Res Eng Design (2011) 22:207–221
DOI 10.1007/s00163-011-0107-8

ORIGINAL PAPER

In-service information required by engineering designers

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Received: 29 January 2010 / Accepted: 7 March 2011 / Published online: 23 March 2011

Abstract This paper describes some 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. The collaborating aerospace company offers contracts under which it remains responsible for the maintenance of engines which have been purchased by airlines through these contracts based on payment for usage. This has triggered a major re-assessment of the design of aero engines to reduce their overall life cycle costs, while maintaining performance efficiency. In this context, the use of in-service experience of existing engines is important in the design of components and systems of a new engine, to tackle in-service issues through design and thus to reduce maintenance costs and increase reliability. This paper aims at identifying designers' requirements regarding in-service information. Semi-structured interviews with designers from an aerospace company were conducted; after these interviews, the designers were requested to comment on a set of questions regarding in-service information, indicating how frequently they might ask each of them when designing a new component or system. In addition, some documents containing the in-service information considered by the designers in designing components and systems of a new engine were analysed. The results indicate what in-service information is required by designers for this new task.

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Keywords In-service information · Engineering design · Design for service · Aerospace engineering · Knowledge management

1 Introduction

Integration of products and services is now seen as being necessary for the long-term success of engine manufacturers, in the global market of air transport. A fundamental shift is occurring in our collaborating aerospace company, away from the selling of products to the provision of services. The company offers contracts under which it remains responsible for the maintenance of engines which have been purchased by airlines through these contracts based on payment for usage. This affects the design of new engines, which now need to have low and predictable maintenance costs, in addition to the previous requirements of reliability and low specific fuel consumption.

In the aerospace sector, it is standard design practice to utilise the experience gained from past projects due to the evolving nature of these products. In-service information related to the issues and deterioration mechanisms of similar aero engines is utilised to avoid the same issues in future designs. A flow of information from the service domain to designers is thus crucial for minimising in-service issues and can also reduce the cost of both planned and unplanned maintenance. In order to develop a method or tool which can enable designers to retrieve the in-service experience of existing engines in an effective and efficient way, it is first necessary to understand designers' in-service information requirements.

There are several explanations and definitions of the terms, namely, data, information and knowledge (Court 1995; Awad and Ghaziri 2003; Nonaka and Takeuchi 1995;

Ahmed 2000; Wallace et al. 2005). There is no common agreement concerning these terms. In general, data consist of symbols and numbers and are algorithmic. Information is obtained from data when it is placed in some context. Knowledge exists in people's minds and includes perception, skills, training, common sense and experience. In this research, we focus on in-service data and information required by designers. Henceforth, we refer this in-service data and information as in-service information.

The outline of the paper is as follows. Section 2 presents the relevant literature and establishes the background for this paper. The aims of this research are presented in Sect. 3. Section 4 describes the research method employed. Section 5 provides the findings of the data analysis. Section 6 discusses the findings of this research. Finally, the conclusions are presented in Sect. 7.

2 Context and background

This research project was undertaken in the aerospace group of a major power systems company from the UK. The aerospace group in this company is involved in the design, manufacture and provision of service support for aero engines. The company offers contracts under which it remains responsible for the maintenance of engines which have been purchased by airlines through these contracts based on payment for usage. Such contracts require long service intervals, ease of service and high reliability (Kirkland and Cave 1999). The maintenance cost of engines has now become a crucial issue for engine manufacturers. The cost of spares and the lives of components are important factors affecting the maintenance costs (Kirk 2003; Jagtap et al. 2006). The body of information about the various deterioration mechanisms of different components can allow designers to improve the design of new engines.

Harrison (2006) has discussed the elements of the process, issues 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 identified the following issues, which can address all of the above drivers positively:

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

James (2005) observes that the failure of an engineering component or structure can be due to incomplete, inaccurate or inappropriate information related to one or more stages of the design process or to poor management of the design process itself. The manifestation and severity of a failure are often influenced by some stage of the total design process for which management of the process could be improved. Insufficient understanding of the requirements of the system may also lead to failures. By incorporating knowledge about the performance of existing products (successes as well as failures) into the design phase of new products, it is hoped to tackle some of the service issues at the design stage itself.

The literature confirms the importance of in-service experience in improving the design of the next generation of products. Alonso-Rasgado et al. (2004) highlight the importance of service data collection and storage. Thompson (1999) describes the importance of information related to maintenance for the design actions. Operating records are a vital information source for designers. Interviews with maintenance personnel, and the records kept by them, also provide potentially 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 similar products should be evaluated, stored and used. A clear understanding of the root causes behind the failures of existing products can help in the design of the next generation of products (Jagtap et al. 2007).

Norman (1988) states that reliability or availability forecasts can be based on past operating experience. These forecasts will be precise if the sample size is large enough and unbiased. Jones and Hayes (1997) describe the importance of collection of field failure information throughout the life of a product in order to evaluate product's reliability. This facilitates improving the reliability of the next generation of products. Sandtorv et al. (1996) have presented the results and knowledge gained from a project called OREDA (Offshore REliability DAta). The application of the OREDA data was in the risk and availability studies in the early conceptual and engineering phases of an offshore development and also in maintenance optimisation. In-service experience can assist designers in fulfilling the various maintainability and reliability requirements (Wani and Gandhi 1999).

Reliability data banks can be based on in-service experience. Cooke and Bedford (2002) identify the users of such reliability data banks as: the maintenance engineer; the component designer and the risk/reliability analyst. Lannoy and Procaccia (1996) state that, for creating a database from operation feedback, it is necessary to identify the needs of its potential users. The data regarding reliability, maintenance, operations, service, market, management focus, etc., help to improve the product. The data have to be stored in systems that make it easy to retrieve, analyse and draw conclusions (Markeset and Kumar 2003). Some of the requirements for the design of such information management system are to identify the users and their requirements. 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. The designers from oil industry were interested in in-service information in a structured form so that it can be used in their different activities during a design process. Abramovici et al. (2009) developed a solution to capture, structure and analyse information on product use. Their solution is based on Bayesian network inference and is integrated in commercial Product Lifecycle Management (PLM) software. Goh et al. (2009) carried out a computer implementation of faceted classification in order to identify patterns in the in-service information documented in several sources.

According to the reviewed literature, the in-service information that is useful in the design stage of a product includes: cost of spares, in-service life of components, types of failure in the field, the causes behind those failures, deterioration mechanisms occurring on the various components, the rate of occurrence and impact of those deterioration mechanisms, and data regarding reliability. This in-service information is useful in:

- reducing maintenance costs;
- evaluating the reliability of the product in the field;
- predicting the reliability, availability of products;
- maintenance optimisation;
- fulfilling the various maintainability and reliability requirements.

3 Research aims

In the field of engineering design research, several studies focusing on engineering information and knowledge issues (e.g. designers' information-seeking practices, knowledge reuse, email communication.) have been undertaken in industrial environment (Court 1995; del-Rey-Chamorro 2004, Aurisicchio 2005; Demian and Fruchter 2006; Wasiak et al. 2009). However, these studies did not focus on a specific type of information such as in-service information. A recent study in an automotive industry, carried out by Rexfelt et al. (2011), devised and applied methods to develop services by involving customers in the process of developing these services. While this study is in the area of product-service systems, it is not focused on in-service information. There is minimal literature on in-service information in general and about aero engines in particular. The paucity of the literature on field feedback has been highlighted by Petkova (2003). The reviewed literature suggests the importance of identification of the potential users' needs in developing an in-service information system; however, this literature does not explain in detail the requirements of these potential users, including designers. In order to develop a tool or method which can enable designers in satisfying their requirements regarding in-service information, it is important to identify their *current* in-service information requirements and the in-service information that they *would like* to access from such a tool or method. Therefore, regarding the designers of components or systems of an aero engine, this paper aims at identifying:

- their current in-service information requirements; and
- the in-service information that they would like to access.

4 Research method

The following research methods were used: (1) interviews and questionnaire study with three designers and (2) document analysis.

4.1 Interviews and questionnaire study

The sampling process of selecting the designers considered aspects such as their roles and amount of experience. In addition to these aspects, the sampling process took into account the types of components or systems designed by them. Bearing in mind the tight schedules of the company employees, the sampling process was negotiated with the company experts. The designers had a different range of years of experience and different roles in the design department. Each of them has designed different components, in different projects (see Table 1).

The designers' in-service information requirements were phrased in the form of questions. A list of 39 questions was identified and assembled in the form of a questionnaire. Table 2 shows the classification of these 39 questions into ten topics. This classification is based on the prominent type of information required to answer the 39 questions. The reviewed literature and meetings with experts from the collaborating company helped to identify these 39 questions. The research, reported in this paper, was a part of a project called Integrated Products and Services (IPAS), which was funded by the collaborating aerospace company. In this project, the company arranged monthly meetings which were attended by the authors of

Table 1 Information about the designers

Designer (D)	Experience (years)	Present role	Components designed
D1	10	Component design team leader	Externals of an engine, e.g., cowling, brackets.
D2	27	Engine module design team leader	High-pressure turbine and low-pressure turbine blades, nozzle guide vanes, transmissions, casings, discs, etc.
D3	20	Engine module design team leader	High-pressure turbine and low-pressure turbine blades

Table 2 Topics of the 39 questions and examples

Topic	Examples
Deterioration information	Deterioration mechanism; deterioration effects such as ABTO, IFSD; deterioration causes; engine manual limits which provide criteria for repair or replacement depending on the severity of a deterioration mechanism.
Maintenance information	Maintenance schedules, repair facilities required, spare parts requirements, monitorability requirements, etc.
Operating data	Operating variables such as temperature, pressure, number of cycles/hrs
Statistical information	Number of ABTOs, IFSDs, etc.
Design Information	Information related to redesign aspects of a component, validation of tackling issue seen in-service, etc.
Life cycle cost	Repair cost, replacement cost, etc.
Reliability	Weibull analysis of reliability
Maintainability	Accessibility, facility to detect and isolate a deterioration mechanism
Customer information	Issues arising from different operators
Standards	Standards, regulations regarding operation of an engine in-service

this paper and the company experts. In each of these monthly meetings, at least one designer and one member of the Technical Services and Operations (TS and O) team from the company were present. One of the roles of the TS and O team is to analyse in-service information and provide relevant parts of this information to designers. In one of the monthly IPAS meetings, the TS and O team members presented a list of 21 questions regarding the in-service information that designers would like to access when they design components or systems of a new engine. They then sent us this list of questions through email. These questions were mainly related to the deterioration information (e.g. deterioration mechanisms, causes, effects).

We added 18 questions to the above list of 21 questions. The reviewed literature helped us to speculate on these additional questions. This reviewed literature (e.g. Kirk 2003; Peres et al. 2007; Davidson and Hunsley 1994; CCPS 1998; Sandtorv et al. 1996) was related to areas such as the use of field feedback in maintenance optimisation, reliability analysis, predicting failures using expert judgement and field feedback. The questions that we added mainly related to the topics other than the topic 'deterioration information'. The final list consisting of 39 questions (21 plus 18) was presented in one of the monthly IPAS meetings with the aim of gaining comments and suggestions from the company experts. The presentation was useful as these experts changed the terms in some of the 39 questions in order to make these questions understandable and unambiguous to the interviewees (i.e. the designers). The monthly IPAS meetings also helped to understand the meaning of some questions and to categorise these questions into different information topics as shown in Table 2.

Semi-structured interviews were conducted with three designers to identify their in-service information requirements. The interviews were divided into three steps.

Step 1: the designers were asked to describe their in-service information requirements.

Step 2: the designers were asked to rank each of the 39 questions based on the frequency with which they might ask them. The options given for each question were: (1) frequently; (2) usually; (3) sometimes; (4) rarely and (5) never.

Step 3: the designers were requested to add any further questions which they might also like to ask.

This sequence was used for the following reasons:

- to avoid any bias in step 1 that might have occurred if step 2 had been conducted first;
- to elicit more requirements in step 3 due to the stimulation effect of the 39 questions in step 2.

In the case of semi-structured interviews, interviewer asks specific questions to the interviewees and provides the room to the interviewees to expand on the answers. In these interviews, the interviewer can clarify questions and probe for additional information (Frankfort-Nachmias and Nachmias 1996). In this research, during the interviews, the researcher deliberately allowed the designers talk without interrupting them to move from one question to the next. The questions were directed towards identifying the in-service information that: (1) was considered by the designers in all their past projects and (2) they would like to access from any future in-service information system that might be developed by the collaborating company. For example, the designers were asked: if you had a magic 'service guru' on your computer desktop, what in-service information would you access from it?

All the interviews were audio-recorded. The time of each interview was about 60–90 min. The notes taken during the interviews allowed documenting the information for further analysis. On the same days of the interviews, these notes were updated after listening to the audio recordings. These updated notes were analysed to identify the following information: (1) the in-service information requirements considered in the past projects that the designers had worked on and (2) the in-service information that designers would like to access.

The data captured in the questionnaire were logged into Excel spreadsheets, and the popularity of each question was then measured by assigning a score for each response, as shown in Table 3.

Thus, each question could score a maximum of 12 (if all three designers said they would ask it frequently) or a minimum of zero (if no designer said they would ever ask it).

The limitations of the interviews and questionnaire study with the designers are as follows. According to Rosenthal (1966), in a research study, the participant's attitude and motivation can alter the results. Participant bias was minimised by telling the participants: the aims of the study; that their performance would not be assessed; that confidentiality would be rigorously maintained. In addition, the designers were individually interviewed in their own environment. The use of an audio-recorder may influence the experiment, because participants may change their behaviour if they know they are being recorded (Ahmed 2000). Before conducting the interviews, the participants were asked if they would agree to the use of audio recording, and all the participants consented. The researcher can also affect the performance of the participants (Rosenthal 1963). In the interviews, researcher bias was mitigated by preparing the interview questions in advance, and the same interviewer conducted all the interviews.

Table 3 Scores for questions

Response	Score
Frequently	4
Usually	3
Sometimes	2
Rarely	1
Never	0

4.2 Analysis of documents

The second research method was the analysis of a class of documents containing in-service information used by the designers in designing components and systems of a new engine. These documents are called 'strategy sheets' in the collaborating company.

In the collaborating company, in-service information is stored in a large number of different documents. The context (e.g. purpose, creator, intended audience) of the strategy sheets was established in the discussions with the company experts. The people who create or refer to these documents can provide an overview of the content of the documents, but often find it difficult to articulate the details of their content. Hence, we collected and analysed ten strategy sheets. Each strategy sheet consisted of 3–4 A4 size pages. These strategy sheets were written mainly from an engineering point of view and were in the form of tables. In contrast to research methods such as interviews, questionnaires, document analysis does not involve any time commitment on the part of the company employees. In addition, there is no transcription burden, which is present in the case of interviews.

The strategy sheets are created through meetings between the designers and members of the Technical Services and Operations (TS and O) team. The strategy sheets are based partly on the in-service experience gained from aero engines already in-service and partly on the engineering assessment of the deterioration mechanisms that could theoretically occur if not addressed in the design phase. In analysing these strategy sheets, the number of occurrences of different deterioration mechanisms was identified. In addition, prominent design changes and the benefits of those changes were noted.

5 Findings

This section presents designers' in-service information requirements identified through the methods, namely interviews and questionnaire with designers and the analysis of the strategy sheets.

5.1 Findings: interviews and questionnaire study with the designers

The findings of the three steps of the interviews and questionnaire study with the designers are explained as follows. These three steps are explained in Sect. 3.

5.1.1 Step 1

This step identifies the in-service information considered by the designers in past projects and the in-service information that the designers would like to access from the future in-service information system that will be developed by the collaborating company. The following list presents the in-service information actually considered by the three designers in the projects that they had worked on. All these three designers considered almost all of the items in the following list.

- The cost of overhaul (including the repair or replacement cost of the component).
- The life of the component, i.e., the number of cycles or hours a component can survive under the given conditions.
- The deterioration mechanisms that a component might face in-service, such as erosion, wear, cracking.
- The repair/replace strategy, i.e., whether it is cheaper to repair or replace a component in-service if it fails to function for the intended time.
- The life cycle cost (LCC), i.e., the cost of a system or component over its entire life span. LCC depends on deterioration rates, cost of spares, repair times, disposal costs, etc.
- Repair limits: these limits enable decisions about the repair or replacement of a component. For example, if the wear of the trailing edge of a high-pressure compressor blade is beyond the acceptance limits, it is either replaced or repaired depending on the cost and other constraints such as the availability of a repair facility.
- Ease of assembly, disassembly, inspection, etc.
- Safety and reliability aspects.
- Monitoring of deterioration mechanisms: this involves observing the condition of a component to estimate its remaining life and avoid issues between overhauls.

The information that designers said they would like to access, from the future in-service information system that will be developed by the collaborating company, is as follows.

- Cost of overhaul, including the cost of repairing or replacing the component. This cost should not be biased, that is, there should not be any inclusion of overheads in the price. Only those costs which can be controlled by the designer should be provided.
- The facilities required to repair a component.
- Any events such as in-flight shut downs (IFSDs) or aborted take-offs (ABTOs) caused by a component. (An ABTO is any event which causes the take-off of an aircraft to be aborted on the runway, after dispatch for the flight; IFSD covers those events where an engine is shut down during the flight.)
- Causes of deterioration.
- Actual achieved life of a component in-service.
- Observed limits of the deterioration mechanism before loss of functionality.
- The list of deterioration mechanisms such as cracking, burning, etc., for a component.
- A list of operators of a particular engine type, e.g., the Trent 800 is used by British Airways, American Airlines, etc.
- Any variation in a given deterioration mechanism with number of hours or cycles for a component.
- Photographs of failed components.
- Information about any previous designs which addressed the relevant deterioration mechanisms.

5.1.2 Step 2

After step 1, the three designers were requested to comment on the list of 39 questions, indicating how frequently they might ask each question when designing a component or system of a new engine. The popularity of each question was then measured by assigning a score for each response, as shown in Table 3. Table 4 shows the list of 39 questions, the collective responses of the three designers and total score obtained by each of the 39 questions. This table also shows the weighted mean score for each of the 39 questions. This weighted mean score is obtained by dividing the total score by the number of designers (i.e. three). We calculated this weighted mean score as it provides an indication of the average frequency of asking a given question. For example, the weighted mean score of 3.33 (associated with the total score of 10) suggests that on average the question with this score is likely to be asked 'usually'. Note that the total score of 10 can be obtained when two designers answered 'frequently' and one designer answered 'sometimes' or when one designer answered 'frequently' and two designers answered 'usually'. The weighted mean score helps to tackle this problem by indicating the average frequency of asking a question. In the case of some questions (e.g. questions numbered 21, 22, 23, etc., in Table 4), the responses of the three

Table 4 The list of 39 questions, total score for each question and information topics

	Question	Number of responses by the designers					Total score	Weighted mean score	Information topics									
		Frequently	Usually	Sometimes	Rarely	Never			Det. info.	Maint. info.	Oper. info.	Stat. info.	Des. Info.	LCC	Rel.	Maint.	Cust. Info.	Std.
1	What are the common deterioration mechanisms associated with this part?	3	0	0	0	0	12	4.00	●			●						
2	Can I see a picture showing a failed/damaged part?	3	0	0	0	0	12	4.00	●									
3	How have previous designs addressed this deterioration mechanism on similar parts?	3	0	0	0	0	12	4.00	●				●					
4	*(With reference to the above question numbered 31)* How effective were they?	3	0	0	0	0	12	4.00	●				●					
5	Do the mechanisms and life of this part vary depending on the engine duty and operator?	2	1	0	0	0	11	3.67	●		●						●	
6	How much damage can this part tolerate before deterioration or loss of functionality?	2	1	0	0	0	11	3.67	●									
7	What are the service standards/regulations for this part?	2	1	0	0	0	11	3.67										●
8	Are there any other deterioration mechanisms, which only occur rarely?	2	0	1	0	0	10	3.33	●			●						
9	How expensive is it if/when this part fails?	2	0	1	0	0	10	3.33	●					●				
10	When this part fails, what other parts are typically affected as a result?	2	0	1	0	0	10	3.33	●									
11	What does it typically cost to replace or repair this part?	1	2	0	0	0	10	3.33						●				
12	How many engine removals, in-flight shut downs (IFSD's), aborted take-offs (ABTO's), etc., have been caused by deterioration of this part?	2	0	1	0	0	10	3.33	●			●						
13	How easy do repair/maintenance engineers find it to inspect/dismantle/maintain/repair/re-assemble this part?	1	2	0	0	0	10	3.33								●		
14	What are the repair options for this part?	1	2	0	0	0	10	3.33		●								
15	What do maintenance engineers like/dislike about this part?	2	0	1	0	0	10	3.33								●		
16	How will the engines operation impact my design's behaviour in-service? E.g. temperature, cycle, pressures, vibration ?	2	0	1	0	0	10	3.33	●		●							
17	Was any re-design of this part required, after the engine went into service?	2	0	1	0	0	10	3.33					●					
18	What are the engine manual limits for this part?	1	2	0	0	0	10	3.33	●									

Table 4 continued

	Question	Number of responses by the designers					Total score	Weighted mean score	Information topics									
		Frequently	Usually	Sometimes	Rarely	Never			Det. info.	Maint. info.	Oper. info.	Stat. info.	Des. Info.	LCC	Rel.	Maint.	Cust. Info.	Std.
19	What are the life requirements for this part?	2	0	1	0	0	10	3.33			●							
20	What are the reparability requirements for this part?	1	2	0	0	0	10	3.33		●								
21	What is the benefit trade-offs between addressing these and compromising other deterioration mechanisms?	1	1	1	0	0	9	3.00	●									
22	What is the longest/shortest service life of this part?	1	1	1	0	0	9	3.00			●							
23	Which parts dominate the cost and reliability drivers in this engine?	1	1	1	0	0	9	3.00						●	●			
24	What criteria determine whether this part is replaced or repaired?	1	1	1	0	0	9	3.00	●									
25	Are there any specific issues regarding this part arising from individual customers?	1	1	1	0	0	9	3.00	●								●	
26	How can the parts that interface with mine impact it's behaviour in-service? Do I need to worry about them?	1	1	1	0	0	9	3.00	●									
27	What does my component typically contribute to life cycle costs and reliability—should I focus on this at the expense of other deliverables?	1	1	1	0	0	9	3.00						●	●			
28	How do I validate that I have addressed this mechanism?	1	1	1	0	0	9	3.00	●				●					
29	What are the monitorability requirements for this part?	1	1	1	0	0	9	3.00		●								
30	How critical is it if/when this part fails?	2	0	0	0	1	8	2.67	●									
31	What are the typical sequences of events which lead to this part's deterioration?	1	1	0	1	0	8	2.67	●									
32	How is this kind of part normally maintained? Repair/Inspection, etc.	1	0	2	0	0	8	2.67		●								
33	Which repair facilities are able to repair this part?	1	0	2	0	0	8	2.67		●								
34	What are the maintenance instructions for this part?	1	0	2	0	0	8	2.67		●								
35	What is the time between inspections/overhauls/repairs for this part?	1	0	2	0	0	8	2.67		●	●							
36	What are the inspection/overhaul/repair/replacement recommendations for this part?	1	0	2	0	0	8	2.67		●								

Table 4 continued

Question	Number of responses by the designers					Total score	Weighted mean score	Information topics									
	Frequently	Usually	Sometimes	Rarely	Never			Det. info.	Maint. info.	Oper. info.	Stat. info.	Des. Info.	LCC	Rel.	Maint.	Cust. Info.	Std.
37 What is the average and standard deviation of the life of this part?	1	0	1	1	0	7	2.33			●	●						
38 What special facilities are needed for the repair of this part?	0	0	2	1	0	5	1.67		●								
39 How would this part's typical life change if the average period between inspections/overhauls was changed?	0	0	0	3	0	3	1.00		●	●							

Det. info. deterioration information, *Maint. info.* maintenance information, *Oper. info.* operating information, *Stat. info.* statistical information, *Des. Info.* design information, *LCC* life cycle cost, *Rel.* reliability, *Maint.* maintainability, *Cust. Info.* customer information, *Std.* standards

designers are different. For example, in the case of the question numbered 21 in Table 4, the responses are ‘frequently’, ‘usually’ and ‘sometimes’. These differences can be attributed to the differences in: (1) the roles of the three designers; (2) their experience in terms of the number of years and (3) the types of components designed by them. For instance, as shown in Table 1, the designer 1 (D1) has designed externals of an engine (e.g. cowling, brackets). D2 has designed a large range of components, and D3 has mainly designed turbine blades.

As mentioned in Sect. 4.1, the 39 questions were classified into ten topics, based on the prominent type of information required to answer them (see Table 2). Table 4 shows the classification of each of the 39 questions into these information topics. In the case of some questions, the type of information required to answer the questions is related to more than one topic, and therefore these questions were listed under more than one topic. For example, the first question in Table 4 has been classified into two topics: ‘deterioration information’ and ‘statistical information’. Table 5 shows the ten topics, together with the number of questions, the average score per question and the associated standard deviation. The average score per question was calculated by dividing the sum of the total score of questions under a topic by the number of questions classified into that topic. For example, the number of questions under the topic ‘statistical information’ is four, and the scores of these four questions are 12, 10, 10 and 7. Therefore, the average score per question for the ‘statistical information’ topic is (12 + 10 + 10 + 7)/4 giving ten (rounded figure). For this information topic, the standard deviation is 2.06 total score, based on the scores—12, 10, 10 and 7. Table 5 also shows the weighted mean score obtained by dividing the average score per question by the number of designers.

From Table 5, following points can be noted.

- The topic ‘deterioration information’ has the highest number of questions (19), and the average score per question is also high (10) with $s = 1.31$.
- Regarding the number of questions under a topic, ‘deterioration information’ is followed by ‘maintenance information’. However, the average score per question for ‘maintenance information’ is small (8) with $s = 2.16$. This means that the frequency of accessing information related to deterioration information topic is higher than that of the maintenance information topic.
- The number of questions under ‘operating information’ is 7, and the average score per question is small (8) with $s = 2.69$.
- The number of questions classified into the remaining topics is small, and therefore the average score per question is statistically insignificant.

Table 5 Categories used to classify the 39 questions

Topic	Number of questions	Average score per question	Standard deviation (s)	Weighted mean score
Deterioration information	19	10	1.31	3.33
Maintenance information	10	8	2.16	2.67
Operating information	7	8	2.69	2.67
Statistical information	4	10	2.06	3.33
Design information	4	11	1.50	3.67
Life cycle cost	4	10	0.58	3.33
Reliability	2	9	0	3.00
Maintainability	2	10	0	3.33
Customer information	2	10	1.41	3.33
Standards	1	11	–	3.67

It was confirmed that the in-service information that had been taken into account by the three designers in the projects they had previously worked on, and the information that they would like to access from the future service information system that will be developed in by the collaborating company was all accounted for in the list of 39 questions.

Some comments from the designers about the list of questions were:

> ‘This is a comprehensive list of questions.’
> ‘During design, I ask some of these questions internally.’

These comments show that the designers found the list of 39 questions useful and comprehensive. During the interviews, designers found it hard to remember the in-service information considered in their previous projects in detail. The list of questions proved useful in helping to identify further items that had not already been elicited during the interview.

Some questions in the list of 39 questions appear to be similar; however, these questions have different connotations. For example, consider the following two questions: (1) which repair facilities are able to repair this part? and (2) what special facilities are needed for the repair of this part? While these two questions appear to be very similar, they are aimed at seeking different information content. The first question seeks information on different types of repair facilities that can repair a given part. The second question aims at identifying special facilities (if any) that are required to repair a given part.

5.1.3 Step 3

After commenting on the list of 39 questions, each designer was requested to write any further questions that they would like to ask, while designing a component or system. No designer mentioned any additional questions that they would like to ask, after filling in the questionnaire.

5.2 Findings: strategy sheets

The strategy sheets contain a list of requirements to be considered by designers while carrying out the design of new aero engines, such that all the lessons learnt from past experience (including from engines that are still currently in-service) can be applied. These documents describe the design changes proposed for new engines to eliminate the deterioration mechanisms or issues, and the anticipated benefits of those design changes.

In-service experience from three different aero engines was covered in the strategy sheets that were analysed. The years of service experience with these engines are: 2.5, 10 and 11.

Of the ten Strategy Sheets we analysed, five related to turbines, three to compressors and two to combustion chambers. A total of 88 ‘cases’ were included in the ten strategy sheets. A ‘case’ consists of a particular deterioration mechanism, together with the design changes to be made in the next generation of aero engines to eliminate that mechanism and the anticipated benefits of those changes. Out of these 88 cases, 48 are related to turbines, 25 to compressors and 15 to combustion chambers. Table 6 shows the number of cases for the different modules, namely turbines, compressors and combustions chambers. In this table, the first two strategy sheets consider cases from combustions chambers, the next five from turbines and the last three from compressors.

5.2.1 Deterioration mechanisms/issues

In the case of aero engines, various deterioration mechanisms or issues can occur. Figure 1 gives the number of

Table 6 Distribution of cases

Strategy Sheet	Name of the component	Number of cases
1	Combustion case	7
2	Combustion liner	8
3	HPT NGV (high-pressure turbine—Nozzle guide vane)	8
4	HPT blade	8
5	IPT (intermediate pressure turbine) NGV	12
6	IPT seal segment	5
7	IPT Blade	15
8	IPC (intermediate pressure compressor) blade retention devices	13
9	IPC blades	7
10	IPC variable vane mechanism	5

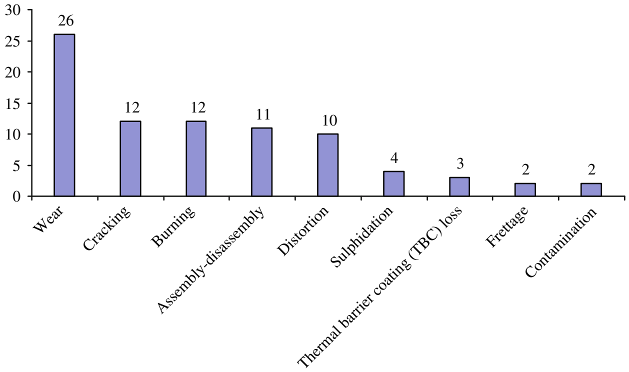

Fig. 1 Occurrences of various deterioration mechanisms/issues

occurrences of different deterioration mechanisms or issues that occurred more than once in the documents.

The deterioration mechanism ‘wear’ (26 occurrences) is predominant, followed by ‘cracking’ (12 occurrences) and ‘burning, (12 occurrences). This is followed by 11 occurrences of the issues related to the assembly disassembly (e.g. difficult to disengage, incorrect fitment, not fully engaged). As the deterioration mechanism ‘wear’ is predominantly seen, we examined its distribution across turbines, compressors and combustion chambers. This distribution is as follows: turbines—15 occurrences (31% of the 48 cases related to turbines), compressors—7 occurrences (28% of the 25 cases related to compressors) and combustion chambers—4 occurrences (33% of the 15 cases related to combustion chambers). In terms of the percentage of cases related to a given assembly, the distribution of ‘wear’ is approximately similar across turbines, compressors and combustion chambers.

A total of 15 types of deterioration mechanism are identified in the 88 cases. Six deterioration mechanisms (40% of the total) occurred only once. In one case, combination of deterioration mechanisms is seen, namely frettage plus fracture. The following deterioration mechanisms occurred only once: blockage, creep, seizure, galling, porosity and frettage plus fracture.

5.2.2 Design changes

For some of the deterioration mechanisms, proposed design changes for new aero engines are also described in the documents. These design changes are of several different types. The prominent design changes are:

- geometry change;
- material change;
- part deletion;
- manufacturing improvement.

Some design changes are initiated by identifying the causes behind various deterioration mechanism or issues, and these were described explicitly in the documents. Such a design change is termed a cause-related one, e.g., a design change to eliminate an area of stress concentration that had caused cracking.

5.2.3 Design benefits

The documents describe the anticipated benefits of the proposed design changes. Several types of benefit are discussed. The most common design benefits are as follows:

- an improvement in some parameter, e.g., increased impact resistance due to an increase in a particular dimension or improved resistance to oxidation;
- the elimination of a deterioration mechanism or issue;
- the reduced likelihood of a deterioration mechanism or issue occurring, e.g., lowering a stress concentration reduces the probability of crack initiation;
- an increased number of cycles in the life of the component;
- a reduction in repair cost.

These findings of the analysis of the strategy sheets suggest that the designers have mainly been asked to consider information on the different deterioration mechanisms occurring on the components or systems of engines in-service. This information comes under the 'deterioration information' topic, which is explained earlier in Sect. 4.1. This topic has highest number of questions (19 out of 39 questions), and the average score per question is also high (10). The proposed design changes are targeted at these deterioration mechanisms. In addition, these proposed changes are evaluated by identifying the benefits of these changes.

6 Discussion

The in-service information requirements that were elicited through the interviews with the designers have been included in the list of 39 questions. This information is classified under the topics of deterioration information, maintenance information, operating information, statistical information, design information, life cycle cost, reliability, maintainability, customer information and standards. The topic 'deterioration information' has the largest number of questions and the significant average score per question (10/12). The strategy sheets analysis revealed that, in proposing design solutions for a new engine, designers mainly consider information on deterioration mechanisms. It is thus clear that the in-service information currently used by designers in the design of components or systems of new engines mainly consists of deterioration information (e.g. deterioration mechanisms, deterioration effects, deterioration causes). Furthermore, the list of 39 questions identifies that designers require information from any previous designs which addressed relevant deterioration mechanisms on components that are similar to the one being designed. For example, in the 39 questions, the question 'How have previous designs addressed this deterioration mechanism on similar parts?' scored highly (12/12).

The findings of the strategy sheets do not show the use of some information that would be needed to answer the 39 questions (e.g. life cycle cost, maintainability, design information). These differences can be attributed to the following facts.

- The findings of the strategy sheets show the *current* use of in-service information by the designers of components or systems of new engines. In contrary, the list of 39 questions identifies the in-service information that designers *would like* to use in the design of components or systems of a new engine.
- The in-service information *currently* used by the designers is mainly provided by the members of the Technical Services and Operations (TS and O) team, and designers find it easier to gain in-service information from this team. On the other hand, the in-service information required to answer the 39 questions is stored in various disparate and heterogeneous sources such as electronic databases, documents. With the existing system in the collaborating company to consolidate/structure the in-service information, a substantial amount of time and effort would be needed to answer many of the 39 questions using these sources directly.

The findings of this paper can form one of the important inputs required to develop tools and methods to support designers in satisfying their in-service information requirements when they design components or systems of a new engine. A method or tool, intended to support designers in satisfying their information needs, requires accomplishing the steps: (1) capturing the required information; (2) processing this information and (3) storing it in an appropriate format such that designers can use it during a design process effectively (Hicks et al. 2002). The authors explain that the intended application of the captured information (i.e. the activities of the designers associated with the required information) in a design process determine the way of presentation of that information to the designers and also the method of processing and storing of that information (i.e. the above steps 2 and 3). In this research, we identified what in-service information is required by the designers of components or systems of a new engine. This understanding informs what in-service information needs to be captured for the designers (i.e. the step 1 above). However, in this research, we have not investigated how designers use this information in a design process, and this understanding is important in accomplishing the above steps 2 and 3 (i.e. processing and storing). We therefore believe that further research is required to understand how designers use in-service information in a design process.

Currently, the TS and O team lacks in-depth understanding of designers' in-service information requirements. The members of the TS and 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 capture the in-service information required by the designers. Educating the TS and O team members regarding the in-service information requirements of designers would facilitate their task of capturing the in-service information required by the designers. This education can consist of the different findings of this paper. Furthermore, computers can help in extracting in-service information stored in different sources to satisfy designers' requirements regarding this information. Opportunities exist to examine the applications of language processing techniques to extract in-service information stored in different documents. Our classification of the in-service information (see Table 2) can provide a structure to browse the extracted information.

The findings reported in this paper are based on the analysis of the data collected from one aerospace company. The interviewees and the strategy sheets are from this single company. Twenty-one questions from the list of 39 questions are formulated by the experts from this company, and these questions are mainly related to the topic 'deterioration information'. The average score per question for this topic is good (i.e. 10) (see Table 5). While there are no empirical studies in the reviewed literature (see Sect. 2) that aim at identifying in-service information requirements of designers, this literature (focusing on manufacturing industries, chemical and process industries, consumer electronics products) proposes that the understanding of the root causes (e.g. deterioration mechanisms, causes) behind the failures of existing products can be important in the design of the next generation of products. This suggests that the findings of our research support the proposals made in the reviewed studies. We therefore believe that our findings should be applicable in other industries. However, additional empirical studies need to be conducted in other companies to test this assumption.

We added 18 questions to compile the list of 39 questions. The topics of these 18 questions (e.g. maintenance information, operating information) also received good average score per question (see Table 5). As mentioned in Sect. 4.1, these 18 questions are based on the reviewed literature. While this literature does not focus on the in-service information requirements of designers, it covers different industries such as chemical and process industry, offshore industry, and manufacturing industry. This suggests that the designers' in-service information requirements that relate to these 18 questions can also be applicable to other industries involved in design tasks that are similar to those in the collaborating aerospace company. The typical design task in the collaborating company can be categorised as variant design. 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 (Pahl and Beitz 1996).

The limitations of our research are as follows. In a design task, designers integrate different types of information such as customer information, testing and analysis findings (e.g. findings of stress analysis), in-service information. In this research, we focussed only on in-service information required by the designers. However, we have not investigated how designers use this in-service information along with other types of information. Another limitation of this research is that the sample size of participants is small (i.e. three designers). However, the use of multiple methods (i.e. interviews, questionnaires and document analysis) increases our confidence in the findings of this paper. Our research used only retrospective methods (i.e. interviews, questionnaires, etc.). There are some limitations of these retrospective methods. For example, a strategy sheet is not written for our research aims. Furthermore, there is a possibility that the creators of the strategy sheets can forget to document some information. The real time data collection methods (e.g. observations, diary studies) can be useful to understand the requirements and use of in-service information in a design process, and how designers integrate in-service information and other types of information in this process.

The availability of products is crucial in the contracts under which products are leased to customers. This availability depends on a number of issues such as design of a product, how it is maintained. Some of these issues can be controlled by designers and some by the teams (e.g. TS and O) that are responsible for the management of existing products and services. While we focused on the in-service information required by the designers of components or systems of a new engine, we have not identified the in-service information requirements of the TS and O team. Identifying the in-service information requirements of the TS and O team is important to support them in the management of existing products and services and subsequently to achieve the desired availability and performance of these products and services. This can be an area for further research.

7 Conclusions

This paper identifies the in-service information requirements of engineering designers in the aerospace industry. Three in-depth interviews with designers were conducted, which allowed an insight to be gained into their various in-service information requirements. The results of the questionnaire, and the comments of the designers about the questionnaire, show that it is a comprehensive list of questions regarding in-service information requirements of engineering designers. The questionnaire helped to identify several in-service information requirements which were not mentioned during the interviews. The designers' in-service information requirements, elicited through the interviews and the questionnaire, are related to the topics of deterioration information, operating information, maintenance information, statistical information, reliability, design information, life cycle cost, maintainability, customer information and standards. Of these, deterioration information has highest number of questions (19) and the average score per question is also high (10), indicating that these questions would all be asked quite frequently.

Analysis of a sample of the collaborating company's strategy sheets provided further valuable insights into what in-service information is considered by designers in the design of components or systems of new engines. In addition, this analysis helped in identifying some of the deterioration mechanisms or issues seen in aero engines. It is clear that designers mainly consider deterioration mechanisms occurring on failed components. The majority of the proposed design changes aimed at resolving these deterioration mechanisms or issues through variant design involving geometry change, and/or material change. The proposed design changes are evaluated by identifying the benefits of these changes, such as the total elimination of a deterioration mechanism or issue, the reduced probability of a deterioration mechanism or issue occurring. These findings corroborate the high average score per question for the 'deterioration information' topic of the 39 questions.

The findings reported in this paper would be useful in developing tools and methods to support designers in satisfying their in-service information requirements. In particular, the findings of our research inform what in-service information needs to be captured for the designers of components or systems of a new engine.

Acknowledgments The authors acknowledge the support of the DTI and Rolls-Royce plc through the UTP for Design and would particularly like to thank Colin Cadas, David Knott, Andy Harrison, and the participating designers and service engineers.

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