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IN-SERVICE INFORMATION REQUIRED BY ENGINEERING DESIGNERS

Santosh Jagtap[1], Aylmer Johnson[1], Marco Aurisicchio[1], and Ken Wallace[1]
[1]Engineering Design Centre, University of Cambridge, U.K.

ABSTRACT

This paper describes 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. Under an emerging 'power by the hour'® paradigm, aero engines are effectively leased to the airlines, with the manufacturing company remaining responsible for their maintenance and repair throughout their service life. This has triggered a major re-assessment of the design of aero engines to reduce their overall life-cycle costs, while maintaining performance efficiency. The main aims of the ongoing research are thus to understand what in-service information is currently available in the company; and to determine what in-service information is required by designers, to fulfil their new objectives. This paper presents the results of the initial phase of the research project. In particular, this paper investigates the following research questions: (1) what questions do designers ask about in-service information? (2) what is the perspective of service engineers regarding in-service information? (3) what are the difficulties faced by the repair and overhaul (RO) centres in capturing this in-service information? Semi-structured interviews with three designers and three service engineers were conducted; after the 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. The results indicate the service information requirements of designers, and also reveal the related perspective of service engineers.

Keywords: In-service information requirements, knowledge management, design for service, aerospace engineering

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 company, away from the selling of products to the provision of services. The company now offers 'power by the hour'® contracts, under which it leases engines to airlines while remaining responsible for their maintenance. 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 failures and malfunctions of similar aero engines is utilised to avoid the same problems in future designs. A flow of information from the service domain to designers is thus crucial for minimising in-service failures, 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 necessary to understand designers' in-service information requirements. In addition, it is useful to understand the perspective of the service engineers regarding the in-service information, and the difficulties they face in capturing this information.

This paper presents the results of the initial phase of an ongoing research project. As a part of this research, a pilot empirical study has been conducted. The aim of the pilot study was to identify the questions, related to in-service experience, that designers ask; and the perspective of service engineers about the service experience. The study involved semi-structured interviews with three designers and three service engineers. After the interviews, the designers were requested to comment on a list of 39 questions drawing on in-service information, indicating how frequently they might ask each question when designing a new component or system.

The outline of the paper is as follows. Section 2 presents the relevant literature. Section 3 describes the research method of the empirical study. Section 4 provides the results of the interviews and questionnaire with designers. It also provides the results of the interviews with service engineers. Finally, the conclusions are presented in Section 5.

2 LITERATURE REVIEW

In this section, we present the relevant literature about the impact of the 'power by the hour'® paradigm on aero engine designs, importance of in-service information in the design of next generation of products, designers' requirements regarding the in-service information, and the gaps in the reviewed literature.

2.1 'Power by the hour'® paradigm and aero engine design

Engines designed for the 'power by the hour'® environment require long service intervals, ease of service and high reliability [1]. 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 [2]. The body of information about the various failure modes of different components allows designers to improve the design of new engines.

Harrison [3] has discussed the elements of the process, 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 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.

2.2 Importance, applications of in-service information in design

James [4] 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 often depends on the stage of the total design process that has not been managed properly. 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 problems 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.* [5], with reference to the design of functional that is total care products; highlight the importance of service data collection and storage. Thompson [6] describes the importance of information related to maintenance for the design actions. Operating records is a vital information-source for the designers. Redesign can help to solve the problem. The interviews with maintenance personnel, and the records kept by them, provide potentially useful information for designers. Sander *et al.* [7], in connection with high volume consumer products, state that in order to improve future products, the entire relevant service experience from the previous products should be evaluated, stored and used. A clear understanding of the causes behind the failures of existing products is important in the design of the next generation of products. Petkova [8] describes the field feedback of the consumer electronics products that companies need to take decisions related with the product quality.

Norman [9] states that reliability or availability forecasts can be based on the past operating experience. These forecasts will be precise if the sample size is large enough and unbiased. Jones *et al.* [10] describe the importance of collection of field failure information throughout the life of a product and analysing the collected data to evaluate the reliability of the product in the field. This facilitates improving the reliability of the next generation of products. Sandtorv *et al.* [11] 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 concept and engineering phases of an offshore development and also in maintenance optimization.

In-service experience can assist designers in fulfilling the various maintainability and reliability requirements. Wani *et al.* [12] state that maintainability is an important aspect of life-cycle design and is important during the service period of the product. Maintainability is the design attribute of system. It eases the performance of various maintenance activities such as inspection, repair, replacement and diagnosis. In their study, they have listed various maintainability attributes for the mechanical systems under broad sections like design, personnel and logistic support [12]. Tjiparuro *et al.* [13] explain the core maintainability requirements are mean time to repair (MTTR), mean time between failure (MTBF) and maintenance policy/philosophy. These factors depend on the logistic support, operation context, design attributes and personnel attributes. Kapur and Lalnberson [14] provide the maintainability design guidelines. Moss (15) develops some fundamental principles of maintainability to obtain the objective of DFMt (design for maintainability), such as standardization and interchangeability. Ireson and Coombs (16) provide a list of guidelines for design for reliability.

2.3 In-service information management system and its users' needs

Reliability data banks can be based on the service experience. Cooke *et al.* [17] highlight the users of the reliability data banks as: the maintenance engineer; the component designer; and the risk/reliability analyst. Lannoy *et al.* [18] 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. facilitate to improve the product. The data has to be stored in systems that make it easy to retrieve, analyze, and draw conclusions [19]. Some of the aspects behind the design of the information management system are to identify the users and their requirements.

2.4 Summary of literature review

According to the reviewed literature, the in-service information useful in the design stage of the products 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. The 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 optimization;
- improving the reliability of the next generation of products;
- fulfilling the various maintainability and reliability requirements.

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 [8]. The reviewed literature suggests the importance of identification of the potential users' needs in developing an in-service information system, but the literature does not explain in detail the requirements of these potential users, including designers.

3 RESEARCH METHOD

The research started by reviewing the literature and meeting the members of the 'design for service' team from the collaborating company with the aim of identifying in-service information requirements. The requirements were phrased in the form of questions. A list of 39 questions was identified and assembled in the form of a questionnaire. At a later stage, semi-structured interviews were conducted with three designers to identify their in-service information requirements. The interviews were divided into three phases. In the first phase, the designers were asked to mention their in-service information requirements. In the second phase, 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. In the third phase, the designers were requested to write any further questions. This sequence was used for the following reasons:

- to avoid any bias in phase 1 that might have occurred if phase 2 had been conducted first;

- to elicit more requirements in phase 3 due to the stimulation effect of the 39 questions in phase 2.

In addition, semi-structured interviews were conducted with three service engineers to identify: (1) their perspective about in-service information, (2) any information that is not recorded by the repair and overhaul (RO) centres, and (3) the difficulties faced by RO centres in capturing in-service information.

All interviews were audio-recorded. The notes taken during the interviews allowed documenting the information for further analysis. These notes were updated after listening to the audio recordings. The time of each interview was 60 to 90 minutes.

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).

Table 1. Information about the designers

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

The differing roles and experience of the service engineers is shown in Table 2.

Table 2. Information about the service engineers

Service engineer (SE)	Experience	Role
SE1	3 months	Summarising collected in-service information
SE2	25 years	Involved in service data engineering
SE3	25 years	Capturing problems across various engine types, co-ordinating the activities of the team members, etc.

4 FINDINGS

The principal information sources used by designers at present are the aftermarket team, and various service documents. The aftermarket team is comprised of service engineers, service representatives, and technical services and operations (TS&O) team. The service representatives act as a medium of interaction between the collaborating company and airlines. The service representatives and service engineers are responsible for populating the document repository with maintenance reports and other similar documents, while the TS&O team is concerned about the in-service operation and management of existing fleet engines and technical publications. Not all the service documents are available online, and designers do not generally have time to make detailed searches through the service information. The aftermarket team therefore provides the relevant information to them in a summarised format. The aftermarket team is principally concerned with the predictability of service, and with reducing the cost of repair and overhaul. Phone calls and face-to-face communication with people from the aftermarket team is possible.

4.1 Interviews with designers

This section explains the findings of the 3 phases of the interviews with designers.

4.1.1 Phase 1

This phase explains the service requirements considered by the designers in past projects, and the in-service information that the designers would like to access. The list of components that are to be designed is provided to the designer at the start of a project. The specifications given at the start are loose. The designer needs to explore the information required for the design. The information provided at the start of the projects consists of targets that the designers are required to achieve, as well as some necessary information that will assist them in achieving these targets.

The service requirements that were taken into account by the three designers in the projects they had worked on, are as follows:

- Failure data:
  - Deterioration mechanisms that a component might face in service, such as erosion, wear, cracking etc.
- Product reliability and safety:
  - Safety and reliability aspects.
- Service instructions:
  - Inspection limits: the goal of inspection is to identify critical levels of damage and replace components before a costly failure can result. Inspection limits help to determine the interval between inspections.
  - 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.
- Maintenance data:
  - Monitoring the deterioration mechanisms: this involves observing the condition of a component to estimate its remaining life, to avoid failure between overhauls.
- Life cycle cost:
  - 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.
  - Cost of spares, repair rate, disposal costs, etc.
  - Cost of overhaul: includes repair or replacement cost of the component.
- Life of component/system:
  - Life of the component, e.g. number of cycles or hours a component can survive under the given conditions.
- Maintainability:
  - Ease of assembly, disassembly, inspection, etc.

The information that designers would like to access, from the future service information system that will be developed in the ongoing research project, is as follows.

- Failure data:
  - Any events such as in-flight shut downs (IFSD), aborted take-offs (ABTO) etc. caused by a component.
  - Causes of failure.
  - The list of degradation mechanisms such as cracking, burning etc. for a component.
- Operating data:
  - List of operators of the engine, e.g. Trent 800 is used by British Airways, American Airlines etc.
  - The environmental conditions, such as speed and temperature, actually experienced by the component.
- Failure data and operating data:
  - Observed limits of the failure mechanism and the corresponding number of hours and cycles of the component.
  - Any variation in degradation mechanism with number of hours or cycles for a component.
- Design information:
  - Information about any previous designs which addressed the relevant deterioration mechanisms.
- Maintenance data:
  - List of all repairs, available at the repair and overhaul centres, for a component.
  - Borescope inspection photographs
- Life cycle cost:

- 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.

- Life of component/system:
  - Actual achieved life of a component in service.

4.1.2 Phase 2

Based on the findings of the meetings with the members of the aftermarket team and the literature review, we identified a list of 39 questions that designers might ask regarding in-service information. After phase 1, designers were requested to comment on this list questions, indicating how frequently they might ask each question when designing a new component or system. Some of the questions are as follows.

- What are the common failure mechanisms associated with this part?
- Can I see a picture showing a failed/damaged part?
- Do the failure mechanisms and life of this part vary depending on the engine duty and operator?
- When this part fails, what other parts are typically affected as a result?

The 39 questions are classified into three broader categories, which are further classified into the sub-categories. Table 3 shows these different categories along with examples. As the purpose of the 39 questions was to gain an insight into the in-service information requirements of the designers, the criteria for this classification is the topic/subject of the information that is required as an input for gaining answer to a question. The questions are classified into the category 'product' when the topic/subject of the information is related to the engine that is designed and manufactured by the collaborating company. The category 'service' refers to the support that is required to maintain the engine in the functional state during its operating life. The category 'product-service' is considered when the information is related to both the categories 'product' and 'service'.

Table 3 Categories used to classify the 39 questions

Category	Sub-category	Example
Product	Failure data	Failure mechanism, failure mode, causes, consequences, how identified, etc.
	Reliability	Weibull analysis of reliability
	Operating Data	Variation of different performance parameters with engine type, operator, etc.
	Design Information	Technical diagrams, the materials used for different components, information related to redesign aspects of an existing component, etc.
Service	Service Instructions	Inspection/repair/replacement recommendations, service standards/regulations, etc.
	Maintenance Data	Maintenance schedules, repair facilities required, spare parts requirements, moniterability requirements, etc.
Product-service	Life cycle cost	Component cost of ownership management strategy, repair cost, replacement cost, etc.
	Life/time	Longest/shortest life of a component, component's average life, change in component life with the change in inspections/overhauls intervals, etc.
	Maintainability	Accessibility, facility to detect and isolate failure

The popularity of each question was then measured by assigning a score for each response, as shown in Table 4.

Table 4 Scores for questions

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

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). Table 5 shows the number of questions and their total score.

Table 5 Number of questions and their total score

Number of questions	Total Score
4	12
3	11
13	10
9	9
7	8
1	7
1	5
1	3
39	

From Table 5, it is clear that the all 3 designers mentioned that they would ask 4 questions frequently. Two questions out of these 4 come under the ‘failure mechanisms’ category and the other 2 under the category ‘design information’. Only 3 questions scored less than 8 out of 12, and this suggests that it would be useful to present designers with information that is required to answer all these 39 questions.
Some of the questions from the list were mentioned by at least one designer during phase 1 of the interview, before they were requested to fill in the questionnaire. Fifteen such questions, or 38% of the total, were mentioned during the interviews. Many of these questions have a high score, showing good agreement between the information gained during the interviews and that from filling in the questionnaire. However, some of the questions which scored highly were not mentioned by the designers during the interviews. In general, all the questions in the questionnaire gained high scores – the poorest-scoring question was one which each designer said they would ask rarely.
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.”

4.1.3 Phase 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 he would like to ask, after filling in the questionnaire.

4.1.4 General observations from the interviews
During interviews, designers found it hard to remember the service requirements of their previous projects in detail. The list of questions was useful in helping to identify the service requirements that were not elicited during the interview. Initial questions in the interviews, eliciting the information such as projects the designer had worked on, and the stage of the project in the product development process, were helpful in eliciting designers’ requirements. These initial questions compelled the designers to think about the past projects they had been involved in. The requirements of the designers for service information depended on the components they had designed, their years of experience and

their role in the design of the engine, e.g. technical leader for the mechanical technology, or turbine blade designer.

4.2 Interviews with service engineers

In the opinion of service engineers, service information for designers should be in a summarised format instead of the raw data and information. The information should be fed back to designers as soon as possible.

The repair and overhaul (RO) centres do not document some information such as easiness of the repair as experienced by maintenance personnel and the mistakes made by maintenance personnel during maintenance activities, such as misplacing a component. The main difficulties faced by service engineers and RO centres in executing their activities are:

- RO centres are independent units; hence it is difficult to persuade them to record more information.
- There is pressure on the RO centres to accomplish all work in the minimum possible time. There is not enough time to get the engine back into service. Things are always needed in hurry – the company has to pay a penalty to its customers for delays, and flight cancellations are expensive.

5 DISCUSSION

The study allowed us to gain preliminary answers to some of the questions of the ongoing research, and it is hoped that the study will shape the further work of the research. Our interviews with designers allowed us to gain an insight into the various service requirements. The results of the questionnaire and the comments of the designers about it seem to be promising. The questionnaire helped to identify several service requirements which were not mentioned during the interviews. The service information requirements of designers, elicited through the interviews and the questionnaire, are related to maintainability requirements, reliability requirements, failure data, service instructions, life cycle cost, operating data, precedent design information, maintenance data, etc.

The in-service information would facilitate designers in formulating appropriate objectives, requirements and constraint for the design of a new component. These requirements and constraints can be seen as wishes and demands. An example of a wish and a demand can be: if a failure mechanism is considered to occur in the new design, wish can be to eliminate it completely and demand can be to eliminate its particular consequence. Furthermore, the in-service experience (successes and failures) of similar existing components/systems (e.g. providing in-service experience of the components such as compressor blades, fan blades, etc., which are similar is some attributes to the turbine blades, to a turbine-blade-designer) would be useful because of the following reasons.

- This would help designers to broaden the information space, which might help them to improve their understanding to infer appropriate requirements, constraints, etc. for a new component/system.
- It would be more likely to obtain a comprehensive set of requirements for the design of a new component/system as the additional information is likely to reveal more relevant issues.
- It can assist in prioritisation of the formulated requirements.
- The information regarding the failures and successes of the similar components can be useful in generating alternative solutions for the new component design.

It is important to understand the criteria for 'similarity matches' in order to identify the existing components/systems that are similar to a new component/system. The characteristics of the component/system design and in-service management can be useful in identifying the similar components. The component/system design characteristics can be comprised of: initial requirements of the component/system; component characteristics such as material, geometry, etc.; operating variables such as pressure, temperature, speed, etc. The in-service management characteristics can be comprised of: repair/replace strategy; inspection interval, etc. Based on the intention of the designers, comparison of one or more of these characteristics can enable to identify the similar components/systems. The in-service experience of these similar components needs to be presented to the designers. During the initial phases of designing a new component, these characteristics are not completely clear and evolve as the design progresses. Therefore, after major design actions, designer would search for the similar components with the changed characteristics (see Figure 1).

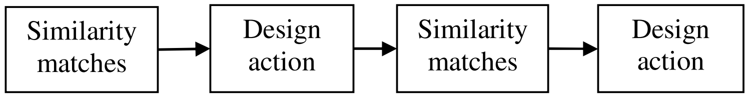

Figure 1 'Similarity matches' and design actions

Figure 2 illustrates an overview of the possible agents that can structure the in-service information for the designers. The available in-service information is stored in various disparate and heterogeneous sources such as electronic databases, documents, etc. This information needs to be structured for the designers relevant to their design activity. The possible agents that can execute this conversion are: human; computer; and human and computer. The designers, members of the aftermarket team can act as human agents.

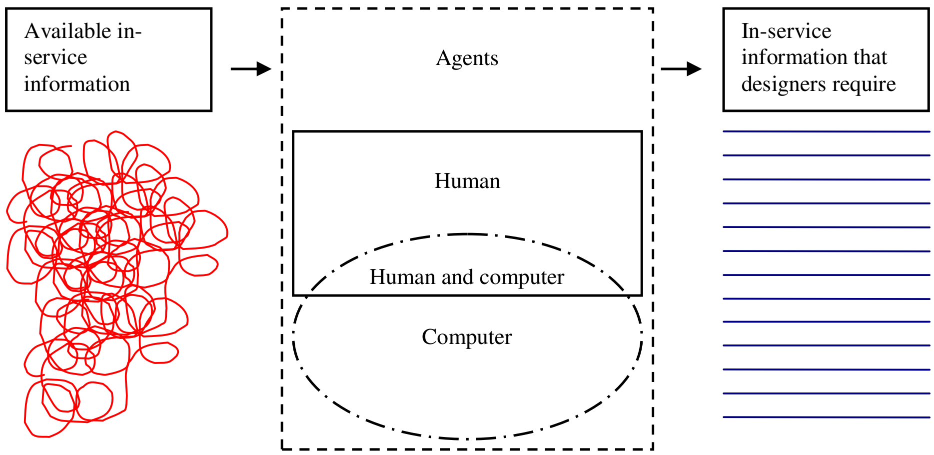

Figure 2 Illustration of a broader picture for structuring in-service information for the designers

Some approaches that consider these agents are discussed below.

- **Human agents (knowledge builders)**

Consider a rudimentary approach, in which the in-service information can be presented to the designers in the form of the raw data. In this approach, all sources such as documents, electronic databases currently storing in-service information can be accessed by the designers. The designers can infer the patterns in this information relevant to their design task. However, the designers do not generally have time to make detailed searches through the various disparate in-service information sources. Therefore, this approach seems to be impractical.

The members of the aftermarket team can create appropriate guidelines, rules by analysing and synthesising the in-service experience of the existing components. These guidelines, rules can be presented to the designers instead of the raw data though the meetings between aftermarket team members and designers. Such rules, guidelines can be useful for the designers in their new design task (see Figure 3). This approach can have the following advantages:

- As one of the roles of the members of the aftermarket team is to capture the in-service information, they can effectively and efficiently reveal the patterns in this information.
- Their accumulated experience can be beneficial in this task of analysing and synthesising the in-service information.

A possible limitation of this approach can be the bias introduced by the subjective judgements of these members. However, this bias can be reduced and revealed by explicitly stating the method of revealing the patterns in the information. The meetings between designers and these members can be useful as these meetings enable the transfer of knowledge from the aftermarket team and DfS team members.

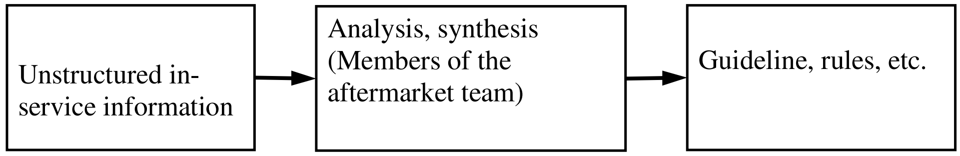

Figure 3 Knowledge builders

- **Computer agents**

The in-service information required by the designers can be stored in an 'in-service information database' in a structured format in order to enable designers to retrieve the information relevant to their design task. The existing in-service information, which is available through various information sources can be extracted by using information extraction tools [20] in order to populate the 'in-service information database'. At present, the various sources of in-service information such as documents, electronic databases, etc. are not designed for satisfying the designers' information requirements. The format of these sources has been primarily developed for managing the operation of existing engines in service. The new in-service information that will be captured in future can be captured in the information sources that are designed to satisfy requirements of all stakeholders including the designers. The in-service information database (see Figure 4) can be directly populated by the information stored in such structured sources without any need of sophisticated computer tools.

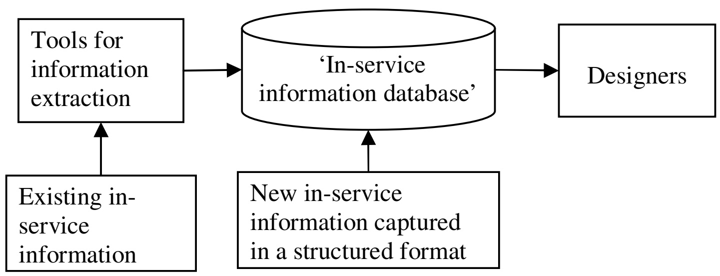

Figure 4 Populating the 'in-service information database' with the existing and new in-service information

- **Human agents assisted by computers**

The members of the aftermarket team can be assisted by the computer tools to structure the in-service information for the designers. In this approach, the level of sophistication is higher as compared to the methods that employ only humans to structure the in-service information (see Figure 5). It is necessary to understand the aftermarket team's activities to structure the in-service information. These activities can be comprised of:

- relating the different characteristics of the information stored in the various documents, electronic databases, etc. to each other;
- searching, browsing, and exploring this information;
- storing the outcome of the analysis of the in-service information in a structured format required for the designers, etc.

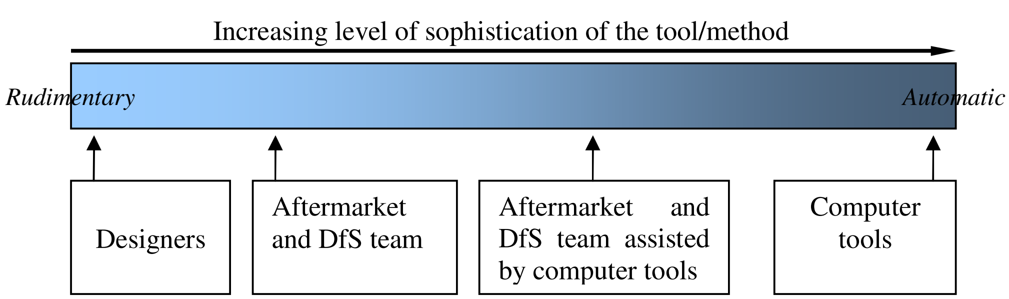

Figure 5 Illustration of the level of sophistication of the method/tool

It has been identified that some service information is not documented, partly because of the time pressures on RO centres to get engines back in service as soon as possible. The challenge is to design a system that can assist RO centres in documenting service information, such that designers can obtain a complete picture from this information. An empirical study at an RO centre would be one way to identify the information that is not currently documented, but which would be of value to designers. It is worth noting that the sample size of the interviews is small. To elicit more service information requirements of designers, further interviews or other data collection techniques may need to be conducted, covering a greater variety of designed components and designers' roles.

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Contact: S. N. Jagtap
Engineering design Centre
Department of Engineering
University of Cambridge
CB2 1PZ, Cambridge
United Kingdom
Phone: +44 1223 332742
Fax: +44 1223 332662
Email: snj22@cam.ac.uk
URL: http://www-edc.eng.cam.ac.uk/people/snj22.html