing (CSC) during slam acceleration, and the source of this information is the findings of testing and analysis. The second example is drawn from the lockstrap case study and quotes some stress analysis findings.

(1) *These investigations include engine testing and analytical methods, and suggest the CSC moves forwards during slam accelerations.*
(2) *The stress analysis of this design is predicting a worst-case cyclic life of xyz cycles.*

Cross-project information

This source of information was coded when a sentence describes or refers to the information from another project in the company. Two examples of the sentences under this information type are given. The first sentence refers to the information from a project related to the 'xyz' engine, when the redesign task was for the 'abc' engine. The second sentence is drawn from the LPT blade damper case study, and presents information on the type of dampers used in other projects requiring additional damping.

(1) *A bellows arrangement is currently under development for the 'xyz' TGT thermocouple access.*
(2) *Under platform dampers or shroud interlocks are commonly used where additional damping is required on other projects, both military and civil.*

Appendix A2: Explanatory analysis - examples

The identification of the three aspects (see Section on the method of explanatory analysis) is explained by providing examples from the burner seal case study. Appendix A1 presents the details of the burner seal.

Identifying the causal chains of physical actions

The steps involved in identifying the causal chains of actions considered by the designers are as follows:

1. identifying the described physical actions;
2. identifying the parts and inputs involved ;
3. interpreting the structural conditions for the physical actions; these structural conditions form the construct 'organs' of the SAPPhIRE model;
4. interpreting the remaining constructs of the SAPPhIRE model.

Consider for example the identification of the causal chain that leads to the action corrosion. The DDR mentions that rings of the burner seal corrode in the presence of high temperature air. In this case, we identified the constructs of the SAPPhIRE model as shown in Figure 13.

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Figure 13. Identified constructs for the action corrosion.

Identifying the intentions behind the alternative solutions

The following steps are involved in identifying the intentions behind alternative solutions:

1. identifying the causal chains of actions considered by the designers in generating the solution;
2. identifying the goal of the generated solution (e.g. tackling the issue of corrosion);
3. identifying the target of the solution within the causal chain (e.g. changing the organ that produce the action corrosion).

These steps are explained with the following example. The DDR describes a design change that modifies the geometry of the burner seal's rings. The liner becomes oval due to a combination of loads caused by thermal expansion, pressure and axial forces. This results in a leakage path if the rings fail to follow the liner's profile. The modified geometry of the rings allows them to follow the liner's profile, and thus avoid creating a gap between the liner and the rings.

Figure 14 shows the causal chain in the in-service information considered by the designers in this design change. The goal of the design change is to avoid the unintended action leakage. In order to achieve this goal, the design change is targeted at the organ (the ring's geometry), which does not allow the ring to follow the liner's profile. The design change modifies the geometry of the ring, and this change eliminates the organ in the causal chain shown in Figure 14; and thus avoids the unintended action leakage.

Figure 14. Causal chain considered by the designers in generating a solution.

Identifying the side-effects and/or 'other' aspects considered

In the case of some solutions, a new action and/or 'other' aspects due to the change suggested by the solution are mentioned. This new action is called side-effect, and it can be *positive* (not obstructing the system's functionality) or *negative* (obstructing the system's functionality). The steps involved in identifying the side-effects and/or 'other' aspects are as follows:

1. understanding the intentions behind a solution, and the change suggested by the solution (e.g. change of geometry of the ring);
2. recognising the actions and/or 'other' aspects identified by the designers resulting from the change.

For example, the DDR describes an action resulting from the design change described above (see Figure 14). The organ created by the rings with modified geometry and the relevant inputs lead to the action that reduces the sliding friction between the rings and the carrier (see Figure 15). In this case, the designers have noted a positive side effect.

Figure 15. Identification of creation of an action due to the organs / inputs created by a design change.

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FIGURES

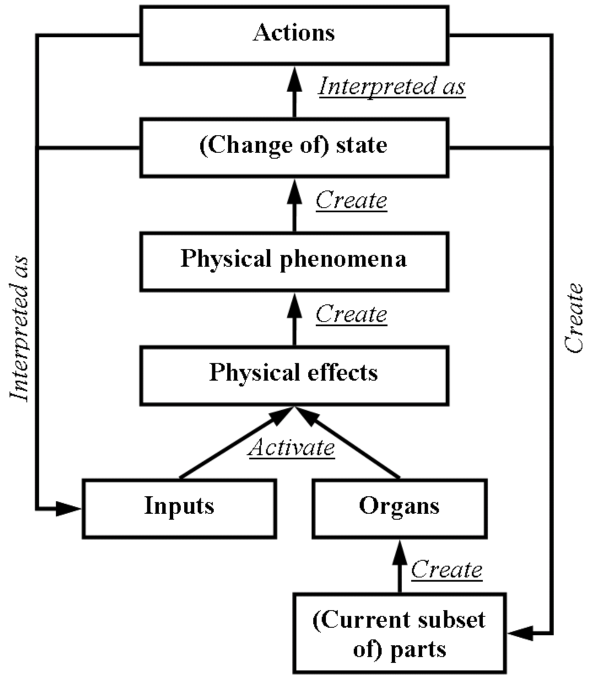

Figure 1. SAPPhIRE model of causality (Chakrabarti et al., 2005).

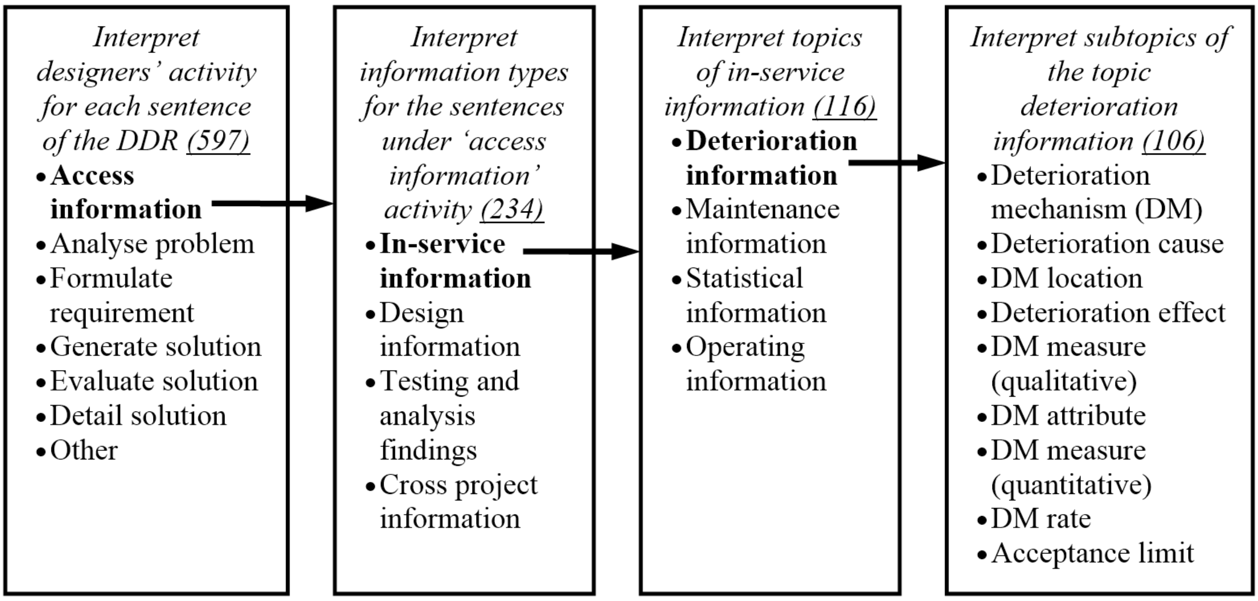

Figure 2. Steps in the coding process. *Notes*: (1) The bulleted lists show the outputs of the coding process; (2) The underlined numbers in brackets show the number of sentences (e.g. for 234 sentences under the 'access information' activity, we interpreted information types).

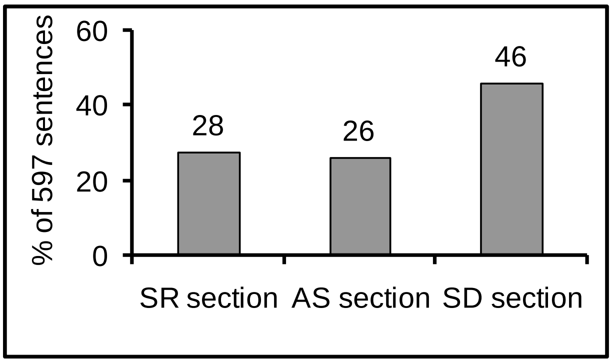

Figure 3. Percentage of 597 sentences for the different sections of the DDR.

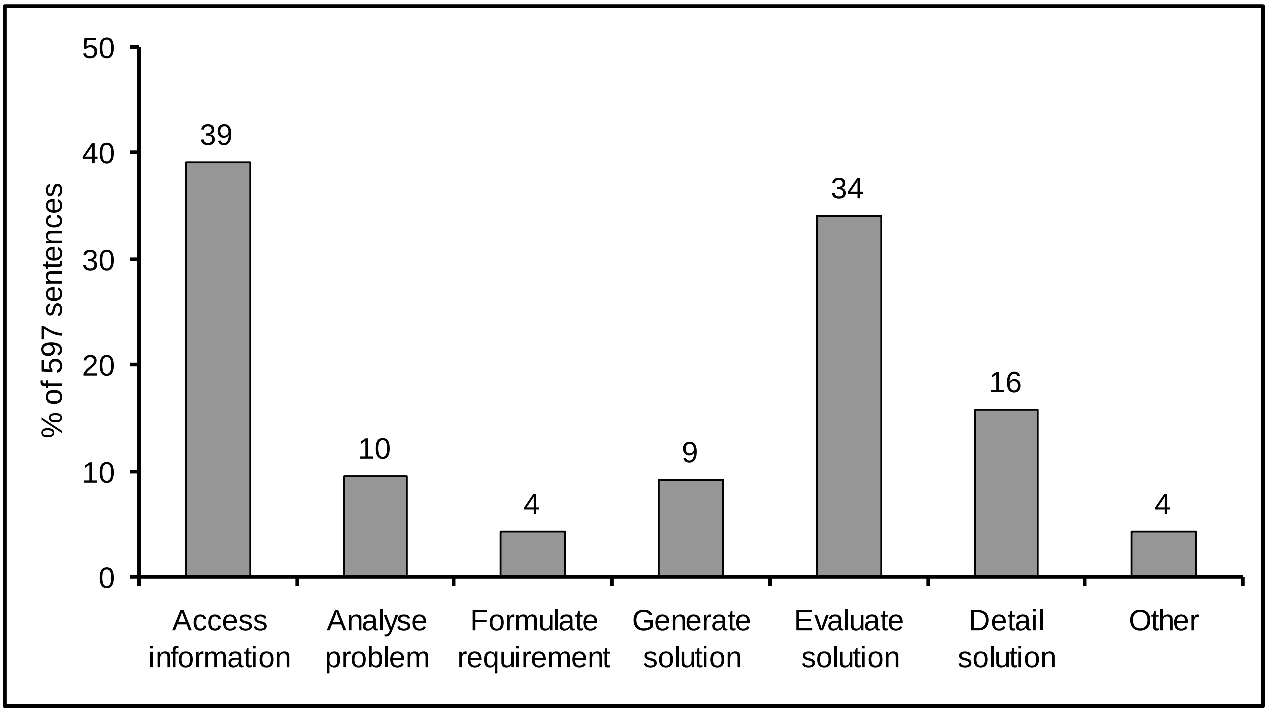

Figure 4. Percentage of the 597 sentences classified into the different activities. *Note*: In the case of some sentences, more than one activity was noticed. Therefore, the total of all percentages (39+10+4+9+34+16+4) is greater than 100.

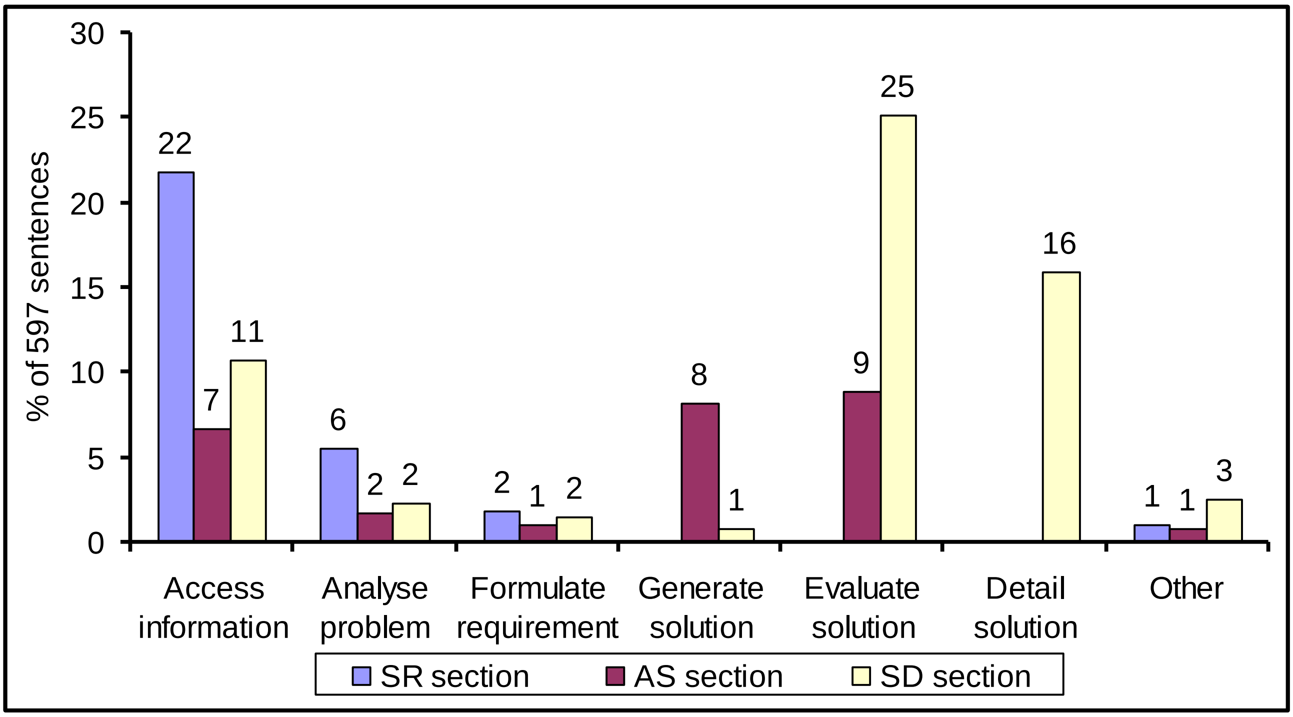

Figure 5. Activities identified in the different sections of the DDR (percentage of sentences based on 597 sentences in the DDRs).

DDR sections	Specification requirements (SR)	Alternative solutions (AS)	Solution description (SD)	
Design process phases	Task clarification	Conceptual design	Embodiment design	Detail design

Figure 6. DDR sections provide insight into the different design process phases proposed by Pahl and Beitz (1996).

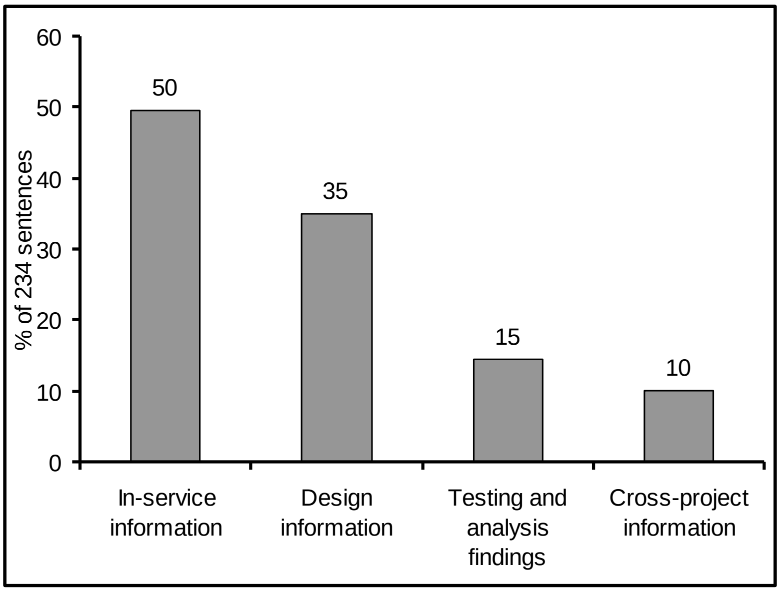

Figure 7. Distribution of the information types (percentage based on the 234 sentences under the 'access information' acti–vity). *Note:* In the case of some sentences, more than one type of information was noticed.

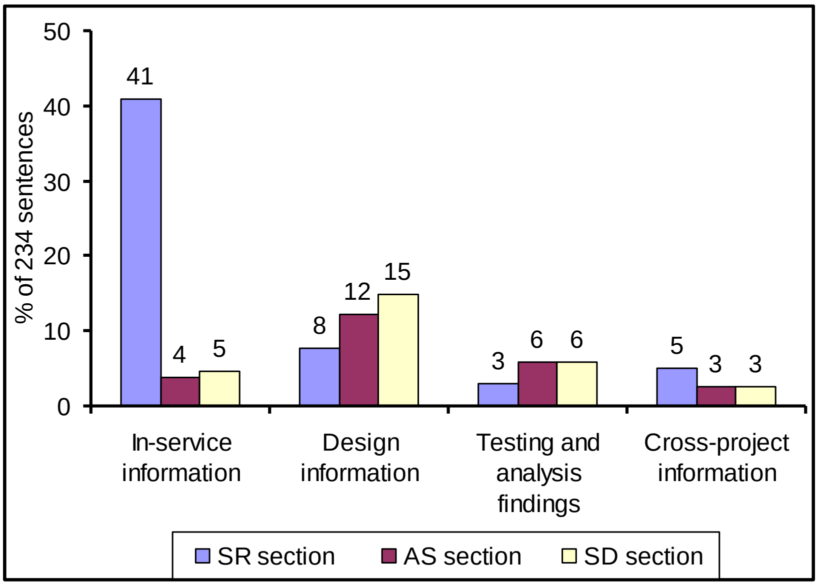

Figure 8. Types of the information in the different sections of the DDR (percentage based on the 234 sentences under the 'access information' activity).

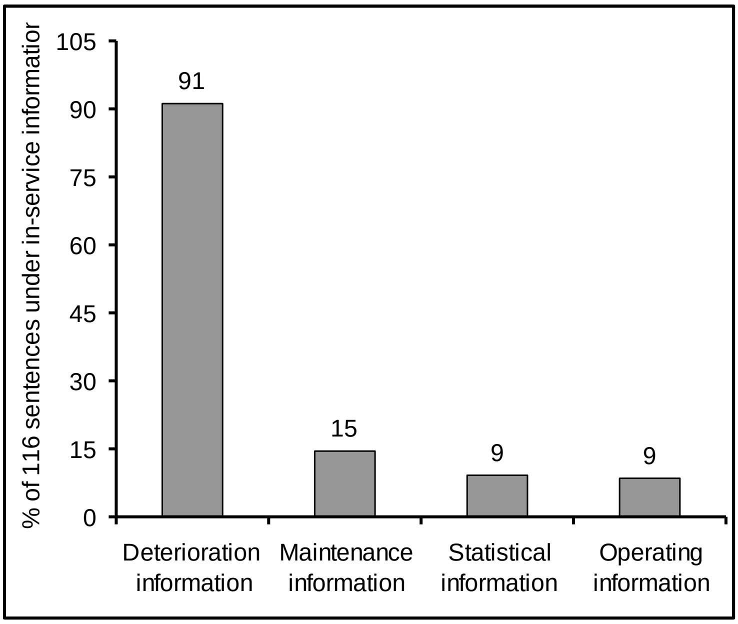

Figure 9. Distribution of sentences under different topics of in-service information (percentage based on 116 sentences under the 'in-service' information type). *Note*: In the case of some sentences, more than one topic of in-service information was noticed.

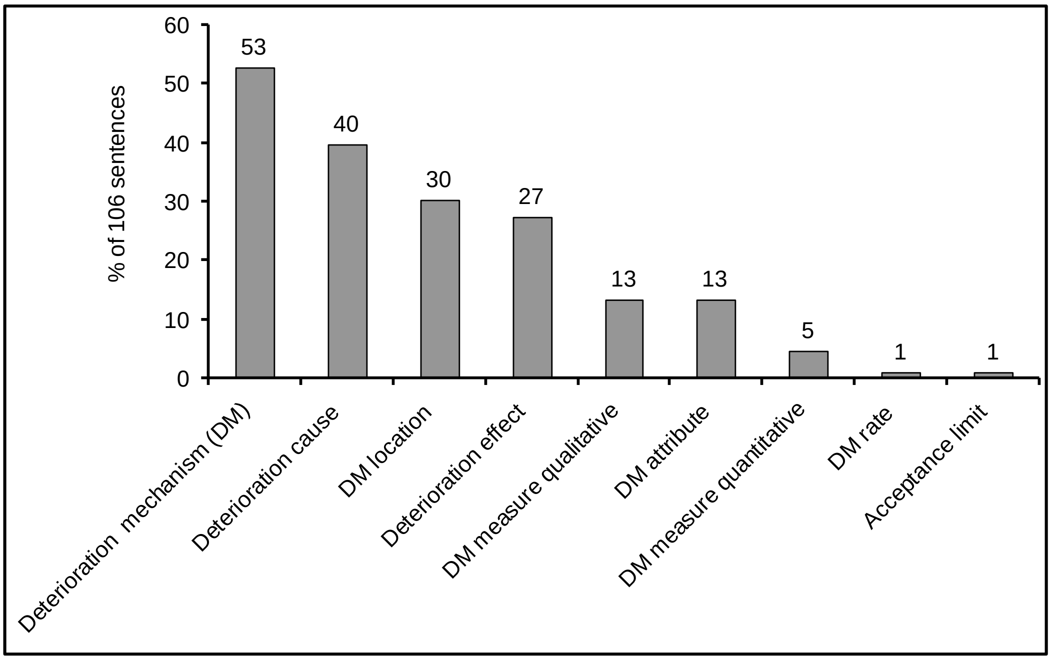

Figure 10. Distribution of the different subtopics under the topic deterioration information (percentage is based on the 106 sentences that are classified as 'deterioration information'). *Note*: In the case of some sentences, more than one subtopic of the topic deterioration information was noticed.

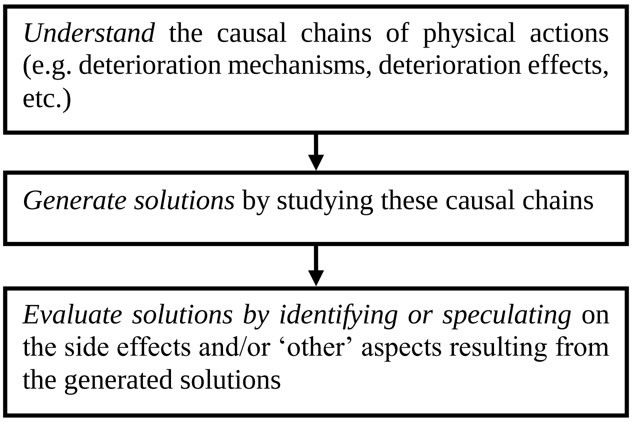

Figure 11. The overall pattern when designers use in-service information in a redesign task.

Key: COC – Combustion outer case; CSC – Combustion support case; FSN – Fuel spray nozzle; HP3 air – High pressure air

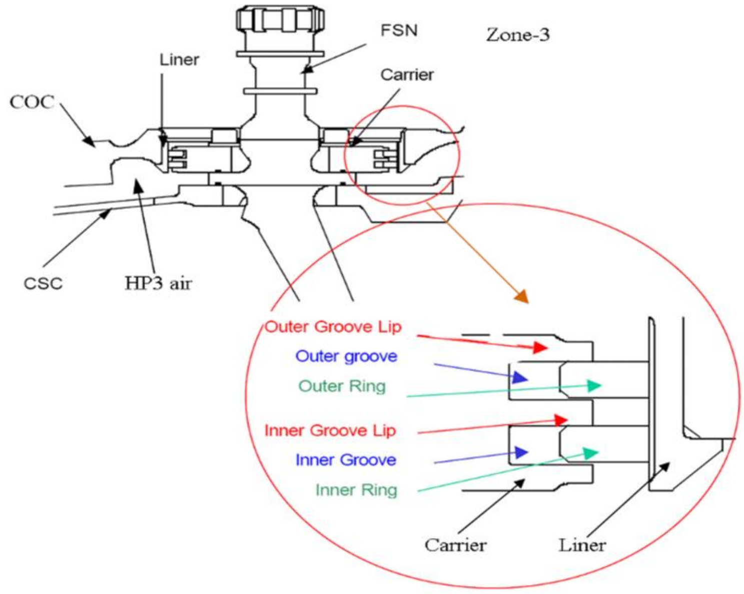

Figure 12. Illustration of burner seal.

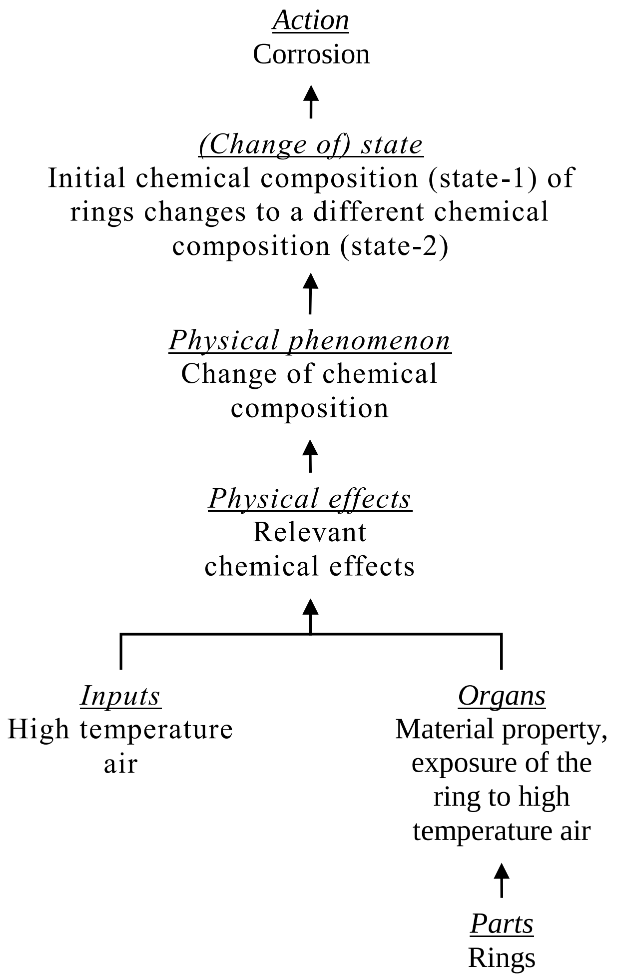

Figure 13. Identified constructs for the action corrosion.

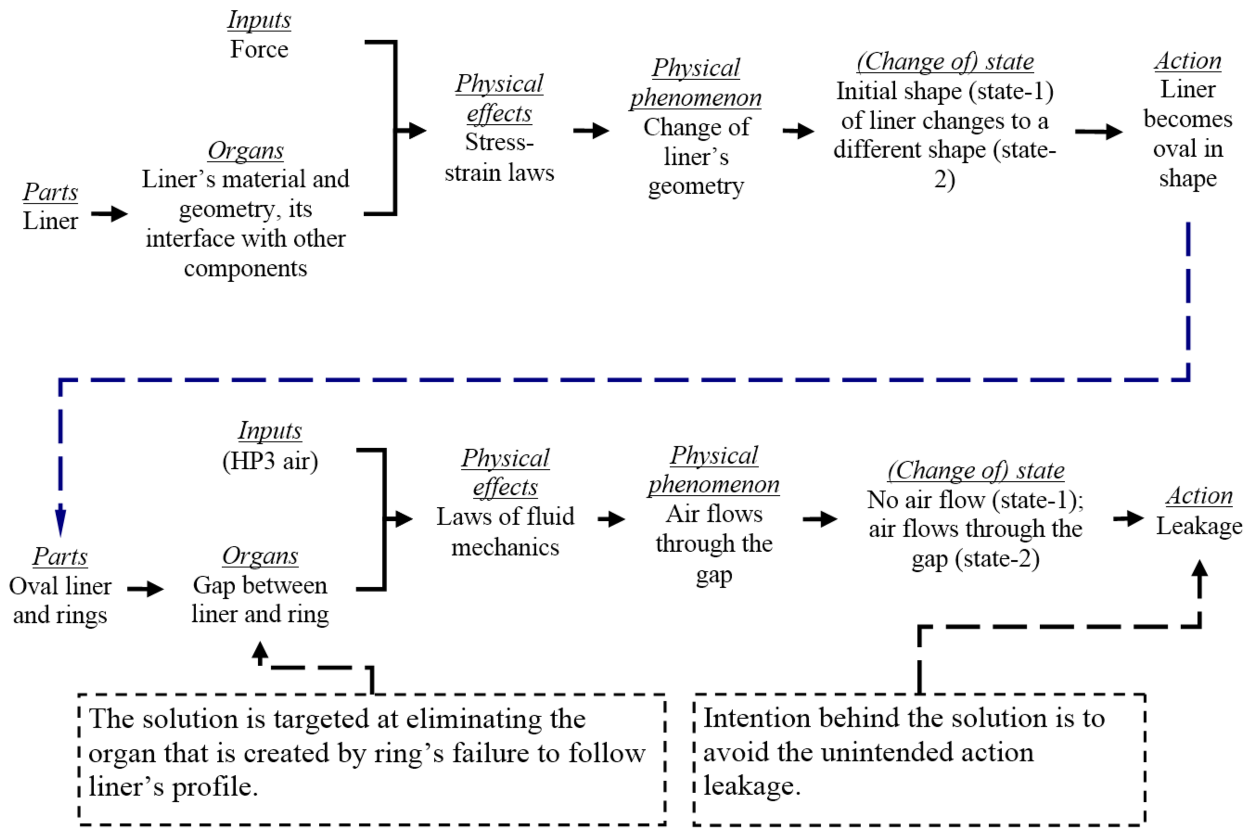

Figure 14. Causal chain considered by the designers in generating a solution.

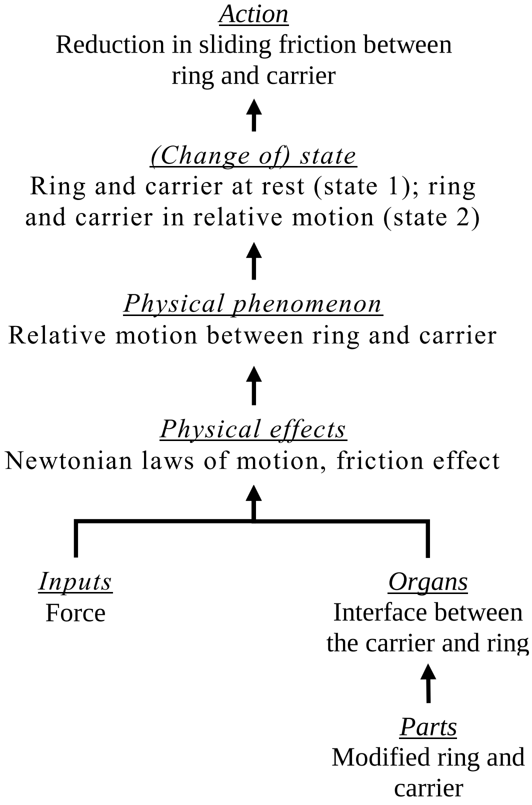

Figure 15. Identification of creation of an action due to the organs / inputs created by a design change.

TABLES

Table 1. Case study components and engine modules.

Component	Engine module
Burner seal	Combustor
Combustion liner inner wall	Combustor
Low pressure turbine (LPT) blade damper	Turbine
Lockstrap	Compressor
Front bearing housing (FBH) rear panel	Transmissions

Table 2. Number of causal chains identified in the in-service information, causal chains used in generating solutions, and number of solutions generated.

	Number identified in the in-service information	Number used in generating solutions	Number of solutions generated from the used causal chains
Causal chains	22	13	37

Table 3. Actual design changes in the case of the burner seal.

Part	Material change	Geometry change
Liner	No	No
Rings	Yes	Yes
Carrier	Yes	No

Table 4. Examples of deterioration information subtopics.

	Sentences from the DDRs	Deterioration information
1	*Some wear was seen on the outer piston ring grooves, and some wear on the inner ring grooves too.*	• Deterioration mechanism (DM) • DM measure - qualitative
2	*The cast iron rings corrode to some extent causing the rings to stick within the carrier.*	• DM • DM measure-qualitative • Deterioration effect
3	*The carrier body corrodes too, due to the temperatures and environment, despite having silver plating on the EIS standard.*	• DM • Deterioration cause
4	*Material loss has been measured to a depth of 0.1 mm at intermittent locations around the liners.*	• DM • DM measure-quantitative • DM attribute • DM location
5	*It's* (the blade's) *wear rate is shown to depreciate in service*	• DM rate
6	*The blade height loss was outside the acceptable limit leading to unscheduled engine removal.*	• Acceptance limit • Deterioration effect