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A NOVEL APPROACH TO PRODUCT LIFECYCLE MANAGEMENT AND ENGINEERING BASED ON PRODUCT IN-USE INFORMATION

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Cette thèse intitulée:

A NOVEL APPROACH TO PRODUCT LIFECYCLE MANAGEMENT AND ENGINEERING BASED ON PRODUCT IN-USE INFORMATION

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DEDICATION

To Heidi

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RÉSUMÉ

L'évolution du marché pour les produits électromécaniques complexes a entraîné un intérêt croissant à la fois des fabricants et des chercheurs dans les produits et services intégrés (IPS). Cela a abouti à une reconnaissance de la nécessité de mieux comprendre les relations entre le développement d'un produit et les activités souvent coûteuses fois de soutien (c'est à dire d'entretien et de réparation) nécessaire pour maintenir sa fonctionnalité plus tard dans la vie du produit. En particulier, il est nécessaire de soutenir les activités de concepteurs grâce à la réutilisation des informations du cycle de vie concernant les fonctionnalités et la performance du produit.

Divers outils de gestion de l'information ont été mis en place afin de soutenir le développement de produits, y compris les outils de gestion de données produit (PDM), la gestion des processus de fabrication (MPM) et la gestion de cycle de vie de produit (PLM). Cependant, la plupart du progrès accomplis se concentre encore sur les premières étapes du cycle de vie du produit, dont la conception et la fabrication en particulier. En conséquence, les informations concernant l'évolution du comportement du produit plus tard dans le cycle de vie restent difficiles à gérer. Cette situation est aggravée par le fait que la plupart des modèles PLM continuent d'être axées sur la structure du produit. Bien que ces modèles puissent fournir des représentations robustes des aspects spatiaux du cycle de vie du produit, elles restent limitées dans leur capacité à rapporter la définition physique du produit avec les aspects temporels et comportementaux du cycle de vie du produit.

La recherche actuelle s'appuie sur des travaux antérieurs indiquant que les essais et la mise en service peuvent fournir des indications importantes à propos du comportement du produit. Alors que dans le passé ces types d'information ont été traités de façon indépendante, la recherche présente vise à démontrer que la combinaison de ces différents types d'information est possible dans ce que l'auteur qualifie l’information de « produit en cours d'utilisation ». Cette dernière est définie comme « l'ensemble d’information recueillie tout au long du cycle de vie concernant le performance du produit en cours d'utilisation. » Il est proposé que cette information puisse fournir un soutien important pour les concepteurs dans leurs tentatives de réduire les coûts futurs du cycle de vie et développer des produits plus fiables. Par conséquent, cette recherche vise

également à étendre les modèles actuels pour appuyer la structuration, la représentation et la communication de l'information de produit en cours d'utilisation.

Une étude approfondie de la littérature relative à la soutenance du processus de développement de produits par l'application de l'information concernant les essais et la mise en service a démontré que divers outils ont été développés pour recueillir et diffuser les différents aspects du comportement d'un produit et son effet sur la performance et les coûts du cycle de vie. Cependant, ces outils ont tendance à être évalué de manière empirique avec un accent sur les implémentations spécifiques, sans l'élaboration d'un cadre généralisé.

Grâce à un projet de recherche en collaboration avec un fabricant de sous-systèmes aéronautiques de haute complexité, une analyse systématique du rôle d’information concernant la mise en service et les essais au sein de ses activités de développement de produits a été possible. Un sondage a démontré la nécessité de soutenir les concepteurs grâce à un accès efficace à l'information concernant la performance du produit. En outre, les analyses des composants individuels ainsi que des familles de produits ont démontrés que l’information concernant les essais et la mise en service fournissent tout les deux des indications à propos du comportement du produit dans des contextes particuliers, notamment de l’information relative aux changements dans la structure et le comportement du produit au fil du temps, des explications possibles pour les événements inattendus et des suggestions de mesures correctives. Malgré ces similitudes, ils sont actuellement considérés comme des ensembles d’information distincts.

En développant des outils pour soutenir les concepteurs grâce à l’information de produit en cours d’utilisation, le cadre de l’analyse des modes de défaillance, de leurs effets et de leur criticité (AMDEC) a été étudiée , ainsi qu’analyses divers à propose des coûts de cycle de vie. Cependant, il a été constaté que le modèle de causalité de SAPPhIRE consiste d’un moyen plus approprié pour la structuration, la représentation et la communication d’information de produit en cours d’utilisation. Ce modèle ne représente pas seulement les chaînes causales trouvées dans les rapports d’événements d’essais et de mise en service, mais peut également fournir une structure pour organiser et communiquer de l’information de produit en cours d’utilisation détaillée, ce qui fournit une perspective approfondie en ce qui concerne les événements en questions. De cette manière, ce modèle fournit un moyen pour faciliter la compréhension de l'évolution interconnectée du comportement du produit et de sa structure au cours du temps. Cependant, le modèle de SAPPhIRE original a été développé pour l'analyse conceptuelle, et certaines constructions et éléments de sa structure ne représentent pas clairement l'évolution du produit tout au long de son cycle de vie. Par conséquent, un modèle de SAPPhIRE étendu a été proposé, mettant l'accent sur la création d'une relation claire avec le cycle de vie du produit. Il a également été démontré que ce modèle permet de représenter l'évolution d'un produit tout au long des phases de cycle de vie de la conception et la fabrication, et a donc un potentiel de servir comme base pour un modèle de gestion du cycle de vie étendue .

La recherche actuelle a démontré l'existence de l'information de produit en cours d'utilisation, a présenté ses caractéristiques principales et a démontré comment l'exploitation de cette information peut aider à résoudre un manque exprimée par les concepteurs. Il a en outre démontré la pertinence du modèle de SAPPhIRE étendue pour la représentation des aspects spatiaux, comportementaux et temporels du cycle de vie du produit. Des travaux futurs seront nécessaires pour l'évaluation quantitative du modèle et de sa capacité à faciliter le développement de produits et de réduire les coûts du cycle de vie du produit.

ABSTRACT

A changing marketplace for complex electromechanical products has resulted in an increased interest from both manufacturers and researchers in Integrated Products and Services (IPS). This has led to an acknowledgement of the need to better understand the relationship between the development of a product and the often times costly sustainment activities (e.g. maintenance and repair) required to maintain its functionality in the latter stages of the lifecycle. In particular, there is a need to support designers' activities through the reuse of product lifecycle information concerning product functionality and performance.

Various information management tools have been introduced in order to support product development, including Product Data Management (PDM), Manufacturing Process Management (MPM), and Product Lifecycle Management (PLM) tools. However, most advances still focus on the early stages of the product lifecycle, in particular design and manufacturing. As a result, information regarding the evolution of product behaviour later in the lifecycle remains difficult to manage. This is compounded by the fact that most PLM models continue to be centered on the product's structure. While these models can provide robust representations of the spatial aspects of the product lifecycle, they remain limited in their ability to relate the physical definition of the product with the temporal and behavioural aspects of the product lifecycle.

The current research builds on previous work indicating that both testing and in-service information can provide important insights into product behaviour. While in the past these information types have been treated independently, the current research seeks to demonstrate that a combination of these different information types is feasible within what the author has termed "Product In-Use" information. The latter is defined as "all information collected throughout the lifecycle concerning product performance during use." It is proposed that this information can provide important support to designers in their attempts to reduce future lifecycle costs and develop more reliable products. This research therefore also seeks to extend current models to support the structuring, representation and communication of product in-use information.

A thorough review of the literature pertaining to the application of test and in-service information for supporting the product development process has shown that a variety of tools have been developed for capturing and communicating various aspects of a product's behaviour and its

effect on performance and lifecycle costs. However, these tools tend to be evaluated empirically, with a focus on specific implementations rather than the development of a generalised framework

Through a collaborative research project with a manufacturer of complex aerospace subsystems, a systematic analysis of the role of in-service and testing within the manufacturer's product development activities has been possible. A survey of designers has demonstrated the need to support their activities through efficient access to information regarding product performance. Furthermore, analyses of individual components as well as product families have demonstrated that testing and in-service information both provide insights regarding product behaviour in particular contexts. This information relates in particular to changes in product structure and behaviour which occur over time, possible explanations for unexpected events, and suggestions for corrective action. Despite these similarities, in-service and testing information are currently treated as separate bodies of information.

In developing tools for supporting designers through the reuse of product in-use information, the Failure Modes and Effects Analysis (FMEA) framework was explored, as well as various lifecycle cost-based analyses. However, it was found that a more appropriate means of structuring, representing and communicating product in-use information is the SAPPhIRE model of causality. This model does not only represent the causal chains found in testing and in-service event reports, but can also provide a structure for organizing and communicating detailed product in-use information. This information provides stakeholders with further insights with respect to the reported testing and in-service events. In this way, the SAPPhIRE model provides a means for understanding the interconnected evolution of product behaviour and structure over time. However, the original SAPPhIRE model was developed for conceptual analysis, and certain constructs and elements of its structure do not clearly represent the evolution of the product throughout its lifecycle. Therefore an extended SAPPhIRE model has been proposed with a focus on creating a clear relationship with the product lifecycle. This model has also been shown to have potential for representing a product's evolution throughout the design and manufacturing lifecycle phases, and therefore could form the basis for an extended model of product lifecycle management and engineering.

The current research has demonstrated the existence of product in-use information, presented its main characteristics and shown how it can help satisfy an information gap expressed by designers. It has furthermore demonstrated the suitability of the extended SAPPhIRE model for the representation of the spatial, behavioural and temporal aspects of the product lifecycle. Future work will be necessary for quantitative evaluation of the model and its ability to facilitate product development and reduce product lifecycle costs.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

ABTO	Aborted Take-off
BMP	Bourse en Milieu Pratique
CAD	Computer Assisted Design
CAM	Computer Assisted Manufacturing
CE	Concurrent Engineering
CNC	Computer Numeric Control
CRM	Client Relationship Management
D	Detection
DfA	Design for Assembly
DFMEA	Design Failure Modes and Effects Analysis
DfR	Design for Reliability
DfS	Design for Service
DfX	Design for X
DMC	Direct Maintenance Cost
DS	Descriptive Study
ERP	Enterprise Resource Planning
FDCS	Field Data Collection System
FFDM	Function Failure Design Method
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
IFSD	In-flight Shutdown
IIS	Industrial Innovation Scholarship
IPDT	Integrated Product Development Team

IPS	Integrated Product-Service
IPSE	Integrated Product and Service Engineering
LCC	Life Cycle Cost
MIR	Maturity Index on Reliability
MPM	Manufacturing Process Management
NCR	Non-Conformance Report
O	Occurrence
PDM	Product Data Management
PDP	Product Development Process
PIR	Product Inspection Report
PLL	Part Lessons Learned
PLM	Product Lifecycle Management
PS	Prescriptive Study
PSS	Product Service System
QFD	Quality Function Deployment
RC	Research Clarification
RPN	Risk Priority Number
RRS	Reliability Reporting System
S	Severity
TER	Test Event Report
X_{R}	X_{Revised}

LIST OF APPENDICES

INTRODUCTION

Design encompasses a broad range of activities, and could on one level be considered a very personal process. However, the reality of design often entails complex scenarios requiring the collaborative efforts of a team of individuals in order to solve difficult problems. While the design process will always contain a certain level of subjectivity (as not all questions will have one optimal answer), the need to work as part of a team requires a certain level of objectiveness so that collaboration may be possible. As Hubka (1982) explains, this requires a design process which is both "rational and effective" to an individual while "as open as possible to inspection" from other team members. This could be taken a step farther by stating that the process must not only be open to inspection, but efforts must be made to ensure that the method is understood and agreed upon by collaborators, so that they may participate in the process.

Furthermore, design of a product intended for manufacturing, sale and use by consumers or clients requires an understanding of the entire product lifecycle (Blessing & Chakrabarti, 2009), from the formulation of the design question to production to end-of-life. As such, the design process is an integral part of the product development process, a process, which similarly must be understood and accepted, at least at a high level, by all stakeholders involved. In order for designers to understand the complexities involved at each stage of the product lifecycle, the management and sharing of product information as it evolves throughout the lifecycle has become an important topic of research. In parallel to a growing body of academic literature on this subject (Grieves, 2005; Sääksvuori & Immonen, 2004; Tichkiewitch & Véron, 1997), various information tools have been introduced in order to support product development, including Product Data Management (PDM), Manufacturing Process Management (MPM) and Product Lifecycle Management (PLM) tools (Brissaud & Tichkiewitch, 2001; Fortin & Huet, 2007). However, as will be discussed in chapter 1, these tools remain limited in their scope, and from both an industrial and an academic point of view there remain aspects of product lifecycle and engineering information which are poorly understood.

The recent recognition by manufacturers that they can better meet consumers' long term needs by providing a service associated with their product has placed a spotlight on one of the key areas in need of increased research. Both this shift among manufacturers and an increased academic interest in Product Service Systems (PSS) or Integrated Product-Services (IPS) (see chapter 1) have resulted in an acknowledgement of the need to better understand the relationship between the development of a product and the often times costly sustainment activities (i.e. maintenance and repair) required to maintain its functionality later in the product's life. Without an efficient means of ensuring this functionality, the cost of providing the required service to consumers can become unmanageable.

Previous research has suggested that an understanding of the relationship between in-service performance and design could be facilitated by the feedback of in-service information from maintenance personnel to designers (Jagtap, Johnson, Aurisicchio, & Wallace, 2007a; Markeset & Kumar, 2005). However, information concerning product failure can also be obtained from the results of testing and prototyping during product development (Ward, A. C., 2007; Wasserman, 2002). It is here proposed that the reuse by designers or, more generally, by advanced design and integrated product development teams, of information pertaining to the use of a product throughout its lifecycle (whether once it is put into service or during testing) would allow the prediction and elimination of many in-service issues and maintenance costs. In studying the support offered to designers through in-service and testing information, several similarities between these two seemingly separate categories have been recognised, leading to the hypothesis that both in-service and testing information can be structured in a similar way, and can be made available to designers by means of a single information management framework. This is in contrast to the separate databases and information systems (sometimes referred to as information silos) currently in use.

The foundation of the current research is determining whether the combination of these different information types is feasible within what the author has termed "Product In-Use" information. The following definition of product in-use information is proposed:

"All information collected throughout the lifecycle concerning product performance during use."

Possible sources may include, but are not limited to, information gathered from functional prototyping, product testing and in-service experience. Currently, attempts to capture and reuse this so-called product in-use information fail to exploit it to its full potential.

The broad objective of the current research is therefore to determine the feasibility of this new category of information, as well as to identify the most appropriate methodology, information structure, and technology to ensure the efficient feedback and reuse of product in-use information throughout the product lifecycle.

This objective can be met by answering the following questions:

- To what extent are in-service and prototyping and testing information similar, with respect to their structure and content, and therefore able to be combined as product in-use information?
- Is product in-use information currently treated as a coherent type of information during the design process?
- How can product in-use information be further exploited to ensure the continued performance of a product and future products during the use phase of the product life cycle while reducing the associated sustainment costs?

Chapter 1 of this report will present the background for this research and its motivation, along with a review of the current literature surrounding the management of in-service and testing information throughout a product's lifecycle, with a particular focus on the sharing and reuse of information pertaining to one product or generation of products during subsequent design projects. In chapter 2, the methodology undertaken for answering the research questions will be explained in the context of the design research methodology proposed by Blessing, and Chakrabarti (2009). These first two chapters will provide context as to how the current research, its goals, and its methodologies are situated within the current body of research surrounding information management for product development and design, and design research in general. As a result, they will discuss how other researchers have attempted to address the above three research questions, and how the present project intends to build on this previous work.

Chapter 3 considers the information requirements of designers and contains an analysis of a survey completed in partnership with an aerospace manufacturer on the topic of access to and reuse of in-service information to support design activities. This chapter provides a basis for answering questions one and three by providing further insight into the important impact in-service or product use-based information can have on the design process, as well as how designers use this information and how they believe their work could be supported by access to additional information.

Further work was conducted with the industrial partner throughout an 18-month collaboration. This involved the collection and analysis of a wide range of development testing and in-service information. The information collected, the analysis methods and the results of a comparative analysis of in-service and testing information are presented in Chapter 4. The goal of this analysis is to answer, in the specific context of the development of complex electromechanical systems, research questions one and two, and in so doing, determine the validity of the proposed category of product in-use information.

Building on the analysis presented in chapter four, a model for the management of product in-use information is presented in detail in chapter five. In addition to demonstrating how current models could be adopted as a powerful means for structuring and communicating product in-use information, a modified version will be presented, which can further support designers. Furthermore, it will be shown how this model offers a potential direction for the robust management of product lifecycle and engineering information. The final section will discuss the recommendations which can be proposed based on the results of this research, as well as several conclusions and directions for future work.

Chapter 1 RESEARCH BACKGROUND

The following chapter is a literature review completed in the context of a project to examine the use of what can be referred to as *product in-use information* and its role within the product development process. Product in-use information is a new term which the author defines as all information collected throughout the lifecycle concerning product performance during use. The main focus of this review is on the increasing need for engineers to consider product in-use information during product development and existing recommendations for how this could be achieved.

Section 1.1 examines a shift in the manufacturer's role in the marketplace and the new demands this places on the product developers, as well the new opportunities it affords. Section 1.2 discusses specific methodologies for the application of in-service and testing information in design, with a focus on Design for X (DfX) techniques. The sources, content and structure of product in-use information are central to this project, and current research in this area will be presented in section 1.3. This is followed in section 1.4 with an examination of proposed strategies for the exploitation of product in-use information in design. Finally, in section 1.5 the findings of this review are summarized and current research opportunities are identified and elaborated upon.

1.1 The shift towards integrated products and services

Over the last decade, a shift has occurred in how the suppliers of complex technological products view their role within the marketplace. While manufacturers traditionally viewed their role as the producers of physical products, they are now increasingly assuming that of service providers (Sääksvuori & Immonen, 2004). In the context of the aerospace industry, this would imply that companies which produce aircraft or aircraft engines may now view their role as one of providing transportation or power, respectively (Jagtap, 2008; Kim, Cohen, & Netessine, 2007). Within the defense industry this is referred to as "performance based logistics", while the commercial aerospace industry refers to this as "power by the hour" (Kim et al., 2007). This is not simply a change in semantics, but has important implications for how a manufacturer manages its internal processes as well as its relationship with its clients (Markeset & Kumar, 2005; Mont, O, 2000; Sääksvuori & Immonen, 2004; Tan, Andreasen, & Matzen, 2008). The reasons for this shift, its effect on manufacturers, and the challenges and potential benefits will be examined in this section.

In the field of complex technological products, such as those that integrate mechanical, electrical, and/or electronic systems, product reliability and performance have increased rapidly throughout the last few decades. This general increase in performance has led to more demanding customers and has made it more difficult for a company to achieve a strategic advantage in the marketplace simply by providing a quality product (Markeset & Kumar, 2005). The complexity of these products has also increased, meaning that to support them once they are in use requires increasingly specialized knowledge which only the manufacturer may possess (Markeset & Kumar, 2005). In order to provide the customer with the needed support, as well as to distinguish themselves from competitors, manufacturers are exploring long term relationships with clients which extend into the use phase of a product's life cycle, and sometimes even to the point of end of life product disposal. Sääksvuori & Immonen (2004) have referred to this as the "extended product" or "lifetime service" paradigm, while Mont (2000) has referred to this as a shift in focus towards the satisfaction of needs through product utilization, rather than simple product ownership. In general, research in this domain attempts to formalize the development and optimization of all aspects of service provision, from service creation to delivery and consumption (Mont, O, 2000; Tan et al., 2008).

Many companies have begun to design services using similar processes to those used to design physical products. While these services may be offered completely independently, when offered in conjunction with a physical product the combination is commonly known as Product Service Systems (PSS) or Integrated Product and Service Engineering (IPSE). In fact, the research into this combination of services and products dates back several decades, with Vandermerwe, and Rada (1988) introducing the term servitization to represent the process of creating value by adding services to products. In completing a thorough literature review of current research on servitization, Baines, Lightfoot, Benedettini, and Kay (2009) have come to define it as

"The innovation of an organisation's capabilities and processes to better create mutual value through a shift from selling products to selling PSS"

They further point out that the research into PSS has been focused to a large degree on the environmental benefits gained from the dematerialization associated with servitization [e.g.

(Mont, O., 2000)]. Taking an even broader view, Park, Geum, and Lee (2012) have identified 13 research terms related to the integration or bundling of products and services, including PSS. In order to develop a taxonomy and typology for this field of research, they have defined a new, overarching term: Integrated Product-Service (IPS). This is defined as “any offering in which products and services are integrated”. It is then possible to update the definition provided by Baines et al. (2009) of servitization to

“The innovation of an organisation’s capabilities and processes to better create mutual value through a shift from selling products to selling IPS”.

Servitization and IPS encompass a broad field of research; in fact, each of the terms identified by Park et al. (2012) and Baines et al. (2009) differ to greater or lesser degrees with respect to their context, focus and objectives, and in some cases the same term has been used differently by different researchers. The fields of research implicated in this domain range from marketing and sales, which uses the term “bundling” when discussing ideas similar to IPS, to environmental impact reduction, which has become closely tied to the use of the term PSS (Mont, O., 2000). It should be noted that with increased focus on the responsibility of manufacturers towards global sustainability, this emphasis on the environmental benefits of servitization has recently become quite prevalent (Mont, O., 2000).

While aspects of these various fields are necessarily related to the current project, in order to maintain a manageable scope it has been decided to focus on scenarios where companies continue to rely heavily on their ability to provide specialized complex products, while at the same time implementing an IPS framework. The aerospace industry is a prime example of this type of servitization. As such, the work of Markeset and Kumar (2005) regarding the shift from “conventional products” to “functional products” is of great interest.

It should be noted, however, that the use of the term “functional” is not standard among researchers in the field of servitization. For example, Mont (2000) defines the service economy as integrating products and services, and defines a functional economy as one where products would be completely substituted by services. Furthermore, while Alonso-Rasgado, Thompson, and Elfström (2004) consider the sale of functional products to include the sale of both service and physical products, Markeset, and Kumar (2005) consider scenarios where the physical product remains the property of the manufacturer with only the functionality being sold. As the aerospace industry is moving towards the scenario described by Markeset & Kumar, where engines remain the property of the manufacturer, and as the latter's research regarding the in-service support of functional products is very pertinent to the current research, the definitions of conventional and functional products given by Markeset and Kumar (2005) will be used.

Within the functional product framework, as described by Markeset and Kumar (2005), the main concern of the supplier is the delivery of performance. In the case of industrial production machinery (e.g. computer numerical control tools) this may be measured in drilled meters per shift or volume of material removed per hour (Markeset & Kumar, 2005). In the field of aircraft engines, performance is typically measured in terms of availability to complete particular missions, which is commonly referred to as "power by the hour" (Jagtap, 2008).

By entering into an agreement concerning product performance, a manufacturer becomes responsible for ensuring a certain acceptable performance level for the length of the agreement. Typically, this agreement involves a payment to the functional product provider on a regular basis which is determined by the level of performance required by the customer (Kim et al., 2007). The idea of the functional product is a large shift from the conventional product framework where the main deliverable is the physical product itself (e.g. the CNC tool or the aircraft engine). A major difference is in the balance of life cycle costs (LCC) incurred by the customer and manufacturer. In a conventional product framework, the costs to the customer include the initial acquisition and implementation of the physical product, as well as the costs of unavoidable support services due to product weakness (i.e. a drop in performance over time), the day to day operation maintenance of the product and any additional services related to performance optimization (Sääksvuori & Immonen, 2004; Tan et al., 2008). These additional services are also referred to as product support and customer support. Product support refers specifically to technical issues affecting the product and is driven by product weaknesses, while customer support involves such things as training and the overall strategy for implementation of the product and is driven by the customer's level of knowledge and expertise (Markeset & Kumar, 2005). In this traditional context, the sale of support services is an extra value stream for the supplier (or a qualified support provider), and can be used as a means to recoup losses incurred during the development phase if necessary. This can lead to conflicts between suppliers and customers, as they are trying to optimize their life cycle profits at each other's expense: manufacturers depend on additional payments from customers for support services, while customers, predicting the need for extra cost services, attempt to reduce their outlay for the initial product (Knezevic, 1999; Markeset & Kumar, 2005).

Faced with this often strenuous relationship, as well as with the previously mentioned need for market differentiation, manufacturers of complex products have turned to the functional product framework. The implementation of such a framework shifts the balance of risk accepted by each party. While the customer gains the most apparent benefit by reducing the risk of suddenly incurring unexpectedly high support costs, the risk to the manufacturer increases, especially in the case of newly introduced products where service requirements typically remains poorly understood (Kim et al., 2007). In fact, once they assume responsibility for product performance they also assume the costs of supporting the product throughout its use and therefore potentially lose a lucrative value stream if they miscalculate the appropriate level for ongoing payments. However, when managed properly, the provision of a service can lead to increased long term stability for the manufacturer due to less reliance on the cyclical nature of the market, and closer customer relationships and loyalty (Sääksvuori & Immonen, 2004). In addition, under a performance based logistics contract, manufacturers are free to determine the best way to fulfill the agreed upon performance requirements, without the need for detailed disclosure to the customer of their process and the associated costs. Markeset, and Kumar (2005) refer to this as a shift towards a win-win situation, where a customer gains reduced operation and maintenance costs as well as an extended product life, while manufacturers can optimize their value chain for maximum competitiveness and gain valuable experience with respect to product implementation and use. This experience can also provide valuable information to be used in the development of support services offered for other functional as well as conventional products.

This shift is not simple, however, and requires manufacturers to re-examine not only how they provide services to customers, but also their product development process (PDP) (Jagtap, 2008; Knezevic, 1999; Markeset & Kumar, 2005). In developing a conventional product, the main concern is to reduce the initial selling price while meeting the necessary product specifications requested by the customer, including certain minimum reliability, maintainability and availability targets. In many cases, maintainability and availability are given a low priority and are only considered late in the design process (Markeset & Kumar, 2005). While reliability, availability and maintainability are closely related, it is important to distinguish between the three:

- Reliability: The probability than an item will perform its assigned mission satisfactorily for the stated time period when used according to the specified conditions
- Maintainability: The probability that a failed item will be restored to its satisfactory operational state
- Availability: The probability that an item is available for use when required (Dhillon, 2006)

While reliability is important to ensure satisfactory product performance, a product can never be 100% reliable, and at a certain point a balance must be achieved between design for reliability and design for service (Knezevic, 1999; Markeset & Kumar, 2005). Design for service (DfS) takes into account the needs of those involved at the product use phase, and so includes such aspects as maintainability, availability, upgrades, warranty, training, documentation, and so on (Goffin, 2008). The means of production can also have an impact on the maintainability of a product, and so trade-offs must also be made between DfS and design for manufacturing (DfM). These concepts are collectively known as DfX and their role in the design of a functional product, along with that of other tools and methodologies, will be discussed further in the next section.

In order to facilitate the application of these methodologies and to ensure that these aspects of the product are fully considered during development, it is necessary that designers be knowledgeable with regard to issues that may arise during product use. This is usually approached in two ways: through the formation of integrated product development teams (IPDT) and by making relevant information available to designers (Jagtap, 2008; Knezevic, 1999; Markeset & Kumar, 2003; Sander & Brombacher, 1999). An IPDT is formed of representatives from various departments who collaborate throughout the development process and share their experience in order to ensure that all aspects of a product and its life cycle are taken into account. This is a key concept in what is known as concurrent or simultaneous engineering (CE) (Blanchard & Fabrycky, 2006; Knezevic, 1999), which Blanchard, and Fabrycky (2006) define as:

"[...] a systematic approach to creating a product design that simultaneously considers all elements of the product life cycle, from conception through disposal, to include consideration of manufacturing processes, transportation processes, maintenance processes, and so on."

As CE is now a common strategy for product development, it will not be dealt with in detail in this paper. However, it remains important to the development of functional products and so will be referred to at certain points.

In addition to the transfer of information through collaboration with experienced individuals, designers should be able to access product in-use information whenever needed during product development. One way to achieve this is through the development of tools and processes to make information collected by in-service personnel available to designers (Jagtap, 2008; Markeset & Kumar, 2005). Another aspect, which is relatively ignored in the literature surrounding functional products, is the role of testing, and testing related information, during the PDP. While design for reliability touches on certain test regimens (Dhillon, 2006; Wang & Coit, 2005), testing and prototyping are not widely discussed in the literature surrounding IPS and functional products. However, as will be explained in chapter 4 the information obtained from these activities can be quite similar to that obtained from in-service sources. One of the hypotheses of this project is that there are sufficient similarities between the content and structure of in-service information and that of testing and prototyping information that they can be grouped together as *product in-use information* and therefore be managed together within the PDP. Finally, in order to ensure that this information is available for sharing between stakeholders and for reuse in the context of future products, its integration into an overall information management framework must be considered. With the increasing use of Product Lifecycle Management systems, section 1.3.4 will explore the requirements for true PLM and current proposals for the management of product in-use information in particular.

1.2 Methods and tools for the design of functional products

1.2.1 Design for X methods

As explained in section 1.1, Design for X (DfX) methods play an important role in the product development process. The concept of DfX originated with Boothroyd and Dewhurst's development of Design for Assembly (DfA) in the 1970s, where they defined a set of assembly constraints which should be taken into account during the design process. Since then, this field has expanded to include various topics such as Design for Quality, Design for the Environment, Design for Life Cycle Costs, Design for Disassembly, Design for Recyclability etc... (Blanchard

& Fabrycky, 2006; Kuo, Huang, & Zang, 2001; Ulrich & Eppinger, 2008). This expansion of DfX is due to the realization that an increasing range of life cycle issues and their specific constraints should be taken into account during design. Of particular interest to the design of functional products are Design for Service and Support (DfS) (which includes aspects of Design for Maintenance (Goffin, 2008)) and Design for Reliability.

1.2.1.1 Design for Service and Support (DfS)

Design for Service and Support (DfS) is described in several publications (Blanchard & Fabrycky, 2006; Goffin, 2008), although certain details vary from one source to another. For example, Blanchard, and Fabrycky (2006) refers to DfS as Design for Supportability and Serviceability, and treats Design for Maintainability as a separate concept, while Goffin (2008) uses the term Design for Service and Support and includes maintainability aspects within his definition. Design for Maintainability is also described in Kuo et al. (2001) as a separate method. Goffin (2008) identifies DfS as a new area of research which has been subject to little academic study, with the majority of the body of literature consisting of empirical studies with relatively inconsistent methodology.

He identifies the value of DfS as enabling manufacturers to better satisfy customer needs by addressing the requirements of after-sales services, or the activities during what the author refers to as the *product use cycle*. This is defined as the phase of the product's life cycle from the time of purchase to the final disposal and can be further sub-divided into 5 elements:

1. Delivery
2. Use
3. Maintenance
4. Supplement
5. Disposal

Goffin identifies complex products, which are typically less reliable, as particularly in need of DfS as they are more likely to need maintenance and repair. Examples given include customer products such as cars, domestic equipment and medical products and business-to-business products such as manufacturing equipment, computer networks and aircraft. These considerations are less important for low complexity, short lifecycle products, where customers are less likely to require repairs and companies may offer replacements rather than repair the product.

Cost of ownership is identified as a critical factor in customer satisfaction, with costs associated to each element of the product use cycle. Therefore, cost analysis is suggested as a widely applicable method to determine whether the product is optimized for the product use cycle. Goffin also recommends that personnel with customer support experience should be involved in the early stages of the design process to ensure that actual product use cycle issues are considered.

It is also important to determine the trade-offs between DfS and the requirements of other product life cycle stages. Of particular interest is the relationship between the constraints necessitated by Design for Manufacturing and Design for Maintainability and Repair. It is noted that products designed for easy manufacturing could as a result be difficult to disassemble and assemble for maintenance and repair purposes once the product is on site. This therefore entails a trade-off analysis to determine which aspects should be given greater consideration. This is especially important as maintenance and repairs are identified as the driving factors in DfS (Goffin, 2008).

1.2.1.2 Design for Reliability

Design for reliability (DfR) is covered extensively in the literature, being included in nearly every recent textbook concerning product or systems design including, as well as many academic papers (Blanchard & Fabrycky, 2006; Kuo et al., 2001; Pahl, Beitz, Feldhusen, & Grote, 2007; Ulrich & Eppinger, 2008; Wang & Coit, 2005). In this section it will not be attempted to define all the strategies used in the application of DfR, but rather to provide a brief overview and explore how it can relate to the application of product in-use information at the early stages of the design process.

As with the other DfX methods, DfR methods are meant to be applied early in the design process, in this case with the particular goal of accounting for possible reliability issues. In order to do so, it is necessary for designers to have an understanding of reliability theory and its application in ensuring the development of reliable products (Dhillon, 2006). Reliability targets are usually set early in the development process in consideration of customer specifications, and are treated as critical requirements for the final product (Dhillon, 2006). In complex products, the general targets are set at the systems level, with specific targets being allocated to the system components later in the process. These targets are allocated in such a way as to ensure the system meets its overall reliability target. These targets can take the form of failure rates (the probability of failure over a specific period) which is the inverse of the reliability of a product, or the mean time between failures (Dhillon, 2006). In order to determine the overall system reliability from the component reliabilities, the system is modeled using network diagrams which represent the layout of the system. Once the appropriate network is determined, such as parallel or series, the overall reliability can be calculated.

While these calculations are crucial to ensuring a reliable product, there are also more qualitative tools for analysing reliability, such Failure Modes and Effects Analysis (FMEA), Ishikawa or Fishbone analysis, and Root Cause analysis (Blanchard & Fabrycky, 2006; Dhillon, 2006). These are primarily focused on determining possible failure modes and their causes and eliminating them from the product, and do not necessarily rely on the statistical calculations used in more quantitative analyses. As will be presented shortly, Jagtap (2008), who has completed what is most probably the most complete analysis to date of the use of in-service information in design, determined that the information most requested by designers is related to deterioration modes, causes and effects. Therefore, the qualitative tools used in DfR could potentially benefit from an increased availability of product in-use information during product design.

In addition, Dhillon (2006) recommends the development of a reliability management program that lasts throughout the product life cycle and assigns responsibilities to various stakeholders. The company management is involved in this program and are responsible for assigning resources, setting specific goals, ensuring that information regarding current reliability performance is accessible throughout the organization and monitoring the progression of the reliability program. While this is not explicitly part of DfR, whether management fulfills its role has an important impact on the ability of designers to consider reliability factors early in the design process. This is especially true of management’s responsibility to ensure that up to date information is available to all departments, as will be seen shortly (Jagtap, 2008).

1.2.2 Design Tools

In order to support the DfX methodologies described above, it is necessary to provide designers with the necessary tools for analysing new designs and products in terms of product in-use information. While this is still a relatively poorly researched area, this section will present several tools which have been identified as beneficial. Although these tools use different techniques for representing information and supporting designers, for example while some are matrix based or document based, others represent information graphically, the objective in each case is the communication of product in-use information to the designer to support their daily work. In some cases, this involves the adaptation of traditional analysis tools to the role of information capture and feedback (this is particularly true for Failure Modes and Effects Analysis).

1.2.2.1 Trade-off Curves

In order to decide between alternative concepts, Toyota's engineers explore the various trade-offs involved through what are known as trade-off curves. Ward (2007) identifies these as a powerful means to quickly assess the viability of a design by allowing the visualization of a large amount of data in a clear, synthesized format. A trade-off curve is basically a large format sheet containing a brief description of the trade-off being examined and a curve showing the graphical or mathematical relationships among the various characteristics (i.e. price and functionality) that the engineers wish to optimize. This can range from a simple stress-strain graph to a graph showing pressure drop versus noise level for a muffler at specific engine outputs. While the curves can be created from various sources of data, they are specifically useful for the representation of information gained from prototypes and testing and allow for the information to be reused in other development projects (Ward, A. C., 2007).

1.2.2.2 FMEA and related tools

Along with analytical tools such as Reliability Prediction, Fault Tree Analysis (FTA), and Robust Design methodologies, the goal of FMEA is to ensure a certain level of reliability for a product (Raheja, 2002). MIL-STD-1629A defines FMEA as

"A procedure by which each potential failure mode in a system is analyzed to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity" (Defense, 1980).

Detailed guidelines for completing an FMEA can be found in many papers, textbooks and standards (Defense, 1980; Krasich, 2007; Raheja, 2002). While some details may vary between descriptions, the general concept remains the same throughout the literature. Briefly, an FMEA begins with a list of all components in the product, grouped by system and sub-system. To each component is then associated its possible failure modes, the effects of these failures on the component as well as on the next higher assembly, and the potential failure causes. Each of these failure modes is then assigned a value for severity (S), rating the impact of the failure on the system; occurrence (O), the likelihood of the failure occurring; and detection (D), the ease with which the failure can be detected before it occurs. The S, O, and D values are assigned based on industry standards, typically ranging from 1 to 10. These numbers are then multiplied to provide a Risk Priority Number (RPN), which serves to identify the most critical failure modes. A mitigation plan is then created for the most serious failure modes, at which point revised values (S_R, O_R, D_R) are assigned, and a revised RPN (RPN_R) is calculated based on the mitigation strategy. This final RPN_R must be below a pre-defined value in order to ensure all risks have been properly mitigated. Several tools, either using a standard FMEA or a similar methodology where functions and failures are related to each component, have been proposed for the exploitation of in-service information during product design.

To begin with, Kraniak & Ammons (2001) have developed a method for integrating the information collected from in-service experience with automated production machinery into the FMEA module of a commercial reliability analysis tool. By associating data from the in-service information database with the software's library, and the creation of a standard list of common parts used across different projects, a system was developed whereby the FMEA of a new product could be populated automatically by historic failure data. While the authors state that this tool allows for faster improvement than their competition, quantitative results are not given and no analysis is performed to determine whether the information is being used to it full potential. Furthermore, the tool is applied only in a very specific context and its general applicability is unclear.

Wirth, Berthold, Kramer, and Peter (1996) attempt to solve some of the problems traditionally associated with FMEA by developing a knowledge-based FMEA technique, WIFA. The problems addressed are the use of natural language and the lack of a well defined standardized methodology, both of which hinder the reuse of past FMEA and lead to subjective differences in the results. The WIFA methodology is based on the use of semantic knowledge organized in the form of taxonomies. Two taxonomies are created in the database, one for the hierarchical arrangement of system elements and one for a set of standard functions taken from the literature. Wirth et al. (1996) also introduce the idea of a 'FMEA case', which contains all the information gathered when conducting an FMEA in which they include in-service information. This case is indexed to the elements of the taxonomies so that it is easily accessible when creating a new FMEA. By creating a standard vocabulary of system elements and functions, information contained in past FMEAs can be reused in similar new product development projects. Field tests showed good initial results for the tool and it has potential to allow the reuse of the information gathered for past FMEA including in-service information for new projects. However, it is unclear how this in-service data is obtained or its content. The treatment of statistical failure information compared to more qualitative failure or root cause information is quite different and could require different tools for its consistent reuse in product development.

In a study of in-service information concerning a fleet of Bell 206 rotorcraft, Stone, Tumer, and Van Wie (2005) introduce the Function-Failure Design Method, a matrix based tool for the use of historical failure data in the development of new products. The first step in this methodology is to create a Function – Component matrix, relating each component of a product to a function based on a detailed functional model of the product. Once the product is in-service, failure data related to each component is collected and organized into a Component – Failure matrix. By multiplying these two matrices together, it is possible to obtain a Function – Failure matrix, relating historical failure data to a specific function. It is this matrix that will allow for the reuse of the historical data at the conceptual stage of the design process. When designing a new product, an initial functional model is created at the conceptual stage. These functions, by means of the Function – Failure matrix, can then be associated with the relevant failure data. Once the possible failure modes are identified, the functional model is elaborated in order to mitigate the possibility or impact of the failures. Based on the detailed functional model, one or several preliminary designs are developed by assigning specific components or assemblies to carry out each function. These components are then compared to the Component – Failure matrix in order to once again ensure that all historical failure data is taken into account and mitigated against. The authors carry out two controlled studies in order to compare this methodology with traditional FMEA, one involving a new product design and one involving the analysis of an existing product. In both cases, the FFDM identified more failure modes and was deemed by the authors as more effective. However, the studies were limited to three design engineers completing individual FMEAs and a single designer using the FFDM method, which is not a very large test base. Furthermore, those completing an FMEA did not have access to any type of historical failure data, but rather relied on their own experience. The authors did not consider how an FMEA supplemented with historical failure data would compare to the FFDM. As a result, it may be more precise to view the study as an evaluation of whether historical data is useful in mitigating failures in new and existing products.

The advancements to FMEA-like tools have been shown to aid in providing up to date in-service information to designers. However, their scopes are limited to the description of specific events with a limited content structure, rather than the full behaviour of the product. As will be demonstrated in Chapter 4, this factor led to the consideration of an alternative model for the current work.

1.2.2.3 Causal modeling with Sym-SAPPhIRE

In order to support designers in their use of in-service information, Jagtap (2008) suggests the storing and structuring of the information using what is known as the Sym-SAPPhIRE model of causality. This is a modified version of Chakrabarti, Sarkar, Leelavathamma, and Nataraju (2005)'s SAPPhIRE model. In order to properly model the causal chain leading from environmental inputs and system components to the expression of a failure mode, Jagtap introduced an extra input of stimuli and the additional 'embody' and 'affect' relationships. The author suggests that this model can help designers use the information during 5 activities:

- Task clarification
- Solution generation
- Searching for similar components
- Identifying potential deteriorations
- Linking design rationale to in-service experience

The diagrammatic nature of the causal model facilitates the task clarification and solution generation by presenting the causal chain in an easy to understand format. As is it easier to process a visual representation than a text based document, this format allows designers easier access to the information and allows them to quickly grasp the important issues affecting component deterioration early in the design stage. It is also possible to associate additional information to the causal chain, such as statistical failure data and images of the deteriorated components. Furthermore, by facilitating the efficient comparison of several casual chains at one time, the use of the Sym-SAPPhIRE model for representing information can lead designers to solutions they may otherwise have missed. In fact, 9 out of the 22 causal chains found in one case study were not initially used by designers when the information was available only in textual format. It is expected that this additional information will be easier to account for when the information is represented diagrammatically.

In the study completed by Jagtap, it was found that designers tended to restrict themselves to searching for other components of the same type when looking for additional information during design. However, additional information could also be found by searching, for example, for components that had the same failure mode or were affected by the same stimuli. By structuring the data in a way that additional common attributes are explicit (e.g. stimuli, action, affect…) it could lead designers to search for other information which could facilitate their work and lead to more innovative solutions. This facilitation in the identification of similar components was also predicted to have a positive effect on the identification of identifying potential deteriorations. By searching for the causal models of similar components already in-service, designers can either discover additional relevant means of deterioration or they can verify whether those they have identified through analysis have been observed in practice. The authors also suggest that the Sym-SAPPhIRE model can be used as a systematic procedure for analysis as well as for modeling. By progressing through each stage of the model and identifying the relevant features (stimuli, inputs, creation, etc…) a designer can systematically identify all factors surrounding a specific deterioration case. Not only does this ensure that the information surrounding the analysis is complete, it also ensures that other designers can understand the rationale behind the analysis.

In order to understand the decisions that resulted in a successful or unsuccessful product in-service, Jagtap (2008) suggests how to link decision rationale to in-service information through the causal model. In this way, past decisions can either be adopted, adapted or avoided depending on the results during product use. Two areas are suggested as being of special importance. First, the researcher suggests the examination of the stimuli and organs (parts) that lead to the unintended physical actions, such as deterioration, which have been recorded in the in-service experience. Next, designers should identify the issues, answers, and arguments that influenced the specification of the stimuli and organs during the design of the existing component. This also includes investigating how alternative concepts were evaluated by past designers and what factors and arguments were seen as the most important during the design process.

1.3 Information to support the design of functional products

As mentioned in the previous sections, in order to successfully complete a product development project within the functional product framework, it is important for designers to have access to information regarding the behaviour of products once they are in use. In reviewing the literature, two potential information sources were discovered: in-service information and prototype and testing information. This information can help ensure that the tools and methods described in section 1.2 are based on proper assumptions, as well as provide a benchmark against which to measure their effectiveness. Furthermore, a thorough understanding of the information available, or which could be available, from testing and in-service can point the way towards new and more effective means of supporting designers.

In this section, the general trends regarding access to, and the reuse of, information within engineering activities will be discussed. This will be followed by a discussion regarding the sources of in-service and testing information identified within the literature, the value of this information in the design process, as well as the typical content and structure of the information sources. Throughout this section, it will be clearly demonstrated how this information is a vital input for the design methodologies and tools discussed in the previous sections.

1.3.1 Information Needs of Engineers

In a survey of 30 engineers in a division of an aerospace company, Crabtree, Baid, and Fox (1993) found that engineers typically spend 12.4% of their time gathering information, but consider it to be the most frustrating activity in which they engage. The reasons for this frustration included the length of time needed for locating information, as well as the time needed for the revision and approval of said information. Furthermore, a lack of standard information and online documentation hampered efforts to find the appropriate information with a reasonable amount of effort. In fact, information acquisition and access was found to represent 56% of coordination problems, with designers frequently needing to ask questions such as:

- Who has the information needed?

- Where is it?
- Is this the latest revision?
- Is change coming?
- Is this my responsibility?
- Whose responsibility is this item or task?
- What is the history of this design?
- Why does it have the form it has?

As the search for information plays such a large role in the work of designers, it is also important to understand how they proceed in the search. Kwasitsu (2003) had a questionnaire filled out by 36 design, process, and manufacturing engineers regarding their information seeking behaviour. In their answers, they highlighted the use of information for solving problems and exploring various ideas. When asked to rate the importance of information sources, “people in the same work group” and “personal notes and files” ranked the highest, with a score of ‘Highly important’. Notable exceptions however were engineers with the highest education, who ranked libraries as their most important information source. Rated as ‘Moderately important’ were people in other work groups and the Internet. It is interesting, and perhaps worrying, that company information, which can be structured and controlled for quality, timeliness and completeness, does not rank highly on this list.

The participants ranked accessibility and availability as the most important influences on their choice of information sources, followed by technical quality and relevance. Similar to the challenges noted in Crabtree et al. (1993), a significant challenge encountered when information was needed was simply knowing where to look. It is therefore clear that companies should invest in not only the construction of reliable information management frameworks and strategies, but the structure and sources must also be clearly communicated to designers. It is important to consider though, as noted in Ward, M. (2001), that there will always be an instinct to ask another person for information, in conjunction with the use of formal libraries. It is important therefore to consider these sources together, for example through the formation of knowledge clubs, and not to represent these strategies as antithetical. In the following sections, the sources and management of in-service and testing, as reported in the current literature, will be discussed.

1.3.2 In-service information

While there is a body of literature dealing with in-service information and its application during the design phase, it is relatively small and is mainly empirical in nature. This is supported by the findings of Jagtap (2008) as reported in his thesis on the use of in-service information to support designers, which is the most complete survey to date on this subject.

One of the first papers to analyse in-service information for use in design is Collins, Hagan & Bratt (1976) where the authors developed what they term the Failure-Experience Matrix. 500 failed parts from U.S. army helicopters were analysed and the function, failure mode and corrective action taken in each case was recorded. A standard list of 40 failure modes was developed based on the literature and the observed data. Similarly, a list of 46 functions along with 40 antecedent adjectives was developed in order to classify the intended function of each part. Finally, the corrective actions were classified in 35 broad categories. While failure mode, function and corrective action were used to classify the information, the researchers attempted to assemble information packets for each component which also contained engineering evaluations of the problem, when and how the corrective actions were implemented, and the quantitative results of the corrective actions in terms of failure statistics from before and after the corrective action. Demonstrating a recurrent problem with the collection of in-service information, it was not possible to form a complete information package for many of the components.

More recently, James et al (2002) examined the application of in-service information related to electronic systems in the aerospace industry. They found that although component removal rate, root cause, trends and the significant factors affecting reliability were available, the information management system was not set up to allow for their application within the product development process in a meaningful fashion outside the reporting of failure rates.

In the field of automated manufacturing equipment production, Kraniak and Ammons (2001) collected in-service information in the form of reliability and maintainability data, but did not specify the precise details of the information content. However, as it was used to facilitate the completion of an FMEA for a new product, it can be presumed that it contained at least information concerning failure modes, and perhaps the causes, effects and occurrence rate as well.

Stone et al. (2005) collected in-service information concerning Bell 206 rotorcraft in order to populate what they term a function-failure knowledge base which is an integral part of their Function-Failure Design Method (FFDM), as described in section 1.2.2.1 in the discussion of relevant design tools. This data was organised in a similar fashion to that in Collins et al. (1976), where failure modes were classified according to a standardized list with an associated occurrence rate for each. Overall, 63 failures were extracted for 25 components, of which 15 of the failure modes were unique.

As previously stated, Jagtap has published the most extensive exploration of in-service information management to date in two papers (Jagtap et al., 2007a; Jagtap, Johnson, Aurisicchio, & Wallace, 2007b) and his PhD dissertation (Jagtap, 2008). Throughout his research he conducted an analysis of the in-service information available at an aircraft engine manufacturer, examining the types of in-service information available, its content and structure, as well as the types of in-service information designers identified as valuable for their work. It was discovered that all the information deemed desirable by designers was available in the in-service database, but was generally unstructured and stored in disparate and heterogeneous databases, making it difficult to access. The designers typically relied on personal communication with service personnel when they required in-service information. The in-service information was stored in 25 different types of documents, of which 19 were collected and analysed, while the other 6, for reasons of intellectual property, were only described to the researcher. The content can be classed as (the number of sources is shown in brackets next to the type):

- Events (4)
- Safety events (4)
- Causes (4)
- Failure mechanisms (2)
- Redesign (3)
- Design requirements (6)
- Statistical analysis (1)
- Repair and Overhaul (RO) centre findings (1)
- Information to customer, RO centers (3)
- Engine health monitoring (1)

Sander & Brombacher (1999) have also examined in-service information, however they have approached it from a different vantage point. They have suggested a method for evaluating the process through which it is collected, as well as the information content, in order to determine the maturity of the process, and through this the reliability of the information as a basis for decision making. They have named this technique the Maturity Index on Reliability (MIR) and have identified different MIR levels based on the company's ability to measure, communicate, analyse and control, and adapt or learn based on the information collected. The levels are as follows:

0. No control loops
   - Manufacturer has no in-service information
   - Number of service calls may be known, but no relation to time of repair or age of product
1. Manufacturer has qualitative evidence of process output and information feedback
   - Origins of problems remain unknown
2. Origins of problems (design, production, material or customer use) known and control loops exist
   - Actual cause unknown
3. Cause known, control loops exist and can solve problems on case by case basis
   - No capacity to prevent similar problems from occurring
4. Can anticipate and prevent problems similar to those which have previously been observed

In order to evaluate the process in question, an activity model of the process is created which demonstrates where reliability information is integrated into the process and where it is used. This has been used to determine the quality of the input to design tools such as FMEA and Quality Function Deployment (QFD) (Sander & Brombacher, 1999). In the future, this evaluation process could be useful as a means to benchmark the various flows observed during the current project, and could also allow for retroactive evaluation of previously published case studies, such as Jagtap (2008).

1.3.3 Testing and prototyping information

While many standard texts as well as articles describe various testing procedures such as reliability growth, life, specification and so on (Blanchard & Fabrycky, 2006; Dhillon, 2006; Pahl et al., 2007; Wang & Coit, 2005), research pertaining explicitly to the capture and reuse of test and prototype results for the purpose of informing product design has been found lacking. Some general observations on the role of testing during the PDP will first be made, followed by a discussion of the few works written on the management of test information.

Eppinger and Ulrich (2008) identify two testing phases, alpha and beta. Alpha testing is conducted on a prototype that is geometrically identical to the intended product, but is manufactured using different techniques. This testing typically is done in-house and is focused on determining whether the product as designed will meet customer specifications. The beta prototype is produced later in the product development process using the intended manufacturing process, but preliminary assembly techniques. This prototype is submitted to more extensive in-house testing as well as customer testing in the intended use environment. However, the information gained typically remains restricted to evaluation of the products ability to meet narrow customer specifications. Considering that it can cost up to $350 000 to create a prototype of a single automobile cockpit, it is important that as much information as possible be extracted from the testing (Wasserman, 2002).

Thomke (2008) is one of the few authors found to explicitly consider learning from prototyping and testing. According to Thomke, many companies underestimate the savings which can be achieved during product development if early testing and prototyping are undertaken. Too often these tools are used as design checks rather than for learning. Testing, it is argued, allows the resolution of uncertainty with respect to technology, production, needs, and the marketplace and facilitates innovation and product development.

The central role of testing and prototyping within design, and that which is the most relevant to this study, is the determination of whether the solution or concept in question will actually work in practice. Ideally, it would be possible to clearly define the independent and dependent variables that come into play and hence determine clear rules for cause and effect. However, the reality is often more complicated and testing can lead to the discovery of unpredictable results. In many cases, iterative tests will only point the experimenter in the direction of a certain trend, and hopefully towards a high quality product design. If the results are unexpected, they should be used to revise and refine the testing procedure. In this way the testing process is a learning experience in itself. Another aspect that must be considered is the simplification of the test setup. While it is common to try to reduce testing costs and complexity by only modeling certain aspects of a product, a balance must be achieved between the fidelity of the setup and its complexity and cost. A lack of fidelity can lead to erroneous results which can in turn lead to an overdesign (i.e. unnecessary cost and weight), or a failure once in-service due to actual problems not occurring during testing (Thomke, 2008).

While Thomke suggests that the role of testing and prototyping is to learn about the product being developed, he does not explicitly discuss how the information gained could be applied to future product development projects. Ward (2007), however, does discuss this in the context of lean product development. He suggests that Toyota offers a superior strategy of "testing to failure", as opposed to testing to customer specification, and identifies this as a key step in lean product development. While testing to specification only allows the validation of a product in a certain use case, testing to failure allows a more broad characterization of potential failure modes. Lean product development, as practiced by Toyota and formalized by Ward (2007), also includes a higher than average number of initial prototypes, allowing for the characterization of a wide range of design options. This is a core aspect of set-based design, in which multiple concepts are examined and eliminated through an aggressive testing process (Liker, Sobek, Ward, & Cristiano, 1996). Eventually this is narrowed to one concept which is then carried forward to completion. This is quite different from traditional point-based design methodology, where a single concept is chosen early in the Product Development Process (PDP) and later refined through iteration (Liker et al., 1996).

1.3.4 PLM Strategies for Product In-use information

Faced with increasingly complex product development projects and the need to reduce time to market in order to remain competitive, companies have adopted strategies such as concurrent engineering (CE), where task are increasingly completed in parallel with only preliminary information available at the beginning of most activities (Evans, 1988). Additionally, with increasing globalization, many teams are no longer co-located but can be spread across countries, time zones and cultures. It has therefore been necessary to develop information technology tools capable of facilitating the communication and sharing of information in an efficient manner. While Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) tools are now widely implemented, Product Data Management (PDM), Manufacturing Process Management (MPM), Customer Relation Management (CRM) and other more advanced information management tools are increasingly found within OEMs as well as their partners and contractors. Furthermore, there is a drive to integrate these tools into so-called Product Lifecycle Management (PLM) tools. The philosophy behind PLM is one that recognizes the value of information within an organization, and the incurred costs of not taking advantage of this information by using it to develop lessons learned for future projects (Grieves, 2005). As such, PLM tools focus on both the capturing and sharing of information across the product lifecycle, in an attempt to make relevant information available to stakeholders when they need it and in a format and structure that is applicable to their work. With this effort to manage information and make it available to those who would most benefit from it, one of the central goals is to eliminate what are known as information silos, which result in the barriers to information sharing previously discussed (for example when the existence of information is unknown to other stakeholders, when information is available only in an inappropriate format or content, etc…). By recognising the common characteristics between testing and in-service information and how this information can be shared with designers in an efficient manner, it is possible to reduce these barriers and move towards a more streamlined information management strategy.

While implementation of a true PLM strategy has been achieved with varying success in the current group of commercial tools, there is a substantial body of research concerning the best model with which to represent the lifecycle information. A central debate is whether it is possible to create a unified information structure which will contain all product related information, or whether it will be necessary to link various structures together due to the widely varying needs of those involved in the product development process (Brissaud & Tichkiewitch, 2001; Huet, Fortin, McSorley, & Toche, 2011). However, much of the research has remained focused on the design and manufacturing stages of the lifecycle, with many questions remaining regarding the integration of, for example, product in-use information into PLM frameworks. Furthermore, a common factor within PLM systems, which is not always considered explicitly, is the need to consider the temporal and behavioural aspects of the product. All PLM systems in one way or another consider the fact that the product, and related information, is evolving over time. With the increasing interest regarding in-service information, the need to properly understand and track product behaviour (in terms of functionality) is receiving more attention. Despite current advances, real PLM, where true information sharing has been enabled through a robust representation of the evolution of the product that is linked to relevant information gathered throughout the entire lifecycle, has not been achieved. However, several researchers have suggested frameworks which could potentially pave the way towards this goal. In this section, a brief overview will be given, with a specific focus on research which has considered the management of testing and in-service information.

To begin, Muller, Muschiol, and Stark (2012), in studying the development of steam turbines, identify the need for information to be shared between the various engineering disciplines involved. In this case, they have split responsibility for the product across two departments: Order Engineering and Service Engineering. Recognizing the fact that a multitude of databases can prevent the efficient sharing of information, they propose the use of a single PDM system to manage all product related information spanning the life of the turbine. However, in contrast to traditional information management strategies, they argue that the information structure should primarily reflect the needs of service engineers. To justify this, they point out that, in the case of long lifecycle products, service engineers play a larger role than design engineers in ensuring the product's satisfactory performance, and therefore must be treated preferentially when it comes to trade-offs with respect to the information structure. They do admit to weaknesses in the system, however, in particular the fact that separate processes in order engineering and service engineering can affect the same documents (for example, each department requires a different process for authorizing and carrying out drawing revisions), and so strict, consistent document control is difficult to implement in a single database configuration. This is reminiscent of the work presented in Baines, and Lightfoot (2009), where they identify the complexity of integrating the management of service delivery with the management of design information as a major challenge to the implementation of PSS.

Also starting from the context of the information needs to support PSS, Zhang, Hu, Xu, and Zhang (2012) have proposed a multi-layer framework using XML to create documents representing the complete lifecycle knowledge surrounding a product. The researchers use a more traditional division of lifecycle stages than Muller et al. (2012), and include six stages during which information is created, beginning with product planning and ending with energy recovery and planning. By studying the range of information generated at each stage, knowledge classes are identified and used as the basis for an ontology. Based on this ontology, XML is then used to structure the information gathered during a case study, taking into consideration the content, structure and representation used in the original documents produced at the various lifecycle stages. This structuring is intended to facilitate the accessibility of the information through a search and exploration interface available to stakeholders, with particular focus being placed on the reuse of service and usage information by designers. A case study, based on the lifecycle of a large crane for heavy construction, is presented, which includes interviews supporting the claim that the application of the framework results in an increased ability to share information throughout the lifecycle. The proposed framework is found to be particularly useful for the communication of in-service and usage information to designers, and hence facilitating design for PSS. It is also interesting to note that failure and success cases were explicitly identified as originating from the Manufacture and Test lifecycle stage, however no discussion was provided as to how the test information could be related to the in-service information collected.

Lee, B.-E., and Suh (2009) describe a framework, termed Ubiquitous Product Lifecycle Support, based on multiple databases in which are stored information collected throughout the lifecycle. The use of multiple databases recognizes the fact that depending on the organization responsible for collecting the information or the tools used for this task, the most appropriate processes and information management strategies could be quite different. To facilitate the sharing of information, these databases are connected through what are known as interface agents. By creating and using well defined ontologies for each area of information collection, the interface agent software can transfer information between systems in a consistent fashion as well make it available through a single, overarching interface known as the Ubiquitous Product Life cycle Information highway. However, the details of how to complete the complex task of translating information across ontologies and combining all information at a single level remain unclear.

As previously mentioned, it is also necessary to consider how a PLM system can reflect the evolution of a product and its behaviour over time, and hence changes to the information being collected. To this end, certain researchers have begun explicitly developing models for information sharing that take into account these temporal and behavioural dimensions. Horvath, and Rudas (2012) have developed Coordinated Request Based Product Modelling (CRPM), which aims to allow designers to search for information based on the intended product behaviour and context, as opposed to focusing solely on parts and assemblies.

Xiao, Xudong, Li, and Guanghong (2010) have approached PLM from what they term the 4D view model, with views including geometry, task, virtual prototyping and lifecycle. This is in order to differentiate between the static structural and the dynamic behavioural aspects of the virtual prototype. Each phase of the lifecycle is considered from the geometry, task and virtual prototype views, while the lifecycle view allows for the correlation of the first three. In essence, the lifecycle view is a temporal view of the product lifecycle. However, this model is only extended to the point where the physical product is put into service, and so it is left to be determined how it would be used for considering the management of in-service information.

Vosgien, Nguyen Van, Jankovic, Eynard, and Bocquet (2012) also take a particular interest in the simulation stage of the product lifecycle, analysing the behaviour of interfaces within the product and defining a standard library for reuse when developing and testing new products. Again, it would be very interesting to see how this information concerning the behaviour of the virtual prototype, in this case with a particular focus on interfaces, could be used in conjunction within in-service information in order to provide a rich view of product behaviour throughout the lifecycle.

1.4 Conclusion

The current research project examines the exploitation of product in-use information during design, where product in-use information is defined as all information collected throughout the life cycle concerning product performance during use. Therefore, the literature review presented here has focused on the research surrounding the use of this information in design and its increasing importance due to shifts in the manufacturer's perceived role in the marketplace. As more and more manufacturers move from the conventional to the functional product paradigm, it will become increasingly important to leverage product in-use information during product development in order to decrease overall costs and maximize both customer satisfaction and the manufacturer's life cycle profits (Markeset & Kumar, 2005). A summary of the relevant findings from this literature review can be found in Table 1-1 below.

It should be noted that, as with all works of limited length, it was necessary to make a decision as to the scope of this literature review. Therefore, while a broad view has been taken, this review is not exhaustive. In particular, statistical approaches from reliability and testing have not been considered in any depth, nor have the detailed aspects information or knowledge management. The focus of this research has centered on how relatively unstructured information concerning product performance (e.g. failure modes, causes and effects found in reports concerning in-service events and testing) can be exploited by designers, and not on the management of statistical data or data and text mining techniques for the collection of this information.

The most important sources of product in-use information have been identified as experience from in-service, prototyping and testing activities, and so special emphasis was placed on the research surrounding these types of information and their application in design. However, as has been shown, the literature surrounding both in-service and testing information for supporting design is quite sparse and the potential for considering both as components within a common information type has not been explicitly studied previously. In comparing in-service and testing information, the application of in-service information for design seems to have been more thoroughly investigated. However, it is clear that testing plays an important role in product development (Blanchard & Fabrycky, 2006; Dhillon, 2006; Ulrich & Eppinger, 2008; Ward, A. C., 2007) and so it is potentially a rich field for further investigation.

The research surrounding in-service information has been found to be generally empirical and case study based, which is confirmed by Jagtap (2008). Many approaches have only examined narrow applications [e.g. (Kraniak & Ammons, 2001; Wirth et al., 1996)] or been confined to small sample groups [e.g. (Stone et al., 2005)]. Therefore, opportunities exist to validate past research as well as to attempt to develop more generally applicable approaches to the exploitation of testing, prototyping and in-service information during design activities. Of particular importance seems to be determining the extent to which information from past product development projects can be applied to new projects, which although mentioned across the literature does not seem to have been explicitly investigated. Chapter 3 will provide additional evidence of the need to support designers via the sharing of in-service information, while chapter 4 will describe the particular characteristics of both testing and in-service information as found within an aerospace manufacturer, and propose a framework for structuring and sharing product in-use information.

A discussion regarding the need for PLM systems to consider behavioural and temporal aspects of the product lifecycle has also been introduced. In order to develop a robust means of managing information created during the product lifecycle for the purpose of sharing and reuse across product development projects, it is necessary to look beyond the traditional product-centric PLM strategies. In chapter 5, the framework proposed in chapter 4 will be modified in order to take into account the particular needs of the product development process, as well as to take into the temporal and behavioural requirements necessary for managing product lifecycle and engineering information.

Table 1-1 Summary of literature review findings (continued on next page)

1.4.1.1 Topic	Comment	1.4.1.2 References
Integrated Product Service Engineering	• Wide scope: Sustainability, contract law, engineering, etc… • Updated definition: "The innovation of an organisations capabilities and processes to better create mutual value through a shift from selling products to selling Integrate Product-Services." • Need to weigh risks and benefits of shift to IPSE • Refine scope to Functional Products with continuous reliance on manufacturers ability to provide specialized complex products.	(Sääksvuori & Immonen, 2004), (Jagtap, 2008), (Kim et al., 2007), (Markeset & Kumar, 2005), (Mont, O., 2000), (Tan et al., 2008), (Vandermerwe & Rada, 1988), (Baines et al., 2009),(Park et al., 2012)
Design for X methods	• Various researchers use different acronyms and scopes for similar or overlapping DfX tools • Relevant DfX tools identified: Design for Serviceability and Support, Design for Reliability • Methods take into consideration different, yet interrelated aspects of the product lifecycle and attempt to address possible issues during design phase.	(Blanchard & Fabrycky, 2006), (Kuo et al., 2001), (Ulrich & Eppinger, 2008), (Goffin, 2008), (Pahl et al., 2007), (Wang & Coit, 2005), (Dhillon, 2006)
Design Tools	• Tools require input information (e.g. product in-use information) in order to provide solutions based on past experience rather than hypotheses. • Trade-off curves provide clear graphical representation, but limited to information where direct correlation is possible • FMEA-like tools aid in providing up to date in-service information but scopes limited to the description of specific events • SAPPhIRE model Intended for conceptual design, but visual representation of structure, behavior and function can provide a rich representation of product behavior	(Ward, A. C., 2007), (Raheja, 2002), (Defense, 1980), (Krasich, 2007), (Kraniak & Ammons, 2001), (Wirth et al., 1996), (Stone et al., 2005), (Chakrabarti et al., 2005), (Jagtap, 2008)

Table 1-1 (continued) Summary of literature review findings

Topic	Comment	References
Information support for designers	• Necessary information can be difficult to locate and continued reliance on informal rather than formal information sources • Various case studies to collect and classify in-service information, mainly empirical results • Need to evaluate quality as well as content of information • Continuous learning and reuse of testing information has been subject of limited research • Product lifecycle management tools continue to rely on product structure for overall framework • Certain models attempt to consider temporal and behavioural aspects as integral part of PLM model, but still at initial stages	(Crabtree et al., 1993),(Kwasitsu, 2003), (Ward, M., 2001), (Jagtap, 2008), (Collins et al., 1976), (James et al., 2002), (Kraniak & Ammons, 2001), (Stone et al., 2005), (Sander & Brombacher, 1999), (Blanchard & Fabrycky, 2006), (Dhillon, 2006), (Pahl et al., 2007) (Wang & Coit, 2005), (Ulrich & Eppinger, 2008), (Thomke, 2008), (Wasserman, 2002), (Ward, A. C., 2007), (Liker et al., 1996), (Evans, 1988), (Grieves, 2005), (Brissaud & Tichkiewitch, 2001), (Huet et al., 2011), (Muller et al., 2012), (Baines & Lightfoot, 2009), (Zhang et al., 2012), (Lee, B.-E. & Suh, 2009), (Horvath & Rudas, 2012), (Xiao et al., 2010), (Vosgien et al., 2012)

Chapter 2 METHODOLOGY

In the previous chapter, a discussion was presented regarding the current academic literature surrounding product in-use information and its role in supporting product development within the field of design research. The goal of the current chapter is to describe the methodology adopted for the current project, which is intended to ensure that the results and conclusions contribute to the evolution of this field. Blessing, and Chakrabarti (2009) state that the aim of design research is two fold: the development of models and theories regarding all facets of design, and the development and validation of support which, based on these models and theories, can help improve the practice of design. While the field of design research has grown over the last decade, it has branched out into so many directions that the community has not come together into a cohesive domain, and in many cases neglects the use of accepted terminology and methodology. In proposing a Design Research Methodology (DRM) framework, Blessing, and Chakrabarti (2009) have put forth a series of guidelines for planning and executing a design research project in a structured fashion while ensuring that focus is placed on achieving tangible advancements with regards to the understanding and execution of the practice of design. In this section, the methodology used for the current project will be placed into context using the DRM framework. The activities undertaken will be described, along with the modifications made as the project progressed, as well as how these activities are related to achieving the project objectives and the possible limitations of the chosen methodology.

2.1 Design Research Methodology Framework

In consideration of the aforementioned aims of design research, the DRM framework is intended to help guide the researcher through the stages of a project, from the initial development of research questions, to an understanding and modelling of the current and desired situations and the support tools or methods needed to progress in this direction, through to the implementation and evaluation of the impact of the proposed support. The stages of the DRM framework are shown in figure 2.1, along with commonly associated means and outcomes.

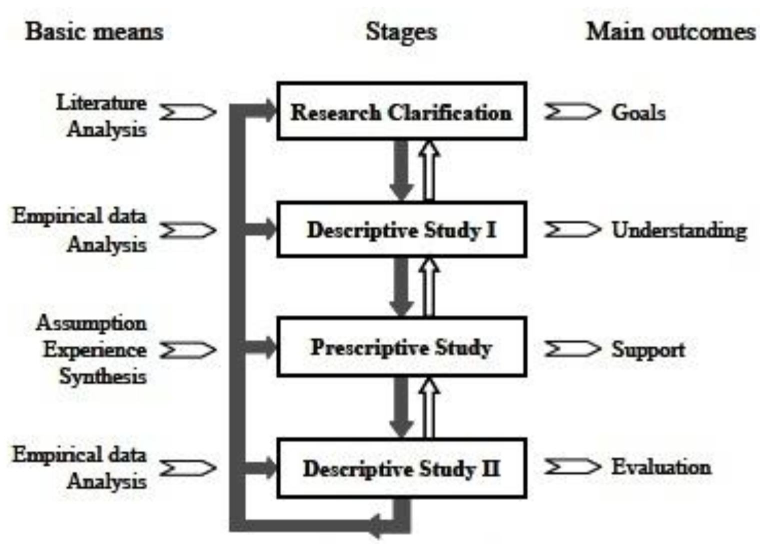

Figure 2.1 DRM framework (Blessing & Chakrabarti, 2009)

Briefly, the stages are as follows:

- Research clarification (RC): Identification of goals and research problem based on an understanding of the previous research. The researcher should develop an initial model of the existing and desired situation and preliminary criteria for evaluating project success.
- Descriptive Study I (DS-I): Development of a deeper understanding of the existing situation, including the relevance of the research topic and the most suitable factors for improving the current situation.
- Prescriptive Study (PS): Determination of key factors to be affected by the prescriptive study, development of the intended support (tool or methodology), and evaluation of the support based on its in-built functionality. Based on this evaluation, it is determined whether the support is ready for to progress to the Descriptive Study II phase.
- Descriptive Study II (DS-II): Determination of whether the support can effectively be used to contribute to success through its effects on the previously identified key factors. Necessary modifications and improvements to the support should be identified.

At this point it should also be mentioned that, as shown by the arrows in figure 2.1, the process of design research can, and should, be iterative. It is often the case that at one stage it is discovered that something was missed or there is a greater understanding needed, and so a return to the previous stage is necessary.

By progressing through each stage, while defining standard procedures to achieve clear deliverables, Blessing, and Chakrabarti (2009) argue that it is possible to understand, develop and evaluate the tools needed to support the practice of design and move the field towards a deeper level of understanding. However, it is rare that a project can successfully cover all stages in the DRM framework. In fact, Blessing and Chakrabarti offer seven possible combinations of stages and the level of completeness achieved for design research projects.

In the case of the present research, the objectives set were to identify the most appropriate tools and methodology for the integration of product in-use information within the product development process. While the previous chapter has presented the completed literature review, which satisfies the RC stage of the DRM, the rest of this chapter will demonstrate the subsequent steps in the completion of this project. These correspond to a comprehensive DS-I as well as a comprehensive PS. This progression is presented in the context of the overall DRM in figure 2.2. Solid arrows denote the planned sequential progression, while the dotted arrows indicate the unavoidable iterations that take place throughout a research project. Although Blessing and Chakrabarti state that a comprehensive PS should be followed by an initial DS-II, it was found that for this project, the PS satisfied the current objectives. A benchmarking within an industrial product development of the developed framework, corresponding to DS-II, will form part of future work.

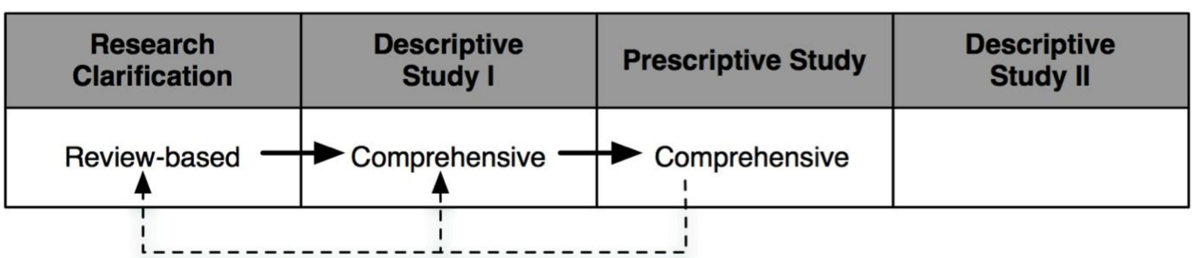

Figure 2.2 Placement within DRM Framework [adapted from (Blessing & Chakrabarti, 2009)]

2.2 Descriptive Study I: Survey and information analysis

This stage was completed in partnership with a manufacturer specializing in complex aerospace systems as part of a Industrial Innovation Scholarship (IIS) / Bourse en Milieu Pratique (BMP). Thanks to this partnership, the author was able to spend 18 months working in closed conjunction with project engineers, designers and service center personnel investigating the factors linking product performance, service strategies and product development within a functional product context. The descriptive study was composed of two major components: a survey of 78 designers regarding their information needs and current practices, and an analysis of the sources, content and structure of development testing and in-service information within the company. The latter was completed by means of general research into company databases as well as specific studies of information related to a particular component and an in-service product model. Full details of the activities undertaken will be given in chapters 3 and 4.

As stated previously, the general objective of the DS-I stage is a better understanding of the current situation, including the relevance of the research topic and the key factors in improving the situation. Through an initial study of how the industrial partner's designers work and the information at their disposal, as well as by working in conjunction with an ongoing in-service information management initiative, it was possible to design a survey questionnaire with appropriate questions for the development of a deeper understanding of the areas in need of improvement and the expected impact on design practice within the company. Furthermore, the case studies completed and their particular focus were chosen to build on the survey results, as well as to provide an understanding at different levels of detail: a very detailed view of product in-use information collected regarding a particular component, as well as a higher level exploration of product in-use information concerning a particular model of the system which is currently in service.

Due to the nature of the partnership, the author was not only working towards specific research objectives, but was a member of a particular department and so the work undertaken was guided to a degree by the particular context of the aerospace manufacturer. However, as will be seen in later sections, it is believed that the results can be generalized to a large degree. In particular, by attempting to build on the work of Jagtap (2008) and others who conducted related research, an effort was made to fill gaps in the current literature, especially with regards to the reuse of testing information and the similarities between in-service and test information. Through this, it is believed that a contribution has been made regarding an improved understanding of the current context and relationship between the test and in-service lifecycle stages (chapter 4).

2.3 Prescriptive Study: Supporting designers through product in-use information

The objective of the PS stage is to develop support for the practice of design and to evaluate the in-built functionality of said support. During the RC stage, various tools and methodologies were explored, as reported in chapter 1. In order to determine the support tools that would play a central role in this project, investigation into several possibilities was begun in parallel with DS-I activities, a full description of which will be presented in chapters 3 and 4.

To begin, Failure Modes and Effects Analysis was explored, however it was found to be restrictive when considering the wide variety of content and format comprising product in-use information. Subsequently, a direct comparison of development testing and in-service costs was attempted, however it was found to be too complex a question for the current project. Upon reflection and further consideration of the information being studied, it was determined that Chakrabarti's SAPPhIRE model, as used by Jagtap (2008) could be expanded on to represent the full body of product in-use information. In order to demonstrate this and evaluate the built in functionality, the product in-use information gathered from both test and in-service reports was modeled and associated with related information, as shown in chapter 4. Based on the results of preliminary modeling, several modifications were suggested in order to adapt the model to the proposed use. Furthermore, in the process of evaluating the functionality and applicability of the SAPPhIRE model, it was decided to explore the possibility of expanding the proposal to the management of all lifecycle information. While the latter was mainly an exploratory study, it is believed that it points the way towards new possibilities for the management of product lifecycle and engineering information..

2.4 Conclusion

The methodology for the current project has been presented within the context of the DRM framework suggested by Blessing, and Chakrabarti (2009). The particular activities undertaken span the RC, DS-I and PS stages, ending with the development and evaluation of support tools. As predicted by Blessing and Chakrabarti, this process was indeed iterative, with questions arising during the PS stage that required the revisiting of both the RC and DS-I stages.

As is often the case, once a project is undertaken, it was at times difficult to remain true to the planned methodology, and therefore it was not possible to fulfill all criteria identified in the DRM frameworks. In particular, the definition of measurable success criteria for use during the PS stage was found to be difficult, and so the conclusions drawn are not quite as robust as may otherwise have been possible. However, a serious attempt made to build on previous work via exploration and evaluation of previously proposed models. By exploring the current field of research into the management of development testing and in-service information and proposing through case studies how the field may advance, valuable contributions have been made to the field of design research. In particular, as will be presented in the rest of this report, the procedures undertaken have resulted in a contribution towards supporting designers through product in-use information, as well as towards the implementation of a robust framework for the management of product lifecycle and engineering information.

Chapter 3 IN-SERVICE INFORMATION FOR AEROSPACE DESGINERS – A SURVEY

In order to increase the visibility of repairability and maintainability issues during design, in-service information should be provided to designers during the development of new products. In order to determine the in-service information needs of designers, as well as how to provide this information to designers during the product development process, a survey was completed. The implementation and results of this survey are the main focus of this chapter.

3.1 Background

As reported in chapter 1, several studies have been published in order to demonstrate the wealth of information available from the in-service phase, and that this information could inform the work carried out by designers. However, very few make an explicit effort to identify the information requirements of the designers.

As previously stated, Jagtap (Jagtap, 2008) has published the most extensive exploration to date of in-service information in the aerospace industry. In particular, Jagtap et al. (2007b) and Jagtap (2008) discuss the in-service information requirements of designers. These papers describe the results of a study carried out in collaboration with an aerospace manufacturer in order to assess these requirements. As part of this research, three designers were interviewed and asked to complete a detailed questionnaire regarding what they believed to be the information required from in-service which would allow them to design products with lower maintenance and repair requirements. The study conducted by Jagtap consisted of three steps:

1. In-depth semi-structured interviews with three designers
2. The designers were asked to score each of a set of questions based on the frequency with which they might ask them. The options given were
    a) Frequently
    b) Usually
    c) Sometimes
    d) Rarely

e) Never

3. The designers were asked to write down any further questions that they would typically try to answer using in-service information

As part of the interviews in step 1, designers were asked to identify the in-service information that they currently use when beginning a project, and what in-service information they would like to be able to use. These responses were also supplemented based on discussions held during module review meetings held at the partner company. The results are shown in table 3.1 and table 3.2 below.

Table 3-1 Information currently used (Jagtap, 2008)

Currently Use
The cost of overhaul
The life of the component
The deterioration mechanisms that a component might face in service, such as erosion, wear, cracking etc…
The repair/replace strategy
The life cycle cost
Repair limits
Ease of assembly, disassembly, inspection, etc…
Safety and reliability aspects
Monitoring of deterioration mechanisms

Table 3-2. Information designers would like to use (Jagtap, 2008)

Would like to use
Cost of overhaul, including the cost of repairing or replacing the component
The facilities required to repair a component
Any events such as in-flight shut downs (IFSD), aborted take-offs (ABTO), etc… caused by a component
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
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

The questions referred to in step 2 were developed based on the interviews with designers conducted in step 1, discussions with service engineers, and the current literature. The list of all 39 question can be found in Jagtap (2008). Once the questionnaire was completed, the responses were analyzed by measuring their popularity. The questions were assigned a score according to each response as follows:

1. Frequently: 4
2. Usually: 3
3. Sometimes: 2
4. Rarely: 1
5. Never: 0

The scores assigned by the three designers for each question were summed to provide the score for that particular question. For example, if all three designers rated the questions as being asked frequently, a score of 12 was assigned. Furthermore, the questions were then grouped based on the topics which they touched on. An average score per question was then calculated for each topic, as show in table 3.3. It should be noted that some questions could be classified under more than one topic, and so the number of questions does not add up to 39.

Table 3-3. Average scores per question (Jagtap, 2008)

Topic	Number of questions	Average score per question
Deterioration information	19	10
Maintenance information	10	8
Operating information	7	8
Statistical information	4	10
Design Information	4	11
Life cycle cost	4	10
Reliability	2	9
Maintainability	2	10
Customer information	2	10
Standards	1	11

As can be seen, deterioration information was referred to in the greatest number of questions and received a high average score. Maintenance information and operation information were covered by a good number of questions, but received a small average score, and so were not referred to as often. The other categories were associated only with few questions, and so were not considered statistically significant.

In step 3, designers were asked to comment on the list of questions and to add any others they thought to be relevant. Their opinion was that the list was complete and there was nothing more to add.

3.2 Survey description

The study of in-service information discussed in the previous section was qualitative in nature and was based on interviews with three designers. In order to build on the work carried out in Jagtap (2008) and previous research conducted by the author and colleagues (McSorley, Huet, Culley, & Fortin, 2008; McSorley, Huet, & Fortin, 2009), it was decided to undertake a more quantitative study of in-service information requirements in an aerospace manufacturer in the form of a survey. Approximately 78 aerospace designers participated, with the number of respondents varying between 71 and 82 per question. This section will describe the context in which the survey was carried out, its main objectives, and the specific methodology implemented.

3.2.1 Objectives

The main objective for the current survey was to determine what information content would be most useful for designers within their day to day work, as well as to understand their typical search strategies.

Furthermore, several questions were included with the goal of determining the current state of in-service information available to designers during the product development process. By obtaining feedback as to the perceived quality of the currently available in-service information, as well as an assessment of the time and effort needed to access this information, it was expected to characterize the difficulties they experience accessing the information, as well as set a baseline against which the results of further studies could be evaluated. This baseline could, for example, be used to verify the effectiveness of recommendations developed from the survey results if they are put into practice. Similarly, this baseline could identify criteria for the evaluation of design support tools and methodologies during the DS-II phase of the DRM framework (Blessing & Chakrabarti, 2009).

3.2.2 Questions

This section will briefly describe the questions included in the survey and their rationale. For the complete questionnaire, please see the appendix. The questions in the survey are split into several sections.

Section one identifies the specialization of the designer and his or her years of experience. The next section seeks to identify the types of information that should be included in the database. Designers were asked to rate each of nine types of information as to whether they are currently used in their work, whether they would like to use the information, or whether the information is not necessary. The nine types of information were based on a study of information typically available at service centers, the experience of several designers, and the current literature (Jagtap et al., 2007a; James et al., 2002; Kraniak & Ammons, 2001).

The third section asks designers how often they require in-service information in their work and approximately how long it takes them to obtain this information. By analyzing these results, and making certain assumptions, it is possible to evaluate the time per year it currently takes to obtain needed information.

Section four seeks to determine how designers evaluate the relevance and quality of the information currently at their disposal. In order to evaluate the quality, the designers were asked to give their perceptions of whether the information they receive is up to date, complete and reliable. This criteria is based on the standard techniques for determining information quality (Lee, Y. W., Strong, Kahn, & Wang, 2002).

When determining the information needs of designers, it is also important to consider how the available information should be organized. Therefore, section five asks the participants to select the criteria they would typically use when searching for information and to add any additional terms not included in the list. Among other benefits, this would allow for the proper selection of the metadata to be associated with in-service information.

3.2.3 Methodology

The survey was created using an online survey management tool through a third party. This allowed for online hosting of the survey and its results. An e-mail was sent to potential respondents, describing the project and requesting their participation. The survey was available for completion over a period of two weeks.

3.3 Results

In this section an overview of the survey results will be presented. For detailed analysis, please refer to the discussion.

3.3.1 Section 1 – Specialization & Experience

As was previously mentioned, the survey received a good level of response, with between 71 and 82 respondents. As can be seen in figure 3.1, the participants were also distributed across seven of eight specializations, the details of which have been removed for reasons of confidentiality. Figure 3.2 shows the years of experience of the respondents. The majority have been over 10 years experience with their current employer, with only a very small number having less than 2 years experience.

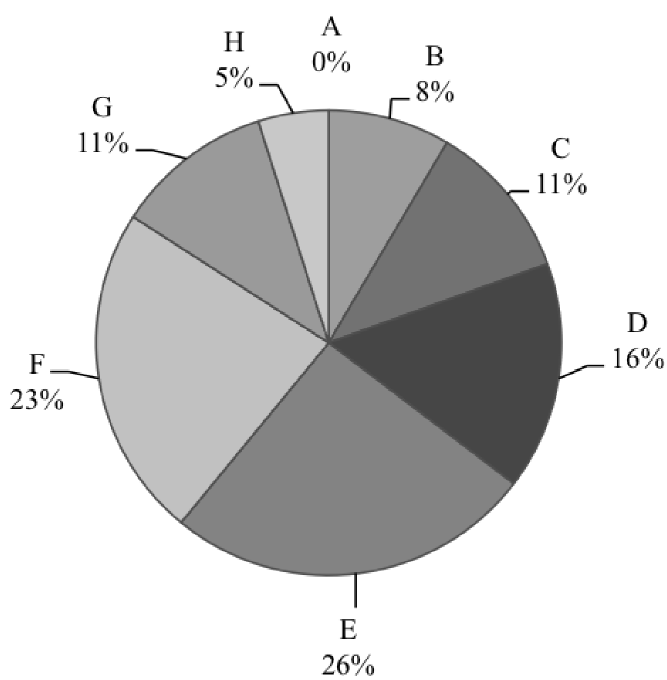

Figure 3.1 Participation by specialization

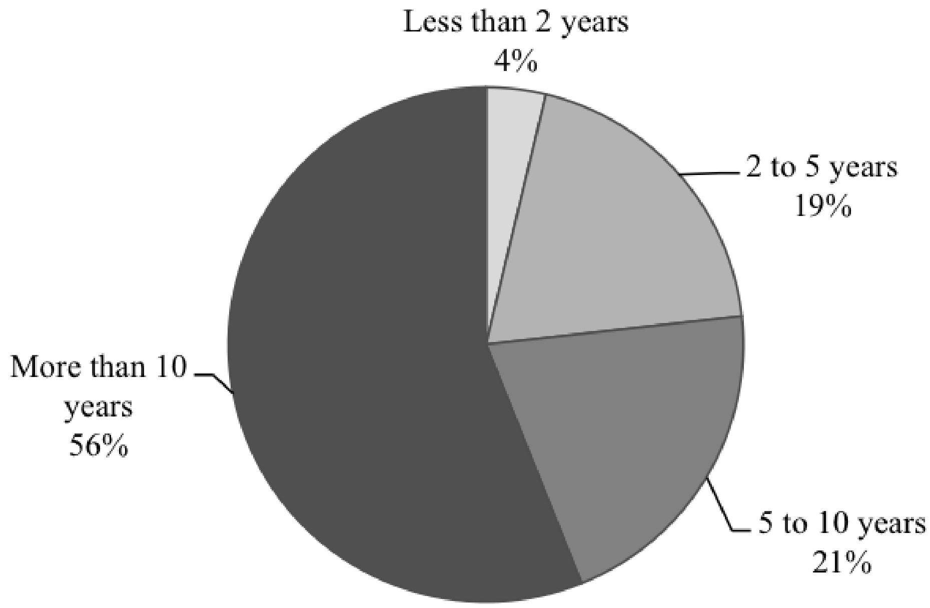

Figure 3.2. Experience of respondents

3.3.2 Section 2 - Information Types

In this section, the designers were given a list of nine types of in-service information and were asked whether they currently use this information, whether they would like to use it, or whether the information is not required. As can be seen in Figure 3.3, the responses demonstrate that the information types identified when creating the survey are in fact important to designers' work. In only two cases (Failure Modes, Causes and Effects and Photographs) did a greater proportion of respondents answer that the information is currently used than answered that they would like to use it. In both cases however, a significant proportion who would like to use this information still do not have access.

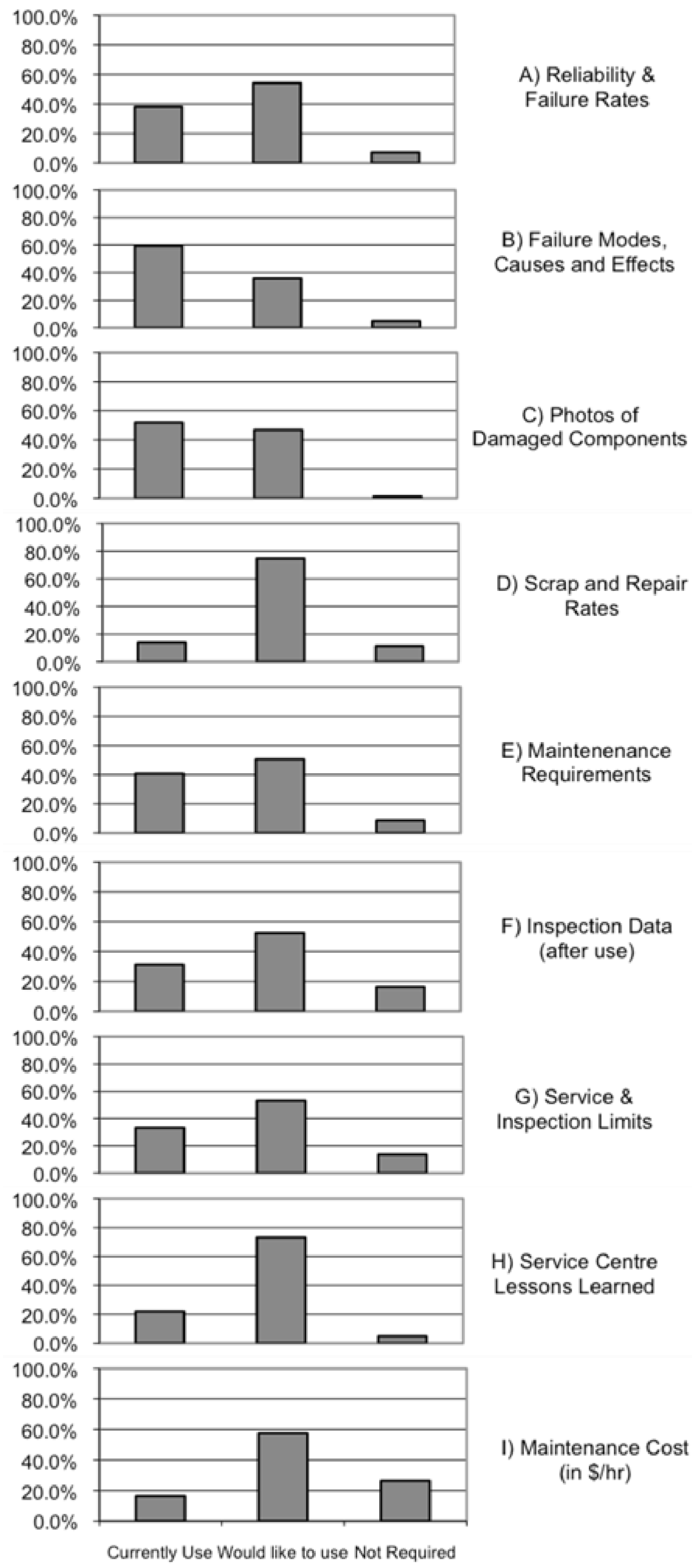

Figure 3.3. Information Required by Designers

The designers were also asked to specify whether any additional information would be useful, with the suggestions being listed in table 3.4. The information types in Table 3-4 are valid suggestions, however it should be noted that a Marciano chart is a means of representing information, not a type of information in itself.

Table 3-4. Other types of in-service information

Other types of In-service Information
"Top Ten" issues per system model
As required, dependent upon nature of specific task
In field repair methods
Marciano Charts
OEM Installation pictures
NCR equivalent database
Repair Scheme
RRS
A summary of all repairs and replacements

3.3.3 Section 3 – Time and Effort

In this section, designers were asked to specify how often they require in-service information in their work, as well as how long it typically takes to access this information. While only 11% require the information on a daily or weekly basis, most designers (76%) will require in-service information throughout the year, and over half (55%) several times (Figure 3.4). While ‘Once per design job’ is not a concretely defined number, this can conservatively be taken to mean several times per year.

With respect to the amount of time it takes to obtain the information (see Figure 3.5), 87% of designers responded that it typically takes less than a week. Of the 13% who responded that it can take over a week, nearly all indicated that the time was dependent on the specific information being requested, and whether they have a personal contact who can help retrieve the information.

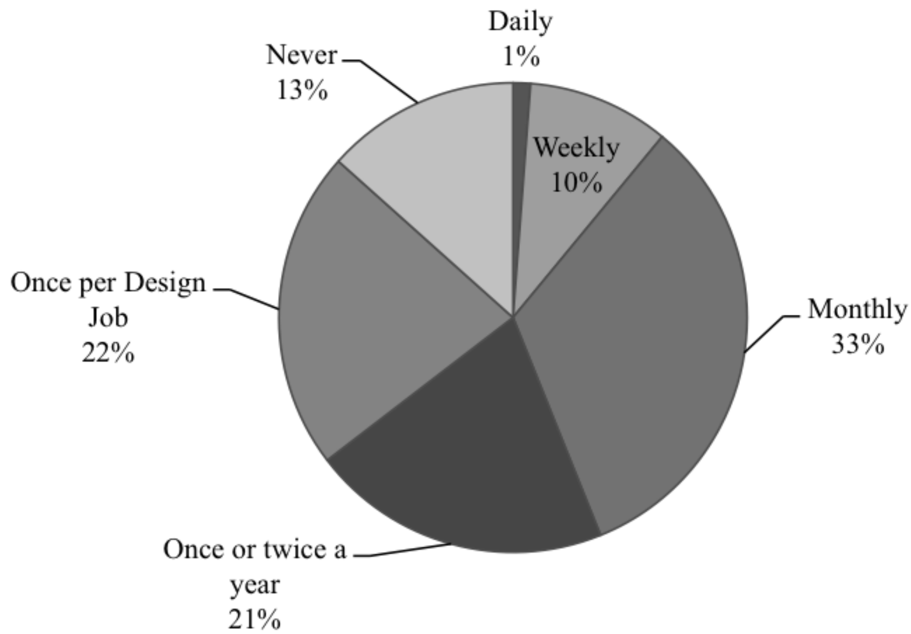

Figure 3.4. Frequency of in-service information use

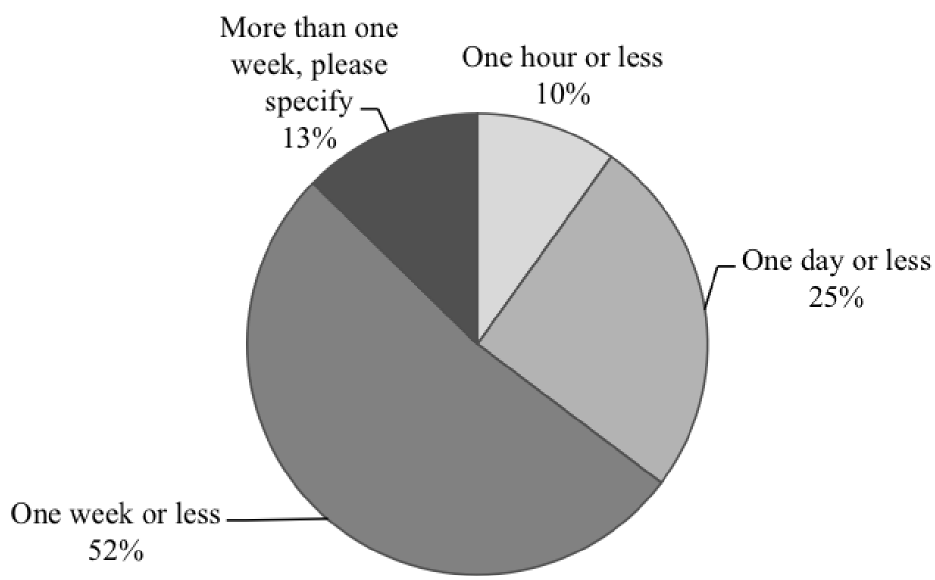

Figure 3.5. Time to retrieve information

3.3.4 Section 4 – Information Relevance and Quality

In this section, the designers were asked to evaluate whether the in-service information available to them at the time of completing the survey was relevant to their daily work and also to evaluate the quality of the information, as they perceived it. As previously mentioned, the criteria used to evaluate the information quality, whether it is up-to-date, its completeness and its reliability, is based on the review completed by Lee, Y. W. et al. (2002), albeit in a simplified form.

The evaluation of the relevance of the information, as demonstrated in Figure 3.6A, is quite positive, with over 70% at least somewhat agreeing. With respect to whether the information is up-to-date and reliable (Figure 3.6B & 3.6D), the responses were mainly positive, although efforts should be made in order to understand why responses are more likely to be 'Neutral' than 'Strongly Agree'. The question of completeness (Figure 3.6C) received the most negative response, with over 10% strongly disagreeing, and nearly 30% somewhat disagreeing.

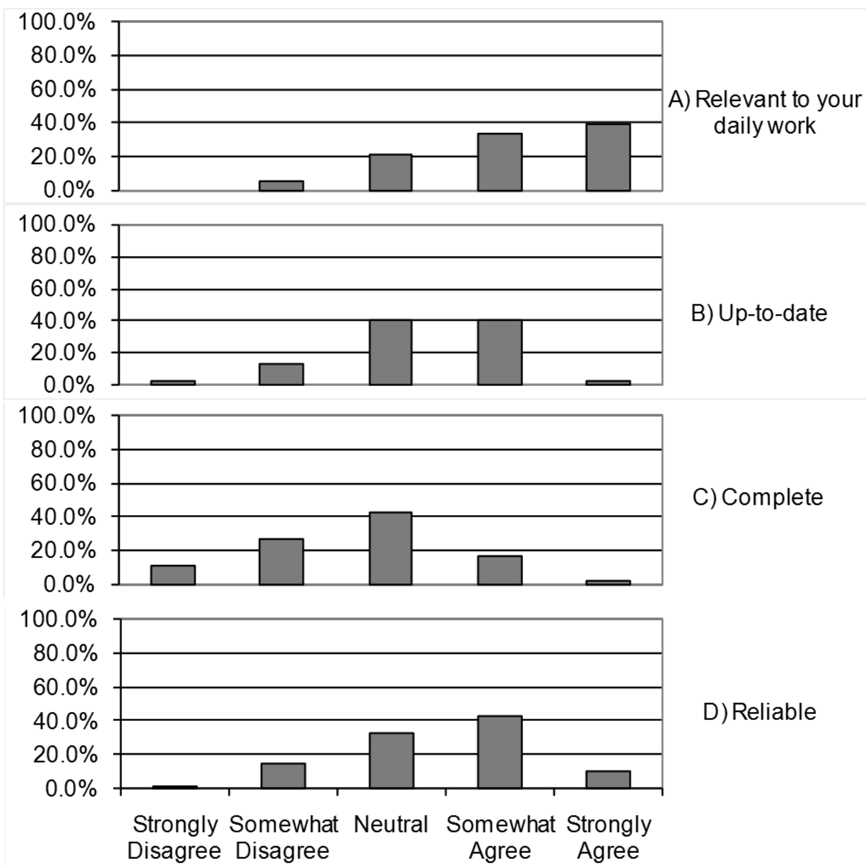

Figure 3.6. Information relevance and quality

3.3.5 Section 5 – Search Criteria

In section 5, the designers were asked to identify what criteria they typically used when searching for information, with the answers shown in Figure 3.7. As expected, the most commonly use criteria were Part Name, Part Number and Product model, accounting for 72% of responses. While no other individual criteria received more than 10%, it would still be interesting to include these as metadata, allowing designers a flexible means of searching for in-service information.

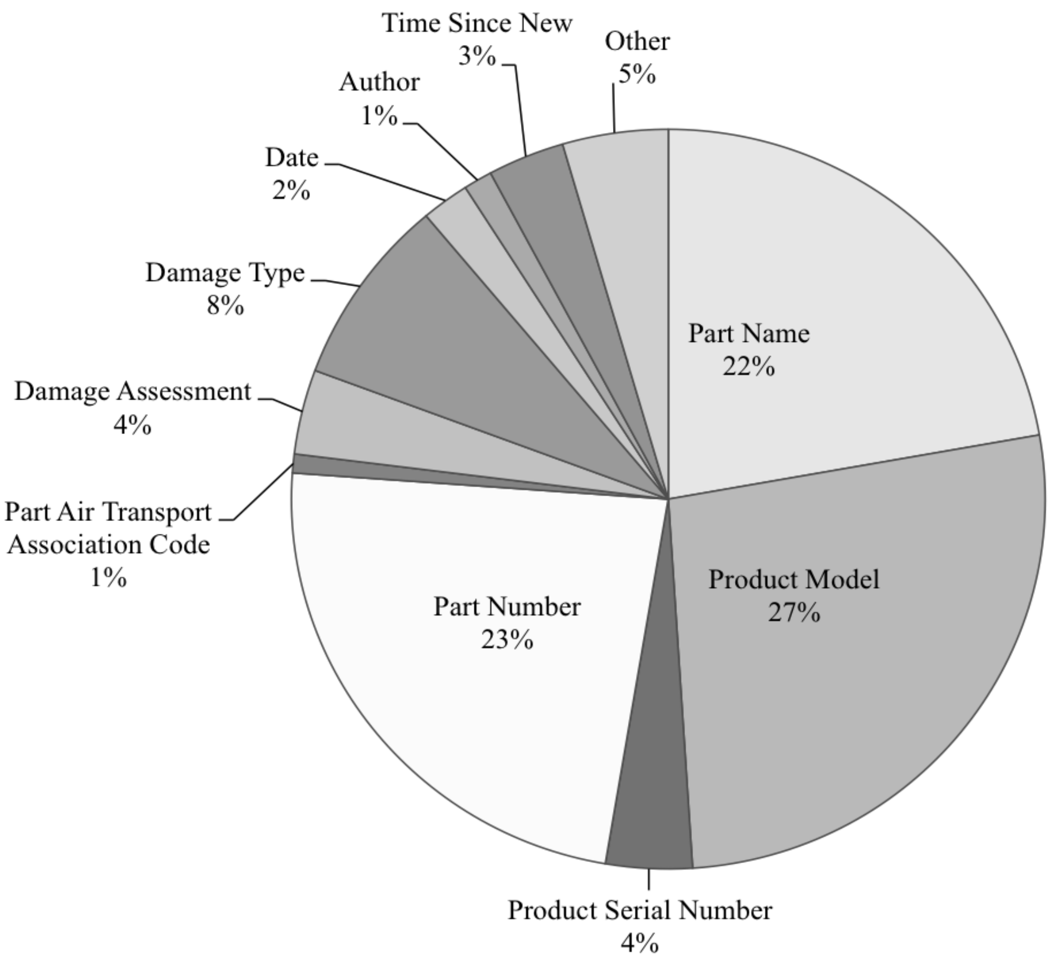

Figure 3.7. Search Criteria

3.4 Discussion

While different authors have addressed in-service information feedback, as previously noted, Jagtap (2008) seems to have presented the only research to have explicitly studied the needs of aerospace designers with respect to in-service information. As such, this discussion will present an analysis of the survey results as well as a comparison with the Jagtap's findings.

To begin with, it should be noted that although the study in Jagtap (2008) began as an academic project, the current survey is firmly based in the industrial context. Therefore, the questions and scope of the current survey were strongly influenced by the mandate of the industrial partner who participated in the survey. It also affected the strategy used for the survey. Whereas in Jagtap (2008) in-depth interviews were conducted with 3 design engineers, one of the goals in developing this survey was to keep it as short and simple to answer as possible, while still obtaining sufficient information for the successful continuance of the project. It was also hoped to confirm the qualitative results of Jagtap (2008) through a quantitative study of a larger group of engineers. Questions that would only be of academic value were also avoided, in favour of questions that would give insight into the general nature of in-service feedback, while at the same time contributing to the needs of the participating manufacturer. Furthermore, the intent of the project was to leverage the information currently collected as much as possible. The survey therefore focused largely on the information known to be available within the company, rather than referring to the literature for the information types. It should be kept in mind, however, that collected in-service information is not necessarily readily available to designers, or found in a format that would be useful in their standard work process.

The answers to the types of in-service information designers 'currently use', 'would like to use', or 'do not require' provide an interesting foundation on which to base further research into the means of providing in-service information to designers. First of all, the results make it clear that all nine information types are considered valuable by designers, as the combination of 'Currently use' and 'Would like to use' answers greatly outweigh the 'Not required' answer in each case. The ranking of information types by the percentage of 'Currently Use" responses is given in Table 3-5.

Table 3-5. ‘Currently use’ response

Currently Use			
Rank	**Information type**	**No. respondents**	**%**
1	Failure modes, causes and effects	48	59.3
2	Photos of damaged components	42	51.9
3	Maintenance Requirements	33	40.7
4	Reliability and failure rates	31	38.3
5	Service and Inspection Limits	27	33.3
6	Inspection Data (after use)	25	30.9
7	Service Center Lessons Learned	18	22.0
8	Maintenance Cost (DMC in $/hr)	13	16.3
9	Scrap and repair rates	11	13.9

As previously mentioned, the only two information types which score higher in the ‘Currently use’ category than in the ‘Would like to use’ category are ‘Failure Modes, Causes and Effects’ and ‘Photos of Damaged Parts’. This is not to say that other types are not used, in fact six of nine types categorized are used by over 30% of respondents. This may seem to indicate that processes already exist for the feedback of in-service data. However in discussion with designers, and in comments made in the open-ended survey questions, it is quite clear that this information is obtained mainly on an ad hoc basis through informal channels, rather than well-structured, formal processes. This matches well with the finding in Wallace, and Ahmed (2003) that engineers prefer obtaining their information from other people rather than documents. However, Wallace, and Ahmed (2003) also points out that new engineers do not usually have this network to rely on, and so it is important to have a well-defined process that can be applied.

With respect to in-service information that designers would like to use (Table 3-6), the strongest response was given for ‘Service Center Lessons Learned’ and ‘Scrap and Repair Rates’. It is also clear from their low response regarding their current use that designers would benefit from an efficient and effective process for the feedback of this information.

Table 3-6. ‘Would like to use’ response

Would like to use			
Rank	**Information type**	**No. respondents**	**%**
1	Scrap and repair rates	59	74.7
2	Service Center Lessons Learned	60	73.2
3	Maintenance Cost (DMC in $/hr)	46	57.5
4	Reliability and failure rates	44	54.3
5	Service and Inspection Limits	43	53.1
6	Inspection Data (after use)	42	52.5
7	Maintenance Requirements	41	50.6
8	Photos of damaged components	38	46.9
9	Failure modes, causes and effects	29	35.8

There is only one case where a somewhat significant proportion of respondents declared a certain information type as not required, that being the Direct Maintenance Cost (DMC). In that case, 26.3% of designers did not believe this index would be valuable for their work (Table 3-7). The DMC represents the total cost of maintaining a part or product over its lifetime, and is typically quite complicated to calculate. However, there are ongoing efforts to create a standardized method for calculating and tracking the evolution of the DMC throughout the development process. This index could potentially be used as a trade off against such things as weight and cost. The lack of a clear, standardized method for calculating the DMC up to this point may be one reason for its dismissal by designers. This may be a case therefore where the DMC should be pushed from in-service towards design, rather than being pulled. The solution to gaining more acceptance may also be a training program for designers on the meaning and value of DMC.

Table 3-7. 'Not required' response

Not required			
Rank	**Information type**	**No. respondents**	**%**
1	Maintenance Cost (DMC in $/hr)	21	26.3
2	Inspection Data (after use)	13	16.3
3	Service and Inspection Limits	11	13.6
4	Scrap and repair rates	9	11.4
5	Maintenance Requirements	7	8.6
6	Reliability and failure rates	6	7.4
7	Failure modes, causes and effects	4	4.9
8	Service Center Lessons Learned	4	4.9
9	Photos of damaged components	1	1.2

This brings up an important issue when deciding what information designers should consider from in-service. Up to now, it has been assumed that designers know what information is needed to facilitate the development of a product that will perform well in-service. However, it is quite possible that they are unaware of certain types of information that could prove valuable, and so the expertise of other departments such as reliability, maintainability and repairability, customer support, and the service centers should also be exploited when developing an in-service information feedback system.

During the interviews carried out with three aerospace designers, Jagtap (2008) also developed a list of the types of in-service information currently used during product development, or that designers would like to use. While the labels applied are different, due in part to the inconsistency in nomenclature from one manufacturer to the next, it is still possible to draw equivalencies between those identified in Jagtap (2008), and those identified in the current study (Table 3-8). In Table 3-8, the types of information contained in a single row can be considered, if not identical, to at least be quite similar for the purpose of informing the designer. It can be seen that there is quite a good overlap between the lists. However, the list compiled from Jagtap (2008) contains five types of in-service information not considered in the study reported here. In future work, it would be interesting to examine the possibility of expanding the type of information to include the rest of the list from Jagtap (2008) and determine whether designers see value in including the extra items in the database. Based on the experience of carrying out this project, the first three items only present in Jagtap (2008), which concern repair facilities, serious field events, and engine operators, would not be too difficult to provide to designers, as they are typically managed by the manufacturer through other information systems and databases. However information concerning past designs, the ease of assembly and service tasks is often treated through documents or informal information, and would be more labour intensive to capture.

Table 3-8. Comparison of findings: Current project & Jagtap (2008)

<table>
<tr><th colspan="2">In-service Information that Designers Currently Use or Would Like to Use</th></tr>
<tr><th>Jagtap 2008</th><th>Current project</th></tr>
<tr><td>The deterioration mechanisms that a component might face in service, such as erosion, wear, cracking etc…</td><td rowspan="2">Failure modes, causes and effects</td></tr>
<tr><td>Causes of deterioration</td></tr>
<tr><td>The life cycle cost</td><td rowspan="2">Maintenance Cost (DMC in $/hr)</td></tr>
<tr><td>Cost of overhaul, including the cost of repairing or replacing the component</td></tr>
<tr><td>The repair/replace strategy</td><td>Maintenance Requirements</td></tr>
<tr><td>Photographs of failed components</td><td>Photos of damaged components</td></tr>
<tr><td>Safety and reliability aspects</td><td>Reliability and failure rates</td></tr>
<tr><td>Repair limits</td><td>Service and Inspection Limits</td></tr>
<tr><td rowspan="2">Observed limits of the deterioration mechanism before loss of functionality</td><td>Service Center Lessons Learned</td></tr>
<tr><td>Inspection Data (after use)</td></tr>
<tr><td>Monitoring of deterioration mechanisms</td><td rowspan="2">Inspection Data (after use)</td></tr>
<tr><td>Any variation in a given deterioration mechanism with number of hours or cycles for a component</td></tr>
<tr><td>Actual achieved life of a component in service</td><td>Scrap and repair rates</td></tr>
<tr><td>The facilities required to repair a component</td><td rowspan="5">No equivalent found</td></tr>
<tr><td>Any events such as in-flight shut downs (IFSD), aborted take-offs (ABTO), etc… caused by a component</td></tr>
<tr><td>A list of operators of a particular engine type</td></tr>
<tr><td>Information about any previous designs which addressed the relevant deterioration mechanisms</td></tr>
<tr><td>Ease of assembly, disassembly, inspection, etc…</td></tr>
</table>

While Table 3-4 lists several types of information suggested by designers that were not included in the list offered to designers, the suggestion of including Non-Conformance Reports (NCR) in the database deserves special mention. Through research and discussions with designers, it has become clear that NCRs play a central role in tracking the quality of the product throughout its lifecycle. It is interesting that no similar information type was included in Jagtap (2008), and further consideration will be given as to how to integrate this information into an in-service information feedback system.

Based on the results of section 5 of the survey, which investigated the frequency with which designers required in-service information and the effort needed in order to retrieve this information, it is possible to determine a conservative estimate of the time associated with obtaining in-service information on a yearly basis. This, however, requires making certain assumptions, as laid out below.

Beginning with Figure 3.4, we make the following assumptions:

- A year consists of 50 weeks
- 'Once or twice a year' has been considered as twice
- 'Once per Design Job' has been ignored due to its ambiguity

The last category has been ignored as it was later determined that the length of a design job can vary significantly, and so an a direct comparison with the other time periods is not possible.

Combining these assumptions with the fact that 82 designers responded to this question, it can reasonably be estimated that an average designer will require in-service information 19 times per year.

Similarly, in order to calculate the time it takes to obtain the information, the following assumptions were made:

- One day is 8 hours
- One week is 40 hours
- In each case, the amount of time is rounded up (i.e. 'One hour or less' is taken as 1 hour)
- The 'More than one week' category is ignored

Upon analysis of the results, the ‘More than one week’ category was considered too vague for a direct comparison with the other lengths of time, and so, as noted, was not used in calculating the average time to obtain given information. For this question, there were 71 respondents, and so it can be estimated that it takes 26.3 hours on average to obtain the needed information. Therefore, it takes approximately 500 hours per year, per designer, to meet their need for in-service information. This time is split between active research by designers or other employees, and the time a request spends waiting to be addressed. While this value is only an estimate, it is clear that a significant amount of effort is exerted to obtain the needed information. While a related study by Crabtree et al. (1993) reported the time engineers spent searching for information as a percentage of working time and not in hours (and were not specifically focused on in-service information), they similarly found that the time spent was disproportionate and led to frustration among engineers.

As stated above, the questions concerning the relevance and quality of the in-service information currently being used were generally positive, however, there is room for improvement. In particular, designers have doubts concerning the completeness of the information being provided. This most likely is related to the informal nature of current in-service feedback processes, where designers take it upon themselves to find the necessary information. In that type of environment, it can be difficult to say for certain that all the necessary information has been obtained. Similar results can be found in a more general study of information use by engineers in Kwasitsu (2003), who also found high reliance on coworkers and personal notes and files. Based on the current results there is increased support within the industrial partner for formalizing the feedback process by means of a component in-service information management system. Once implemented, this system should ensure that designers will have more confidence in the information being provided. Not only that, but a more robust feedback process should ensure that the information is as complete, up to date, and reliable as possible. In more general terms, this supports the need for the development of a robust framework for the reuse and sharing of in-service information, possibly through future PLM systems. This will be further discussed in chapter 5.

The final question of the survey is also directly related to the implementation of an in-service information management system. In order for designers to be able to find the relevant information, it is necessary for the management system to support a search strategy that allows the user to quickly find relevant information. By understanding the typical search strategies used by designers, it should be possible to structure in-service information in such a way that designers would be able to effortlessly find relevant information. These results have been used to support the work presented in chapters 4 and 5 when developing a proposal for an appropriate model for product in-use information management.

3.5 Conclusion

A survey was conducted across seven engineering specializations with participation of approximately 78 designers. As part of the broader goal of the current research is to facilitate the feedback of in-service information to designers, the main focus of this survey was to unveil/categorize the types of in-service information needed to facilitate design, as well as to determine the views of designers with respect to the in-service information they currently use. Furthermore, the results provided a deeper understanding of the existing situation and the relevance of the current research project, two major objectives of the DS-I stage within the DRM framework (Blessing & Chakrabarti, 2009), and provided further confirmation of results reported in related studies of information use by designers (Crabtree et al., 1993; Jagtap, 2008; Kwasitsu, 2003; Lee, Y. W. et al., 2002; Wallace & Ahmed, 2003).

The survey identified nine different types of in-service information, all of which were of interest to designers. This closely matched the conclusions of a previous study (Jagtap, 2008), which was based on the in-depth interview of three designers and the observation of the design process at another large aerospace manufacturer. Furthermore, an estimate of the time required to answer requests for in-service information was calculated. It was determined that it takes roughly 500 hours per year, per designer, to fulfill in-service information requests.

The findings of the survey highlight the inefficiency of the current system of informal in-service information feedback to designers, established mainly through personal contacts. Furthermore, the current in-service feedback approaches do not necessarily ensure that appropriate, complete information is always available in a timely manner for designers. However, it is important to note that the required information does exist within heterogeneous databases, with one challenge being the implementation of a formalized in-service information feedback process to ensure that the required information is available.

The comments received from designers based on the survey were very encouraging, with nearly all respondents recognizing the benefits of an in-service information feedback system. However, as shown by the somewhat negative response to the applicability of the DMC to the design process, the task of implementing an in-service information feedback process is not simply one of responding to information requests from designers. Interaction between in-service information experts (such as service center personnel), those responsible for implementing any future feedback processes, and designers is essential to ensuring that all stakeholders are aware of the in-service information that is available and its implications for the development of new products. In some cases, for example, it might be appropriate to push information towards designers, rather than simply allowing them to pull the information they decide is necessary.

One item which was frequently mentioned and which was not covered by the survey was the use of Non-Conformance Reports (NCRs) to indicate instances of non-conformance during the in-service phase. Future research should examine the content of the NCRs and their potential for integration into the in-service information database.

As previously stated, the results presented here can be considered as a baseline for future evaluation of the impact that design support tools and methodologies have on the ease with which designers can access information. While this is not a direct measure of improvement to the practice of design (i.e. reduced time, reduced cost and increased product quality), it does provide a first level assessment of whether a tool facilitates access to information which several researchers have identified as vital to a robust product development process and PLM strategy. In subsequent chapters, the results reported in this chapter will provide context for the development of a model for the representation of product in-use information as well as factors by which it can be evaluated.

Chapter 4 PRODUCT IN-USE INFORMATION IN PRODUCT DEVELOPMENT

The results of the survey presented in chapter 3 described the need for capturing, sharing and reusing in-service information in order to support designers. However, as shown in chapter 1, previous research has demonstrated that testing information could also provide similar support in terms of evaluating product performance. Based on this, a central hypothesis of this project is that in-service and testing information can be grouped together into what we call here product in-use information, defined in chapter 1 as "all information collected throughout the lifecycle concerning product performance during use".

To examine this hypothesis, a study was completed of both testing and in-service information collected by a manufacturer of complex aerospace systems. In this section, the results of this study will be reported and analysed in order to compare and contrast the content and structure of the relevant information sources. In this way, the existence of product in-use information and its key characteristics will be demonstrated. Following this, several possible methods for structuring and representing product in-use information will be explored in order to develop an effective means of managing this information with the goal of supporting designers.

4.1 Information Collection & Analysis

As reported in chapter 2, the descriptive study portion of this research was completed in conjunction with an aerospace manufacturer over the course of an 18 month long collaborative project. During this time, activities were undertaken as part of a team studying the aftermarket performance of the complex systems produced by the manufacturer. Several key components and subassemblies became the focus of this collaborative work, and it was possible to study their history, including the information collected with regards to both in-service and testing activities undertaken throughout the product lifecycle. In studying these components, it was possible to gain an understanding of the overall scope, content and structure of the available information. In particular, information was collected regarding two particular product models, each of which target a different market but which are similar in terms of complexity and function. In order to ensure clarity while retaining confidentiality, these will be referred as products A and B. Section 4.1.1 will describe the information collected during development testing of the products as well as associated activities, while section 4.2.2 will discuss the information collection and management process once a product enters into service.

4.1.1 Testing information

The aerospace manufacturer completes tests with various objectives throughout the product lifecycle. In the context of the current project, the information of interest was collected during the product development stage, and resulted from what is referred to as *development testing*. These tests were completed when verifying that a new product model or build is ready for release. There exists other test data within the company, such as that collected for research and development purposes or when investigating particular issues. For example, a failed development test or an unexpected in-service event may require further testing of particular components in order to complete a root cause analysis. However, these types of tests and their processes were not included within the current project.

Each time a development test is failed, a report, referred to here as a Test Event Report (TER), is filed. In order to understand the work completed during the development process, it was decided to analyse the TERs filed during the development product A. This consisted of 231 TERs filed over a period of six years. The issues identified within the TERs were not limited to hardware malfunction, but also included human error, tooling problems, and issues with software. However, the scope of the analyses that follow will be limited to those issues raised regarding hardware components, which were the most prevalent.

These reports provide details with regards to the date, the type of test, the problem identified, the components involved, the product section, the product build, model and serial numbers, and possible solutions. More precisely, the reports are split into the following sections:

1. Report Identification
2. Originator Information
3. Problem Information
4. Part Information
5. System Information
6. Reference Information
7. Problem / Root Cause / Corrective Action

8. Distribution List
9. Attachments

Once filed, a TER kicks off a process to investigate, evaluate and solve the problem identified. While the majority of TERs are addressed and resolved, certain low risk items may be left open as the project progresses. In the sample studied, 74.5% of TERs had been closed, while 25.5% remained in progress or "not actioned". It is believed that by further facilitating product in-use information flow, even these low risk items can be addressed efficiently early in the development process. Furthermore, while the reports do have a clear overall structure, the tendency to include certain information in blocks of natural text resulted in a number of differences among reports in terms of the vocabulary used as well as the details provided regarding root causes and corrective actions. While this is not a major issue when it comes to resolving the immediate issue raised by the TER, it can complicate the reuse of the test information for the design of subsequent products when the designers are not necessarily aware of all past test initiatives. It is therefore important that any framework for the management of product in-use information support the efficient collection of testing information as well as its clear representation for both experienced and neophyte designers.

4.1.2 In-Service Information

As explained in section 2.2, the majority of the time spent working with the industrial partner was as part of a department studying the factors linking product performance, service strategies and product development, as well as how these factors affect the costs incurred during the in-service phase. As a result, it was possible to gain a broad view of the information collected once a product is put into service. The in-service information was collected by means of case studies of differing scope and depth. An overall appreciation of the information collected was gained by collecting information from service centers in order to support ongoing initiatives within the company. This covered a range of product models and components. Next, an in-depth study was completed of a particular type of seal used in multiple product models, during which detailed information was collected concerning its in-service behaviour across all instances of product A that had been put into the field. Finally, information regarding unexpected field events and the associated invoice costs for product B were collected from the Field Data Collection System

(FDCS) and invoice reports. This section will give an overview of the databases and documents examined during these studies and their information content.

In the case of the studies completed in support of cost management and product improvement initiatives, as well as the study of specific components, the information examined covered a wide range, including problem and event descriptions, subsequent investigations, supporting information and findings (such as customer, part number, and part condition, among others), and proposed corrective actions or solutions. This information was obtained from various sources, each of which varied in term of content and format.

The first source, the Field Event Reports (FER), is contained within a formalised system meant for the identification, tracking and resolution of field events. The events recorded in these reports typically meet two criteria. First, the event is unexpected, meaning it does not consist of wear or damage already considered within the maintenance plan. Second, the events are noticeable by end users, namely operators. The sections of the report are similar to those of the development testing TERs, with the addition of customer, mission and field event information. The content of these reports is also more focused on the effect on the user in addition to the technical performance of the product, the latter being the main consideration of TERs. This database is part of the recognised means of addressing serious field events and therefore the status of each item is tracked and controlled. These field reports provided an extensive amount of information and were an important resource for the analysis to be presented in chapter 5.

In contrast to the field reports, two additional documents, here referred to as Product Inspection Reports (PIR) and Parts Lessons Learned (PLL), were found to be created and controlled in a less formal fashion. Product Inspection Reports are completed on each product that is serviced with the goal of noting the level of wear of each component, placing particular emphasis on unexpected wear or damage. In cases where the product is being serviced as a result of a particular event, the PIR also endeavours to identify the cause of the problem. Included in these reports are:

1. Historical data (Model, Serial Number, Time Since New, Date of removal, etc…)
2. Reasons for removal
3. Relevant inspection results supported by photographs of product components
4. Recommendations for further action

Product Inspection Reports are used to supplement the information collected by the Field Event Reports with the goal of facilitating the resolution of the event in question. However, while these documents contain information that would also be useful for designers working on the development or modification of other products, these reports are not considered design documents and so are not managed as such. Therefore, the contents are not systematically made available to all designers, and their structure is not optimised for this type of information sharing. As will be demonstrated in chapter 5, by implementing an information management framework that explicitly recognises the advantages of sharing this information with designers, the information being collected can be further exploited.

While Product Inspection Reports are created systematically using a standard template and are stored in a controlled fashion, another document known as Parts Lessons Learned (PLL) is treated somewhat less formally. These documents are created on demand and with the goal of answering a specific query from a designer or other engineer in need of in-service information, usually with respect to a single component or subassembly. In general, the PLL is a shorter version of a PIR with a particular focus on recommendations for corrective action and product improvement, hence the “lessons learned”. Therefore, despite their less formal nature, PLLs remain rich sources of information for designers and typically present a concise, understandable summary of in-service information in a more design-centered format than other sources. As such designers tend to find these documents useful for quickly fulfilling the information requirements identified in section 3.3. However, these documents are not part of the formal workflow and therefore a designer may request a PLL without knowing that one has already been developed for use in another project. Therefore, in the case of both the PIR and PLL, there are potential efficiencies to achieve in terms of information sharing and reuse by designers.

While the previous reports tend to be centered around particular events, there is also data which is systematically recorded during the detailed inspection carried out during regularly scheduled maintenance activities. This data tends to be more formally collected and stored, but is not necessarily intended for communication to those outside the service center and therefore can be difficult to access or summarise in a way conducive to typical design work. These inspection results are directly reported within an enterprise resource planning (ERP) system. This data is collected according to the procedures set out in inspection manuals and determines whether parts must be replaced, repaired or may remain in-service. As this data is stored in the ERP system, it is possible to track the necessary repairs, replacements and their respective rates. This data can facilitate the discovery of historical trends for different types of component degradation and help identify so-called top offending components or systems in terms of repair and replacement rates and cost. This type of analysis was carried out as part of the research carried out in conjunction with the industrial partner and proved to be a valuable asset when studying in-service product performance over a given time period.

A further source of in-service information identified is a system that compiles statistics regarding the occurrence of severe component damage and field events, which must be tracked for warranty, reliability, and safety purposes. However, this analysis tends to target the most serious events and the results are communicated to designers either directly or via reliability engineers. The main interest of the current project is with regards to the gap in tracking information concerning unexpected component degradation that may reduce performance levels and increase costs without necessarily posing a threat to safety or mission completion. Therefore, this system was not studied in detail.

In the case study of product B, the main sources of information were the Field Data Collection System (FDCS) and the invoice-based Trend Reports (TR). The FDCS reports contain similar information to the previously described TERs and FERs (e.g. event description, product section, possible causes and solutions, actions to be taken, etc…) along with additional information concerning customers and mission. However, these reports are completed by customer service representatives and are more focused on tracking the product condition and availability as well as recording interactions with the client and service centers than technical analysis, and are usually solely text based. The narrative nature of the information makes these reports more difficult to analyse than the more technical reports previously described.

The Trend Reports (TR) present which parts and how many are replaced in the field over a period of time, along with their direct costs, and whether removals were planned within regular maintenance activities or were unplanned. In the case of this particular study, the costs were compiled in real 2010 dollars for all parts replaced from the start of available records (January 2008) to the date of data collection (December 2010). These were tabulated for all removals as well as for unplanned removals only. While this information can offer guidelines as to how to prioritize in-service issues, it is important to note that the part cost alone does not provide a complete view of the costs involved in servicing the products. A determination of the complete costs was not feasible during this project, however this is part of an ongoing initiative of the manufacturer. This will be further discussed in section 4.2.3.

4.1.3 Discussion

While several more report types were identified for in-service information than testing, the contents of the FERs, PIRs and PLLs were found to be quite similar to the contents of the TERs. Although the context in which the information was created was quite different, and the in-service information placed a greater focus on the customer, both in-service and testing information discussed discrepant events and provided detailed information regarding affected components and systems, relevant damage or failure modes, root cause analyses, possible solutions, and corrective action. These topics were identified as being important inputs to the product development process both within the design survey (Chapter 3) and through discussions with various experts, and therefore it is proposed that product in-use information is a real and important class of information, which should be managed within a global product lifecycle and engineering information management system.

While the transfer of in-service information to designers was imperfect, there was evidence of an effort made to learn from in-service experience, with the PLL being a prime example. However, there was little evidence for the same type of information transfer when studying the management of testing information. While test results are sometimes included in design reports, which are used by designers, it could be beneficial to also present the information in a new testing lessons learned document. Furthermore, based on the similarities found between test and in-service information, it may be possible to apply some of the lessons learned from the in-service information survey (chapter 3) to testing information. For example, the inclusion of photographs to support the information found in the TERs could help support designers in their work

It has been demonstrated that there is valuable product in-use information being collected throughout the product lifecycle, however based on the findings in chapter 3, discussions with designers and engineers, as well as the author’s personal experience within the industrial partner, there remain opportunities for the creation of a consistent, easily accessible body of information as well as providing the support tools and methods necessary for representing, sharing and reusing the information. In particular, six different documents or systems were identified as major sources of in-service information, all of which a designer must be accustomed to and check on a regular basis in order to stay up to date. However, the information found in each is related and often similar in content, and so it is proposed that the development of an information management framework with the explicit goal of supporting the structuring and sharing of product in-use information could greatly increase the efficiency of the information searches carried out during the design process. In the rest of this chapter, several solutions to these issues will be discussed. By demonstrating a common means of representing and structuring product in-use information, this work will further advance the case that information gathered during the in-service and testing lifecycle phases can be regarded in a similar fashion.

4.2 Supporting designers through product in-use information

To further understand product in-use information, several strategies have been considered for structuring and representing this information in order to capture it and make it available to designers or other stakeholders across an organisation. In this section, three of these strategies (Failure Modes and Effects Analysis, Cost Analysis and the SAPPhIRE model of causality) will be described in order to demonstrate the evolution of this project and the steps leading to the final analysis and recommendations presented in chapters 5 and the conclusion. First, however, it will be necessary to discuss the perspectives of several stakeholders within the product development process in order to better understand the relationship between their roles and activities and the management of product in-use information.

4.2.1 Perspectives on Product In-use Information

Before proposing how best to support designers through product in-use information, we will briefly discuss the various perspectives, as found within the industrial context and compare with those reported in the literature presented in chapter 1. When examining information use and reuse within product development, it is necessary to consider the viewpoint of several stakeholders. While it is difficult for a single tool, methodology or model to satisfy all points of view, it is important that these different perspectives are taken under consideration within the overall strategy. In this case, the focus will be placed on those directly implicated in the creation, collection and use or reuse of product in-use information.

To begin with, those working in the service centre, whether engineers or technicians, play a role in both the creation and communication of in-service information, a major component of product in-use information. However, frequently the first priority in a service center is not the improvement of the product design or the collection and communication of information to designers, but reducing the turn around time and cost for receiving, tearing down, inspecting, refurbishing and/or reassembling, and reintroducing into service each product (Markeset & Kumar, 2005; Sander & Brombacher, 1999). Quality is an important factor, however it is frequently addressed in terms of more efficient or robust repairs, or finer resolution inspection techniques, rather than communication of possible design improvements with designers. This is not due to lack of willingness, as when discussions were held regarding in-service issues, the service centre personnel of the collaborating company frequently identified possible design improvements. However, due to operational constraints within the industry, their resources were necessarily focused on inspection and service activities, rather than on product improvement initiatives. As will be discussed further, safety concerns were the main driver for detailed root cause analyses and systematic communication of in-service information to designers.

Next, from a development testing point of view, the goal is to troubleshoot all issues in order to introduce into the marketplace a product at a relatively high level of maturity. In this case, information tends to be more reliably communicated with designers as it is easier and less costly to introduce design changes at the testing stage than once a product is in-service. However, once again there are time constraints, as there are launch dates to be met. This means that test personnel are sometimes more concerned with overall test results, rather than trying to learn to a greater extent about the product. This can lead to testing to specification, rather than attempting to characterize the product with the goal of improving future design iterations (Ward, A. C., 2007). Therefore, in the case of development testing, it is not a question of whether the results are communicated with designers, but rather the type of information collected and its pertinence to multiple and future projects, rather than to the specific product being tested and a particular customer's requirements.

As can be expected, those directly involved in designing products have a different point of view. This is has been discussed in more detail in chapter 3, but some general observations will also be made here. Designers tend to be interested in information pertaining to product performance during testing and in the field. This information can confirm or contradict their assumptions as well as the accepted best practices. However, the information must be relatively easy to access. With efforts to decrease the duration of the product development process, designers does not always have time to spend searching through statistical databases or lengthy reports, which may not be relevant to their work. Many designers are therefore interested in accessing a summary with pertinent conclusions, with the option of accessing well-presented detailed information when necessary.

From a customer perspective, there is always an incentive to improve the time to market, cost and quality of the product, however these three factors can often enter into conflict, as it is difficult to optimize all three concurrently. In the aerospace industry, the factors influencing the customers point of view can change depending on their specific market, whether commercial, business or military, and the state of the overall economy. In times of economic downturn, as in the decade since 2001, cost can become a larger factor than time to market or innovation.

Finally, from the point of view of design research, it is important to understand the dynamics of the trade-offs between the various factors affecting the stakeholders, namely time, cost, quality. By understanding these factors, one can determine how compromises are made and how a system can be developed to support product development that is adaptable to various situations. From a fundamental basis, it is also important to model the process of product development and the product lifecycle, which demands an understanding of not only how the product is designed, but also how it is manufactured, maintained, and disposed of or recycled, and how these phases of the lifecycle interact. For researchers interested in information management, a vital question is how information flows from one stage to another and what information is shared. For this reason, a strong emphasis is placed on modelling, tools and methods for understanding and coordinating the entire product lifecycle, including information management.

4.2.2 FMEA to support information feedback

A general description of Failure Modes and Effects Analysis (FMEA) and related tools, as well as their application for the capture and sharing of in-service information was presented in section 1.2.2.2. In light of these applications, during the preliminary stages of this project it was considered whether FMEA could be expanded into an efficient tool for the management of product in-use information throughout the product lifecycle and across various product development projects. The starting point of this investigation was the fact that a design FMEA

(DFMEA) report is typically structured based on a hierarchical breakdown of the product structure, similar to the structure traditionally used for PDM systems. As such, it was initially proposed that product in-use information could be represented in an FMEA report, the elements of the report being associated to the relevant parts and assemblies found within a product structure (McSorley et al., 2009).

However, several challenges were found when investigating this solution. To begin, FMEA is frequently used as a reporting tool for regulatory compliance or contractual purposes, rather than its intended use as an analysis and decision aid tool whose content should evolve as the product design progresses. Therefore, despite the work reported in chapter 1, in practice it was found that the application of FMEA at the initial (e.g. advanced and conceptual) design stages has been limited. Next, the product in-use information found during this project and identified in the previously reported survey is quite varied, and so it is not clear that an FMEA report would be able to incorporate all the information required. Finally, FMEA can be difficult to generalise from one product to another, as in its typical implementation it is heavily linked to a specific embodiment of the product. As a result, it was decided to continue searching for a more generally applicable framework for the management of product in-use information and its application in supporting designers in their work.

4.2.3 Cost analysis for development testing and in-service events

In order to support designers and the product development process through the reuse of test and in-service information, it was next considered whether a quantitative relationship could be found between field events and discrepancies observed during testing. By identifying such a relationship, it was proposed, designers would be able to make better-informed decisions on where to place their focus during the product development process, as well as predict where it would be necessary to focus continuous improvement efforts once the product was in-service. It was decided to use the cost of in-service events and development testing discrepancies as the basis for this analysis, and to compare the costs associated to each product section during these two stages of the product lifecycle. In order to do so, several sources of information were studied, both from the aftermarket and the testing phases. It was also decided to focus on product B as it was developed recently enough that most information was stored electronically, while at the same time being mature enough to have an extensive body of relevant information.

The first step in this process was to analyse the costs associated with resolving TERs recorded during the development of this product. Once filed, a TER kicks off a process to investigate, evaluate and solve the problem identified. However, not all TER go through the entire process: if it is determined to be a low priority or irrelevant, the TER may be closed without further action, or may be left open as the project progresses. Furthermore, the level of detail recorded can vary from one TER to another, including the details regarding the activities undertaken to resolve TERs. As a result, in order to complete the intended analysis some processing of the reports was required.

First, a summary of all TERs regarding development testing of the product were exported. These were then analysed to determine the product section implicated in each TER, with each being assigned to one of six product sections or deemed not applicable (N/A). The N/A category was applied in cases where the problem was not directly related to the product (i.e. process or tooling problems) or was impossible to determine. Next, it was attempted to determine the associated costs. However, this information is quite difficult to compile, as it is not tracked in a systematic fashion and would require a detailed financial analysis. Therefore, the work reported as being completed in order to resolve each TER was analysed and associated to a number of hours and cost based on the following criteria (costs evaluated at $200/hr), developed by the author with feedback from the industrial partner:

Table 4-1 Test Event Report Costs

Activities	Hours	Cost ($)
No action taken	0	0
Investigation, no corrective action.	2	400
Clarification of process, drawing, documentation, etc…	5	1000
Minor modification of existing tool, software or part	8	1600
Major modification or new tool design	40	8000
Major modification or New version of software	40	8000
Major modification or New part	160	32000
If test involved in investigation, add:	8	1600

This analysis yielded the results presented below (Table 4.2 and figure 4.1). Note that all values are reported as percentages or have been normalised, and product sections have been designated by the letters A through F in order to protect the confidentiality of this data. In this context, a "product section" refers to a nomenclature used by the company to reference various physical regions of the product, which in certain cases correlate to major subassemblies. As can be seen, section A was associated with by far the highest cost, while the contributions of sections E and F were negligible.

Table 4-2 TER Costs per Product Section

TER Cost (%)	
Section	**All**
A	0.581
B	0.238
C	0.105
D	0.060
E	0.012
F	0.004
Total	1.000

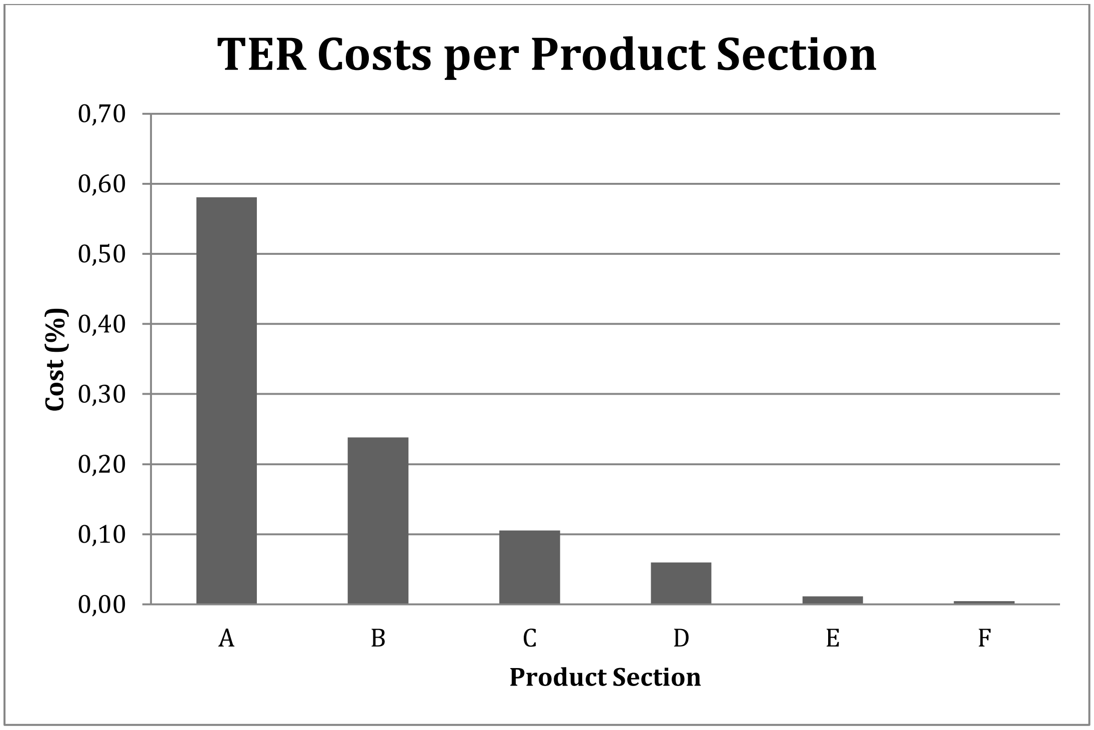

Figure 4.1 Cost per Product Section

The costs were then further broken down into those associated with TERs that had been closed and those that remain under review. As can be seen in table 4.3, the costs due to activities associated with in review TERs make up only 11% of the total costs, and so 89% of the value has been expended in conjunction with resolved items. In figure 4.2, one can observe that although section A has received the most attention overall, 87% of the value associated to unresolved discrepancies is related to section B.

Table 4-3 TER costs by status (normalized to total costs associated to section A)

DR Cost (Normalized)		
Section	**All**	**In Review**
A	100.00	0.43
B	41.00	16.53
C	18.14	0.57
D	10.30	0.85
R	1.98	0.33
F	0.76	0.38
Total	172.18	19.08

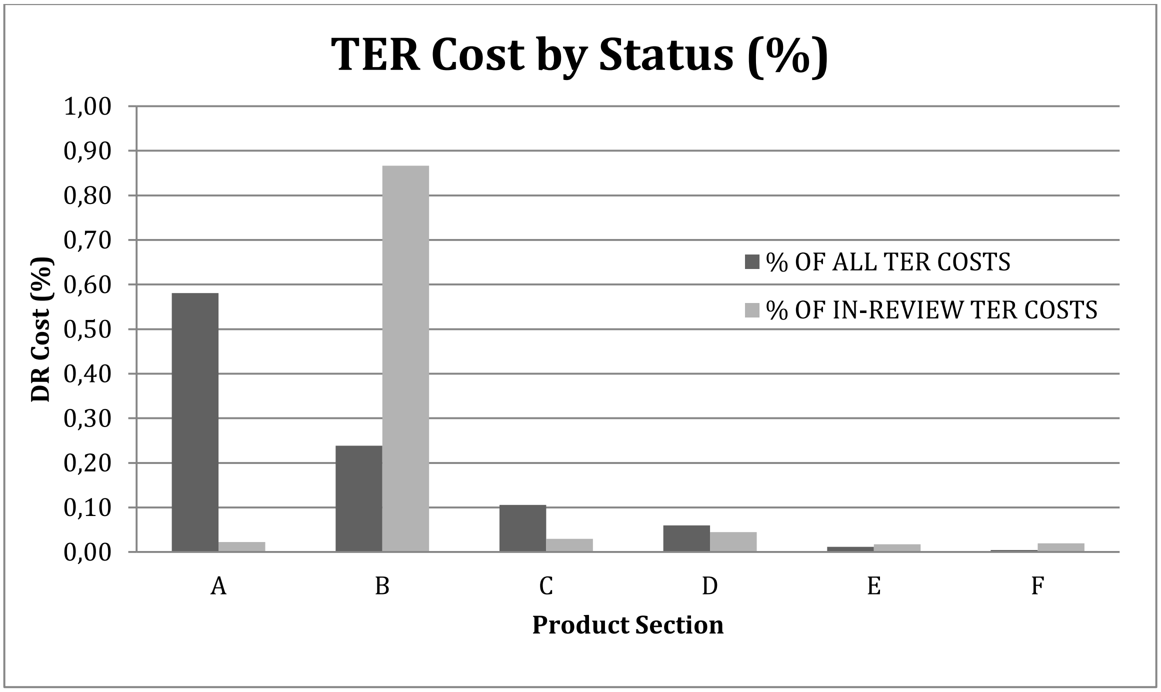

Figure 4.2 Percentage of TER costs by status

As the costs associated to in-review TERs represent effort that has not led to a definite conclusion, it can be hypothesized that the problems associated with section B are the most serious, the most complicated, or a combination of both. It is recommended that future work include a more thorough analysis of the type of test event and the analyses in progress to determine why issues pertaining to section B remain in review to such a greater extent.

In order to determine the costs associated with in-service events and the related aftermarket costs, several information sources were considered. At first, it was attempted to conduct a similar analysis to that completed on the TERs by analyzing the Field Data Collection System (FDCS) reports concerning in-service events on the product. These reports contain similar information to TERs (e.g. event description, product section, possible causes and solutions, actions to be taken, etc…) along with extra information concerning customers and mission. However analysis of these reports proved lengthy and it was difficult generate firm conclusions regarding the actual parts replaced or repaired. It was hoped that these reports would also allow the determination of costs related to downtime and transit of parts or products, but this information was not recorded in a systematic fashion in the FDCS, and costs were not directly reported. Faced with the difficulty of finding this information within the FDCS database, it was next attempted to find this information through analysis of invoices and the specific activities of particular service centers involved in various repair activities associated with the events recorded within the FDCS system. However, this would also imply a detailed financial analysis which was outside of the scope of the current research project and was not feasible.

Therefore, the main documents for this cost analysis became the Trend Reports (TR) which report which parts and how many are replaced in the field over a period of time, along with their direct costs, as well as the reasons for and scope of the removals (e.g. whether the replacements were planned within regular maintenance activities). The costs compiled were those for each part in real 2010 dollars, and were for all parts replaced from the start of available records (January 2008) to the date of data collection (December 2010). These were tabulated for all removals, as well as for unplanned removals only, and once again were grouped by product sections. These costs are recorded in table 4.4 and figure 4.3, while the average costs per removal for each product section are shown in figure 4.4. As can be seen, the general trends between total and average costs are the same, however the proportions are slightly different, with the cost due to section A comprising a smaller percentage of unplanned than total removal costs. It can also be seen that while the average cost of removal for section B is one of the highest for planned, it is by far the highest among unplanned removals. Finally, from table 4.4 and figure 4.3, it can be seen that 72% of costs are due to unplanned removals.

Table 4-4 Total and unplanned removal costs per product section

Aftermarket Removal Costs (Normalized)		
Section	**All**	**Unplanned**
B	100.00	91.66
A	59.08	25.54
C	6.61	3.95
E	67.64	50.04
D	3.33	1.77
F	3.77	1.12
Total	240.44	174.08

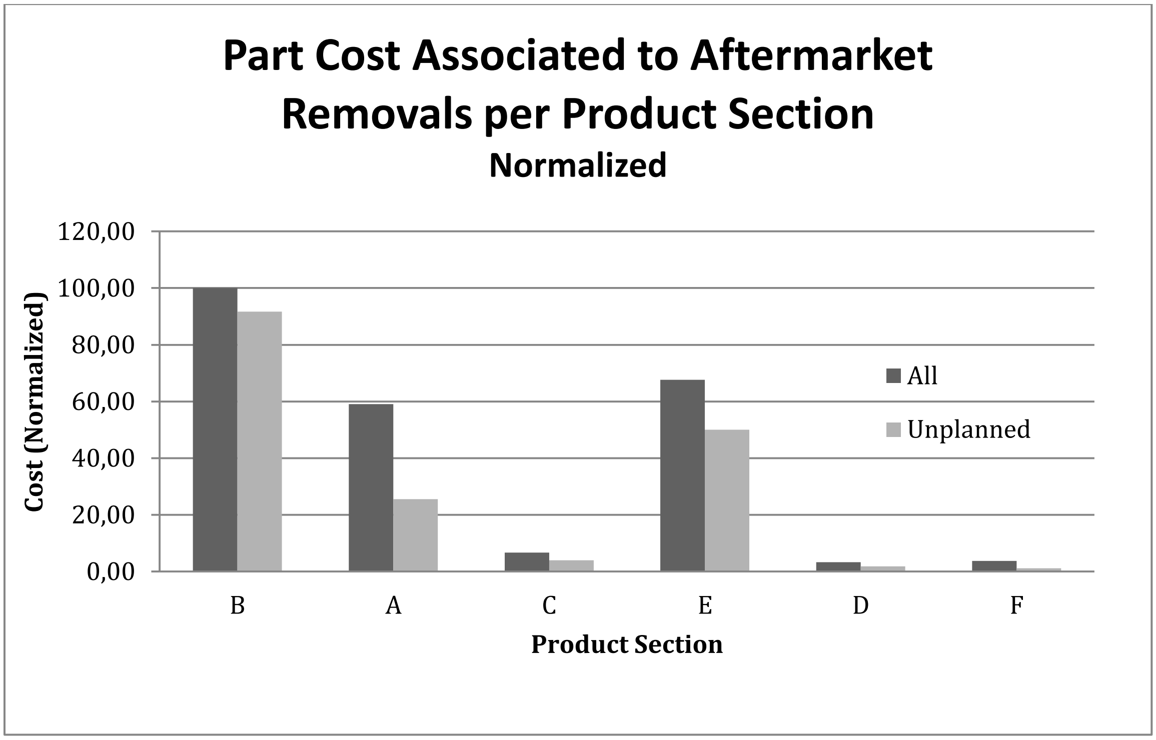

Figure 4.3 Part cost associated to aftermarket removals per product section

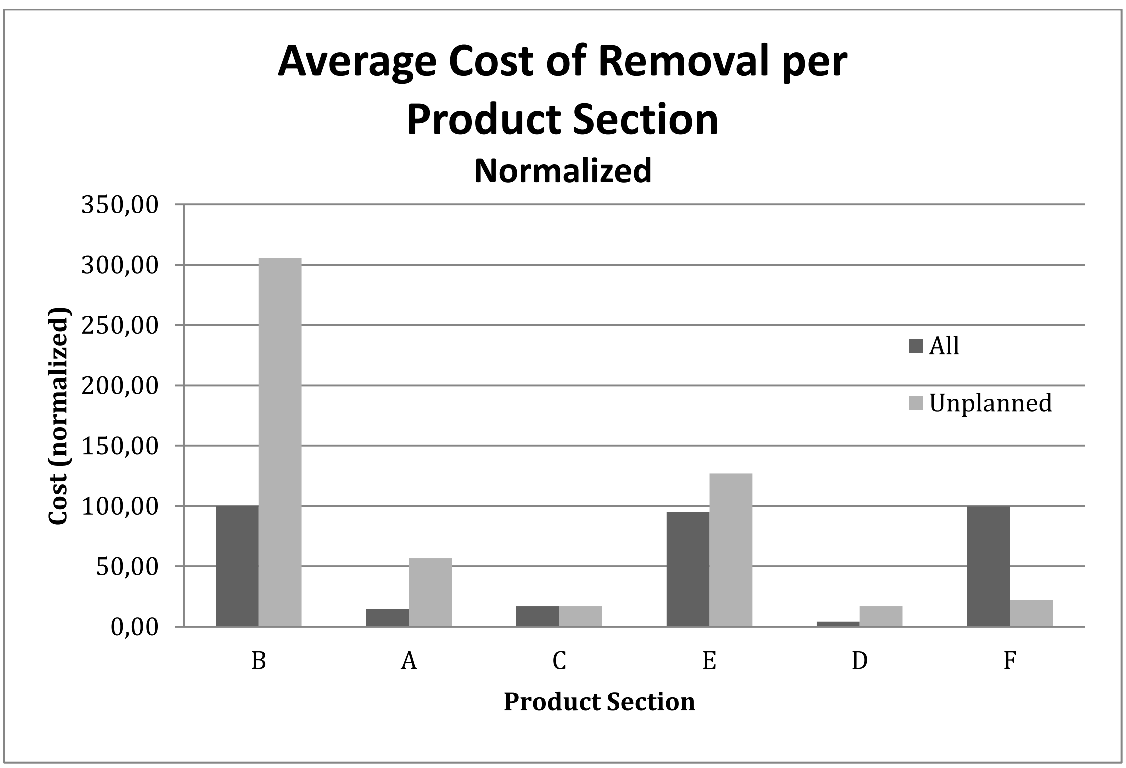

Figure 4.4 Average cost of removal per product section

The costs for development testing and in-service part removals were compared, and the most interesting trends were discovered when the unplanned removals were compared to the in review TERs. The comparison between in review TER costs and unplanned removal costs is shown in figure 4.5.

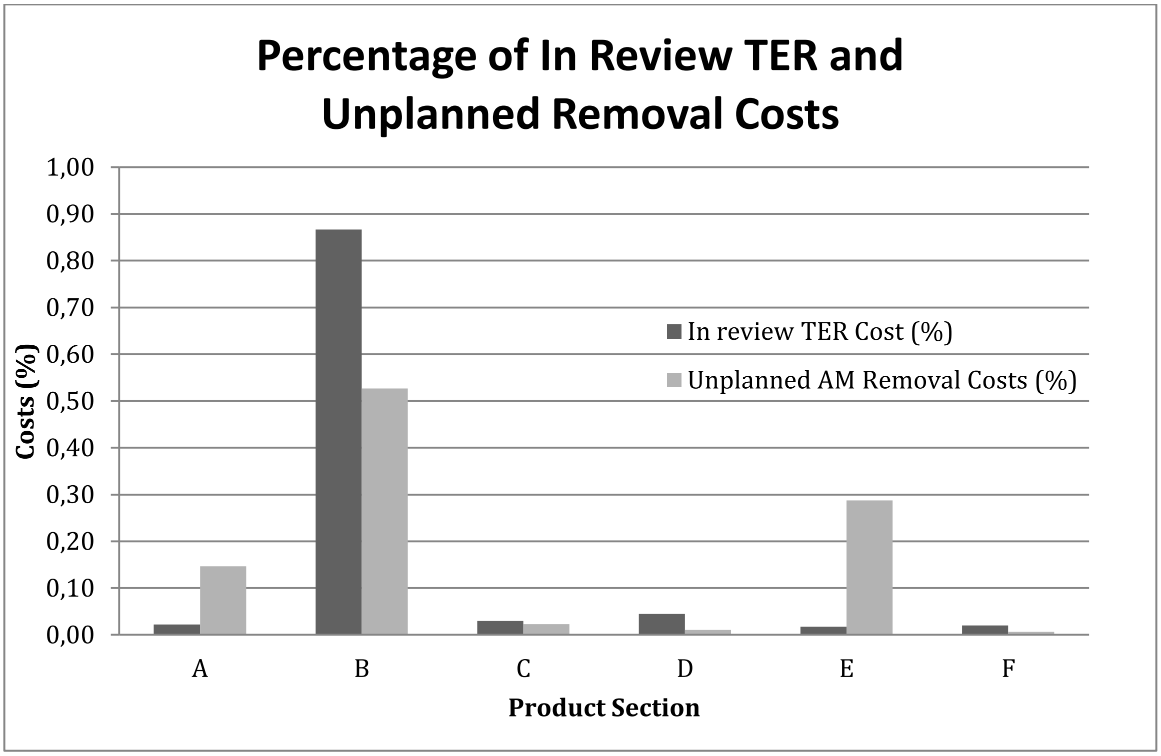

Figure 4.5 TER & Unplanned removal costs

As can be seen, section B accounts for the highest percentage of both in review TER and unplanned removal costs, composing 87% and 53% of the costs respectively. While sections A and E both account for significant portions of the unplanned removal costs, the other sections contribute negligible amounts to the in review TER costs. While it is difficult to draw concrete conclusions from these observations, it is possible to suggest interesting directions for future work.

First, in the case of section B, it was found that it has the greatest amount of resources devoted to unresolved TERs while at the same time contributing the highest percentage to unplanned removal costs. Meanwhile, sections A and E both have a much lower costs associated with both in review TERs and unplanned removal costs, while contributing significantly to the total cost of

TERs. It would therefore be interesting to investigate whether devoting more resources to ensuring the closing of section B TERs would reduce the aftermarket costs.

However, it is also possible that the ratios seen are due to the level of complexity of the problems surrounding section B. If this is the case, and the problems prove relatively intractable, it may be possible to achieve greater reductions by applying only slightly more resources to the section E and A TERs which remain open. Particularly in the case of section A, a comparison of figures 4.1 and 4.5 indicates that closing a significant amount of the TERs may lead to a significant reduction in unplanned removals.

It should also be noted that the contribution of aftermarket labour costs was not considered, which could have a significant effect on the total costs. For example, approximately 50% more unplanned removals were due to section A than section B (figure 4.6). If labour costs were taken into account, it is possible that the distribution of costs would shift, resulting in higher in-service costs for section A. In discussions with engineers from the industrial partner, however, it has been indicated that section A is relatively easy to access in comparison to section B, and so labour costs may not have a significant effect.

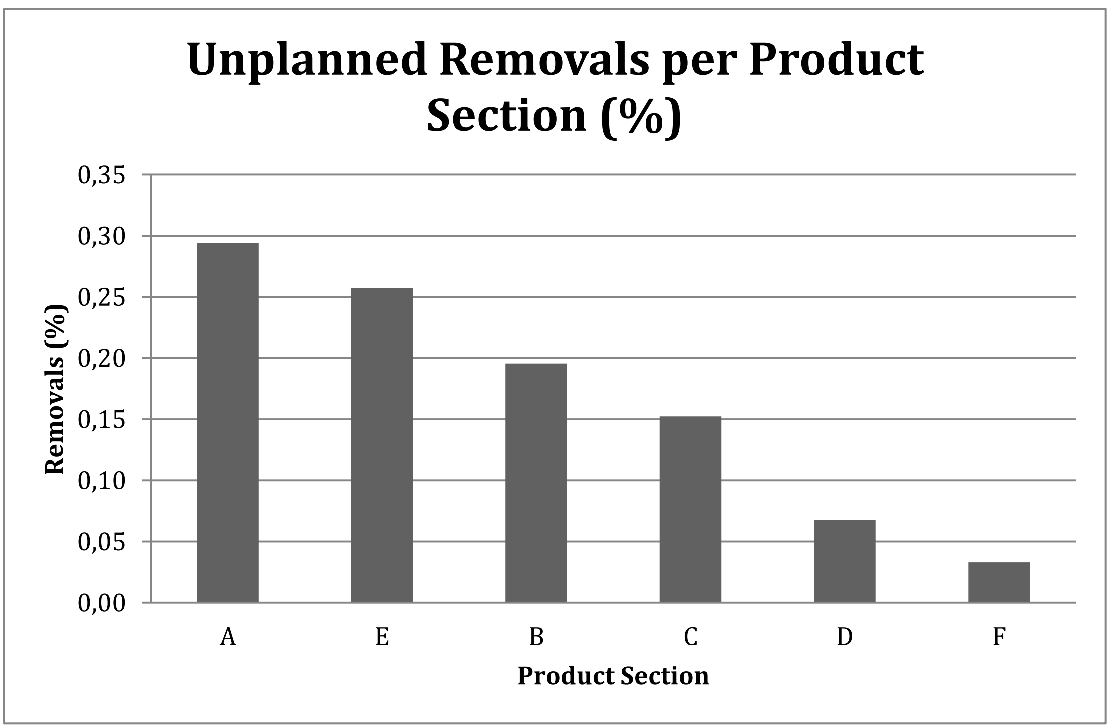

Figure 4.6 Unplanned removals per product section

Based on these facts, several recommendations can be made. First, the possible trends should be further confirmed and investigated by more closely tracking both the total aftermarket costs, as well as the costs associated with the activities that take place during development testing. In the case of aftermarket costs, this should include part costs, labour, and opportunity costs due to reduction in product availability during both scheduled and unscheduled maintenance. For development activity costs, it was found that the work completed in resolving the development testing issues was not explicitly linked to the TERs reported. If this relationship was explicit, it would be possible to track actual costs associated with particular testing events. In this way, the costs of resolving similar development and aftermarket issues could be compared and further relationships could be discovered.

While this would involve a significant analysis and a subsequent modification of relatively complex processes, a simpler first step would be to examine in more detail the root causes for both development testing and aftermarket events. By comparing the reasons behind the events, a greater understanding of how the costs are generated could be obtained and therefore a comparative analysis could be completed on a more equivalent basis.

Finally, once a greater understanding of the costs involved in development testing and in-service events is obtained, it should serve as the basis for a case study where the observed trends are used to guide development testing activities of the next version of a similar product model. By using this analysis as a guide and then tracking future in-service costs, it would be possible to evaluate whether the history of similar products could provide guidance in significantly reducing overall lifecycle costs of future products.

While this analysis has demonstrated the potential for future research and for developing an understanding of the relationship between development and in-service costs, it does not provide a direction for an overarching product in-use information management framework. Rather, by developing such a framework, it would become easier to support analyses such as those presented in this section. In section 4.2.4, a more general model for information management will therefore be considered.

4.2.4 SAPPhIRE Model of Causality

In studying the similarities between in-service and testing information and defining the characteristics of product in-use information (as presented in section 4.1), it was discovered that many of the important characteristics were similar to those identified by Jagtap in his study of in-service information (Jagtap, 2008). It was therefore decided to carry out a closer examination of the use of the SAPPhIRE model for representing in-service causal chains as presented in his thesis. As will be explained, it was found that the SAPPhIRE model offered several characteristics which are useful in the management of product related information, and it was decided to expand upon this previous work by applying the modelling technique to the complete body of product in-use information, as well as to determine how it could be adapted to further facilitate the support of designers throughout the product development process. In this section a brief background on the SAPPhIRE model will be provided, as well as the reasoning behind adopting it as the central analysis tool for this research. In chapter 5, it will be shown how the model can be adopted as a powerful tool for the management of product in-use information.

The SAPPhIRE model was first developed in order to provide a richer representation, at various levels of granularity, of the relationship between the function, behaviour and structure of a system than previous models, such as those of Hubka (1982), Gero, and Kannengiesser (2004), and Umeda, Ishii, Yoshioka, Shimomura, and Tomiyama (1996). The goal of the SAPPhIRE model is to represent the causality of a system, of which previous models only provide partial views (Chakrabarti et al., 2005). While several definitions for function and behaviour have been developed in the literature, those used by Chakrabarti et al when developing the SAPPhIRE model will be used here. In this case, function is considered to be intentional, and occurring at a higher level of abstraction than behaviour, the latter evolving naturally from the structure of the system and related physical laws, and being the way in which the function is achieved. The structure itself consists of the elements and interfaces that form the system and its surrounding environment. As will be seen in the model, the behaviour, and hence function, of the system is brought about through one or multiple changes of state which occur due to the specific structure of the system and the physical laws which come to bear upon it. The model is composed of seven constructs, which are related as shown in figure 4.7 and are defined in table 4.5 [based on (Chakrabarti & Srinivasan, 2009)].

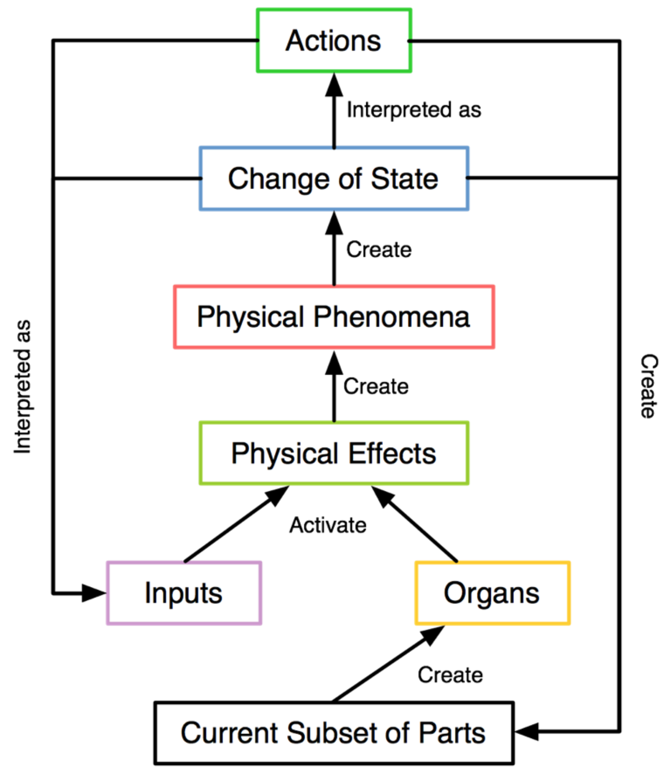

Figure 4.7 SAPPhiRE Model and Constructs

Table 4-5 Constructs of the SAPPhIRE Model (Srinivasan & Chakrabarti, 2009)

Construct	**Definition**
State change	The state of a system is defined as the attributes and values of attributes that define the properties of a given system at a given instant of time during its operation. The state change is therefore the change in these attributes between two given points in time. eg: The temperature change in a system.
Action	An abstract description or high level interpretation of a change of state, a changed state, or creation of an input. eg: Temperature drop can be considered the action of cooling of a body
Part	A physical component or interface, one of a set, the sum of which constitutes the system and its environment of interaction. eg: A body surrounded by a medium
Phenomenon	A set of potential changes associated with a given physical effect for a given organ and inputs. It refers to an interaction between a system and its environment, also known as a Physical Phenomenon. eg: Heat flow from a body to its surroundings
Input	The energy, information or material requirements for a physical effect to be activated; interpretation of energy/material parameters of a change of state in the context of an organ. It comes from outside the system boundary and is essential for an interaction between a system and its environment. eg: A temperature difference which is necessary for heat transfer between a body and its surroundings
ORgan	The structural context necessary for a physical effect to be activated, including the properties and conditions of a system and its environment required for an interaction between them. eg: Heat transfer through convection depends on the fluidic nature of the medium, the surface area of the body and the heat transfer coefficient
Effect	The law of nature governing a change, also referred to as Physical Effect. eg: Convection law governs heat transfer between a body and its surroundings

As can be seen from the arrows linking the constructs, the model is not meant to simply indicate a series of activities, rather it is meant as a logical process for understanding a causal chain within a system. Of particular importance are the connections from *change of state* and the interpreted *actions* to both the *current subset of parts* and the *inputs*. These arrows indicate that the results from the *change of state* or *action* can modify the configuration of a system, giving rise to physical, behavioural and functional changes over time. The model therefore does not only represent the spatial dimension of the product (*parts* and *organs*) and the product behaviour (*physical effects* and *phenomena*), but also the temporal dimension (*inputs*, *change of state*, *actions*). This classification is shown in figure 4.8. This characteristic of the model is important both from the point of view of offering a rich model of causality, as intended by Chakrabarti, but also from the point of view of the management of product in-use information. In section 4.1, it was demonstrated how there is a wide variety of information available concerning product performance, or behaviour, during use, including product structures, use cases, historical trends, test evaluation criteria and photographs of damaged parts, among others. As will be seen in chapter 5, the versatility of the SAPPhIRE model will facilitate the management of such a broad range of information types within a logically structured framework.

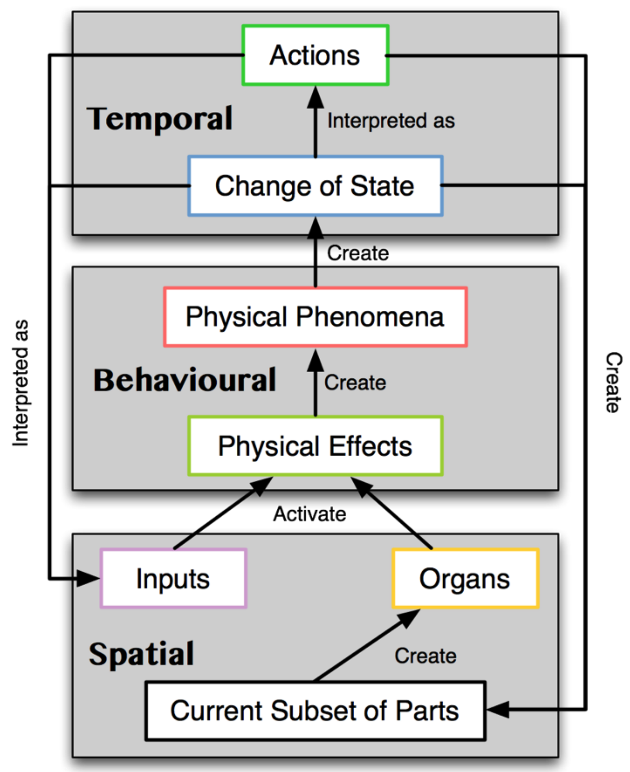

Figure 4.8 Temporal, behavioural and spatial aspects of SAPPhIRE model

Furthermore, as discussed in section 1.3.4, the ability to represent the behavioural and temporal dimensions of the product throughout its lifecycle is a shortcoming of current PLM frameworks.

The ability of the SAPPhIRE model to represent these dimensions will play a significant role in the discussion of the future of PLM in chapter 5.

4.3 Conclusion

This chapter has provided a description and analysis of the types of information collected while working with an aerospace manufacturer, as well as describing several options for analysing and managing this information, including their strengths and weaknesses. In the first part of the chapter the content and structure of testing and in-service information were analysed, and it was found that the similarities between these two seemingly disparate categories of information provide a basis for what is here referred to as product in-use information. Following this, the evolution of the author’s attempts to analyse this information and determine the appropriate means of facilitating its sharing and reuse across product development projects was presented. In doing so, the limits of FMEA and cost analysis have been demonstrated, while the SAPPhIRE model of causality has shown unique qualities which could potentially handle both the breadth of the information available, while also being robust enough to manage the varying levels of completeness of the information available. The applicability of the SAPPhIRE model for the management of product in-use information will be further explored in chapter 5.

Chapter 5 PROPOSED MODEL OF CAUSALITY FOR THE REPRESENTATION OF PRODUCT IN-USE INFORMATION

The purpose of this section is to demonstrate the benefits of representing product in-use information using the SAPPhIRE model of causality. It is proposed that the use of this model will facilitate the communication of product in-use information to engineers involved in design and product development who normally have limited access to such information. Furthermore, several scenarios and events found within the in-service and testing information collected will be presented at different levels of granularity using both detailed and simplified versions of the model. This will demonstrate how the model may help overcome the challenges associated with communicating product in-use information across present and future product development initiatives. Finally, it will be considered how the SAPPhIRE model could facilitate the representation and communication of the information, and how this model could fit within a larger information management framework.

5.1 Application of the SAPPhIRE Model to Product In-Use Information

The first, and most extensive, applications of the SAPPhIRE model were carried by Chakrabarti and his collaborators (Chakrabarti et al., 2005; Srinivasan & Chakrabarti, 2007) and were focused on supporting the conceptual design stage. The model was used both in the analysis of existing systems in order to study the relationship between the systems' structure, behaviour and functionality, as well as in the synthesis of conceptual solutions to design problems. However, the application of the SAPPhIRE model to the current project is more closely related to the work completed by Jagtap in his thesis. There, drawing on the work of Salustri, Weerasinghe, Bracewell, and Eng (2007), Jagtap made the case that by graphically representing the causal scenarios discovered in service reports, in-service information could be more easily communicated to designers. A graphical representation could also help designers to consider multiple scenarios when attempting to solve a problem, and hence lead to new, more robust designs. Jagtap also proposed that supporting information, such as photos and failure rates, could be linked to the SAPPhIRE model. In the present research, this work will be built upon in four ways:

1. The SAPPhIRE model will be applied to both in-service and testing information, further demonstrating the feasibility of combining test and in-service information within the proposed product in-use information categorisation
2. Two levels of simplification will be proposed, in order to provide designers with different levels of granularity at which to study causal chains
3. The association of supporting product in-use information with the model (in order to facilitate the investigation and understanding of the causal chains) will be demonstrated in detail, forming the basis for an overall product in-use information management framework
4. A proposal will be made for the adaptation of the model for more efficient use within the product development context

5.1.1 Causality modelling for testing and in-service information

In this section, several examples, drawn from the previously described information sources, will be used to demonstrate the applicability of the SAPPhIRE model to the representation of both in-service and development testing events. The main objective is to demonstrate how this representation can be useful for supporting designers, however by representing both test and in-service information using the same model, their similarities will also be emphasised.

The first event is drawn from the database of development TERs, and occurred during testing of the second type of product. A summary of the record is found in Table 5-1 (Note that part and build numbers have been redacted due to intellectual property concerns).

Table 5-1 Sample TER - Development Record

Date:	11/03/04
Title:	OXIDATION ON SECTION B
Section:	B
Parts involved:	Three part numbers identified
Description:	Type X coating was added to the component and is now on the new drawing. This fix was actually tested on BUILDXXX (ZZZ hrs) and found acceptable. It is planned to be additionally tested on BUILDYYY during the next test as well. Also, part was run outside of the intended design envelope. Closed.
Status:	Closed

While this is a brief summary, by discussing the event with knowledgeable engineers and through an understanding of the problems related to oxidation in this component, it is possible to represent the event using the SAPPhIRE model as show in Figure 5.1.

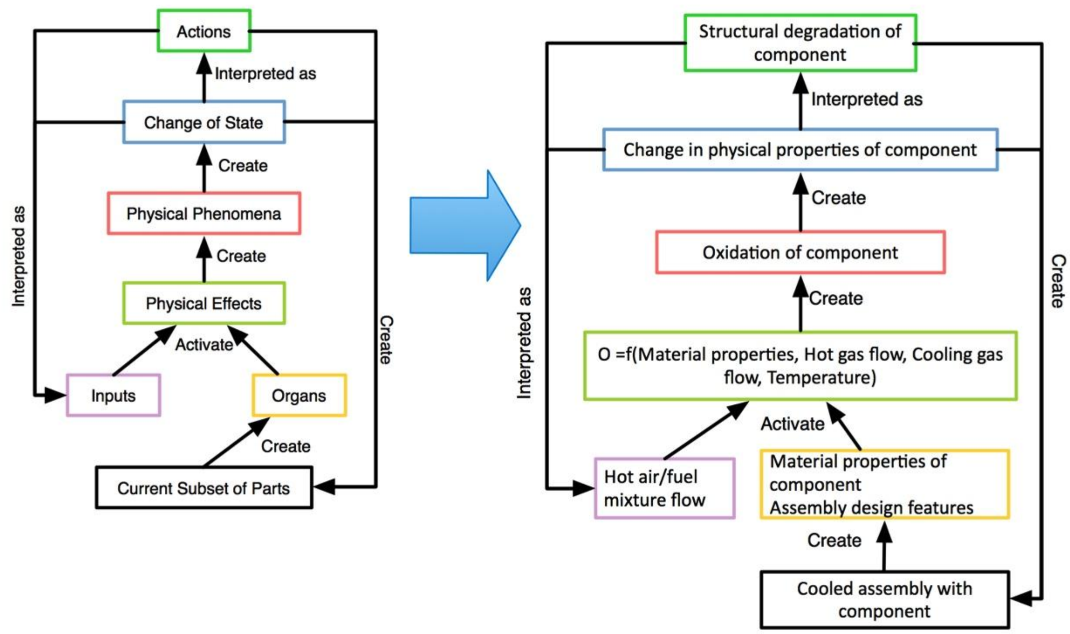

Figure 5.1 Representation of testing event using SAPPhIRE model

As can be seen, the various elements of the scenario, along with some extrapolated information, have been used to satisfy the constructs of the SAPPhIRE model. While the information has been generalised for the sake of confidentiality, in some cases the information recorded by the manufacturer is quite specific, for example the *parts* and *physical phenomena* involved are recorded directly within the database record. In other instances, such as the *inputs* and *action*, it was necessary to complete further research as to the causes and effect of oxidation on the component under consideration. Finally, in the case of *change of state* and *physical effects*, although the details were not recorded, it may be possible to fill in the sections by conducting further research, such as determining common factors affecting the oxidation process. While an analytic formula is not included in figure 5.1, relevant factors are included. Furthermore, as the *change of state* was not recorded in detail in the TER, this is left as a high level observation. This demonstrates one of the ways in which the SAPPhIRE model is flexible: although it requires thought as to how to complete each construct, if certain information is missing, a general description of the required information can be included. As will be discussed later, these models will be supplemented with product in-use information as it is collected during other events on the same or similar products, and so as the amount of information collected increases, it will be possible to define each construct at an acceptable level of detail.

Similarly, as has been demonstrated to a degree in Jagtap (2008), the SAPPhIRE model can be used to represent in-service events. In this case, the event was recorded both as a field event within a FER, and within a related PIR. An overview of the event is as follows (note that certain details have been redacted or modified due to confidentiality concerns):

Table 5-2 Sample Field Event Report (FER)

Date:	18/03/05
Title:	OIL SMELL IN CABIN
Section:	Section C / Section E
Probable cause:	Sealing arrangement
Description:	The vicinity of seal Q showed fresh and coked oil. Removal of the seal revealed wear/scoring as well as fretting on the seal surfaces (Photo No. 27). The mating seal runner diameter showed extensive cracking of the hard face coating. The contamination of the secondary air system by oil is most likely the result of the degradation of the O-ring around the seal R housing and oil scavenge tube as well as the scoring observed on seal Q combined with the cracking of the hard face coating of its mating runner. The seal R area being pre SBXXXXX is likely a contributing factor. Seal TSN:XXXX

As can be seen, the information is recorded in a slightly different format than that of a TER, as the parts involved and status are not recorded directly. However, by drawing on the content of the

FER and the PIR report, it is possible to create a relatively detailed representation of the event via the SAPPhIRE model. To begin, the focus will be placed on a single component, seal Q, and the corresponding information represented in Figure 5.2.

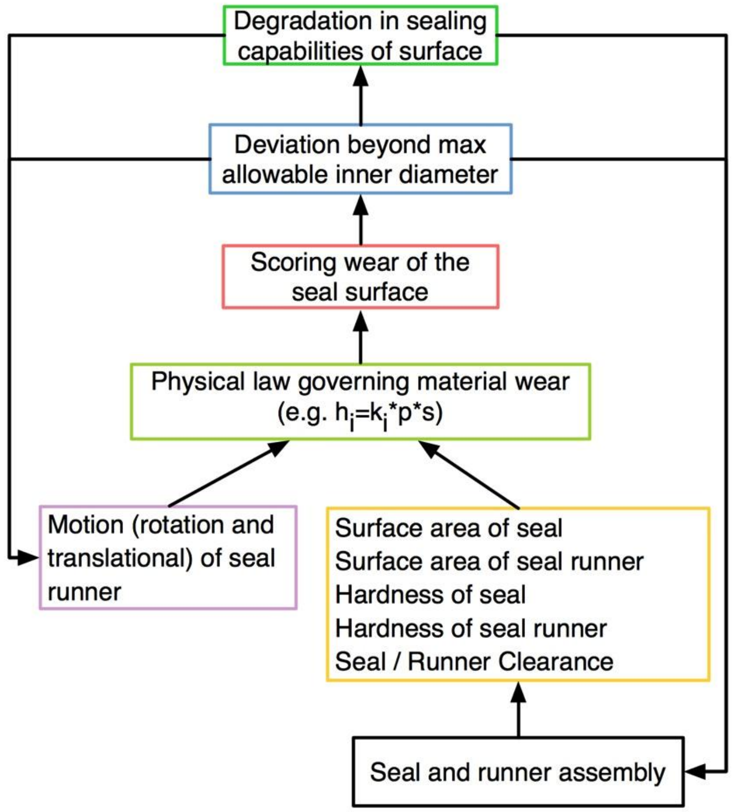

Figure 5.2 Representation of in-service event using SAPPhIRE model

In this case, as an extensive study of seal behaviour within a particular model of the first product type was conducted as part of the industrial collaboration, it is possible to complete a more detailed model. However, in both the testing and in-service examples represented in figures 5.1 and 5.2, similar information concerning product structure, behaviour and functionality are represented and communicated.

It should be noted that although the information content and structure are similar, the contexts in which testing and in-service information is collected must be considered. Information gathered from a controlled test versus that collected in the field will have different levels of confidence and accuracy, and the intent of the reports used to record this information is also different. Furthermore, a build (or version) of a certain product may be used in tests and not in the field, or a design change could entail a change in product configuration while the product is in use. In cases where such a change is necessary, service instructions are issued detailing the exact changes, including build numbers, part numbers and versioning information. Such a change may be required to address out-dated components, implement product upgrades or to satisfy specific customer needs. Therefore, it is not recommended that in-service and testing information be mixed together, rather that it be made available within a common system and using a common means of representation. As such, and based on the modelling presented above, it is believed that there is a strong case to manage both types of information within the overarching category of product in-use information.

While the models presented in figures 5.1 and 5.2 represent events and the resultant behaviour of particular components, it is also possible to create larger, more complex models, which represent the behaviour of a system. This is completed by linking models representing events at various levels of complexity within the product (for example a single component versus a sub-assembly versus a complete product) or by demonstrating how the behaviour of various components in parallel can contribute to a system's overall behaviour, or an event where the most important effects manifest at the system level. The full event described in table 5.2 is an example of such a scenario, and can be represented as shown in figure 5.3. In this case, three separate events led to the degradation of the sealing capabilities of product components. However, at a system level, these individual events contribute to the contamination of the secondary air system. As a result, the modified parts (having undergone their representative *changes of state)* from each of these three models would be used, with appropriately defined *organs* (or features), within the model of the contamination event. For conciseness, this new 'Contamination of Secondary Air System' model is simply represented by a placeholder in Figure 5.3.

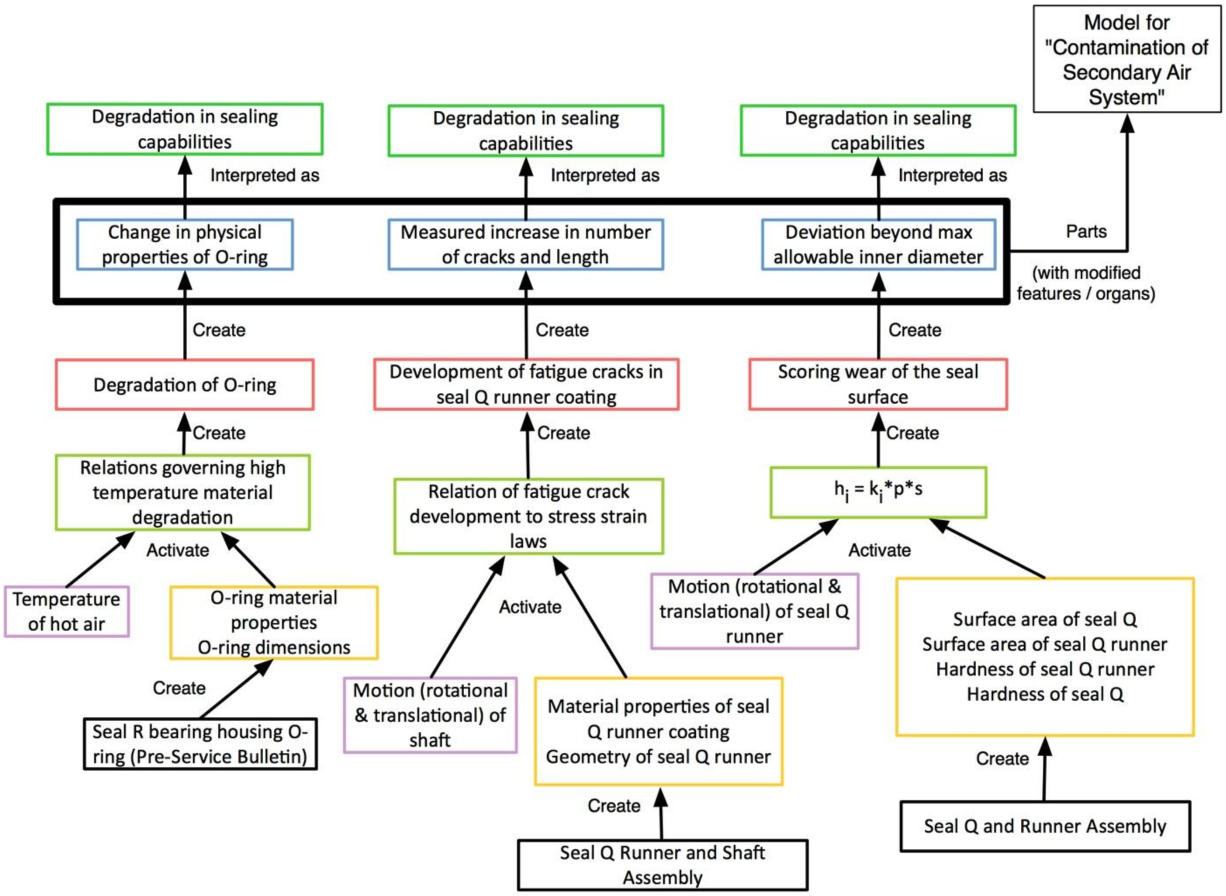

Figure 5.3 Representation of complex scenario using SAPPhIRE model

While it has been demonstrated that the SAPPhIRE model can represent a complex scenario, it is also possible to simplify the model in order to provide a high level, or summary view of a causal chain. In particular, by combining *physical effects, physical phenomena, and change of state*, it is possible to provide an overview of the structure, behaviour and function of a system which retains the benefits of a graphical representation, while being more concise and convenient. This simplification is shown in figure 5.4, with an example given in figure 5.5.

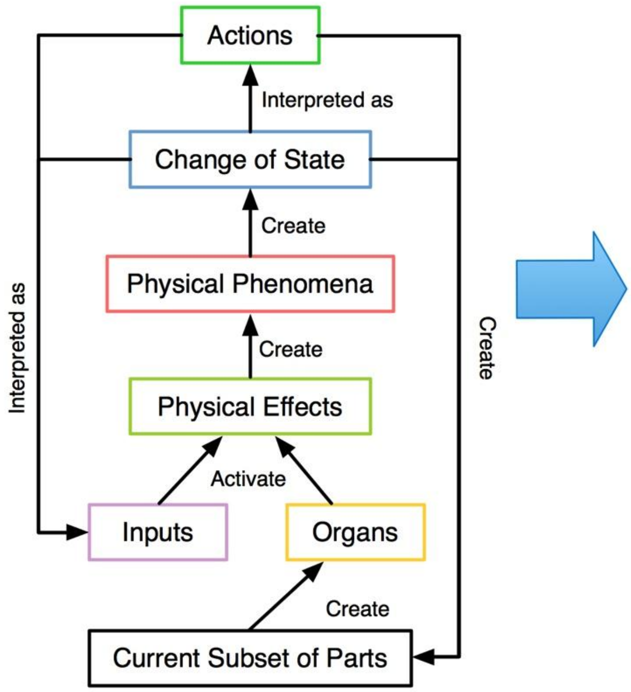

Figure 5.4 Full versus Simplified SAPPhIRE Model

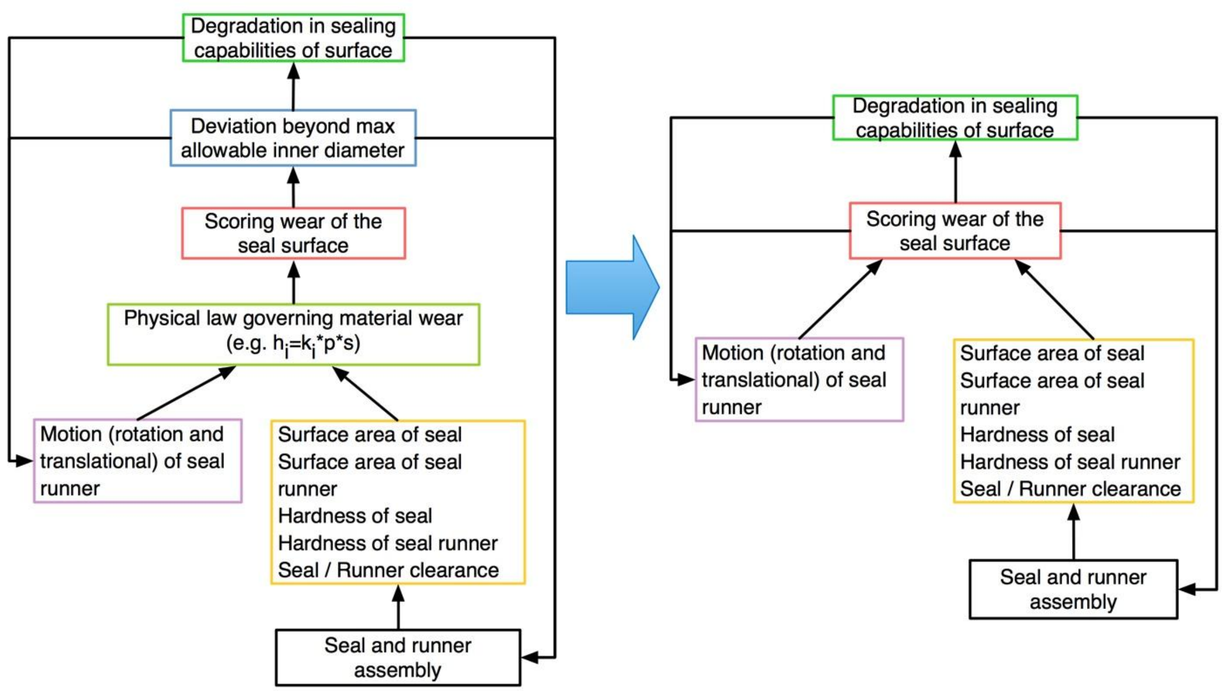

Figure 5.5 Simplified Model of In-Service Event

This simplification is proposed for several reasons. First, in reviewing event reports, the most commonly reported aspect of the system's behaviour is the observable, qualitative aspect, which in SAPPhIRE is the *physical phenomena*. Only after this is observed, are details reported concerning the constitutive laws governing this phenomena (*physical effects*) or the quantitative *change of state*. In fact, it can be argued that the *physical effect* and *change of state* constructs serve to support and provide more details regarding the generalised system behaviour as described by the *physical phenomena*. It therefore follows that a simplified version of SAPPhIRE where the *physical effects* and *change of state* are represented implicitly by the *physical phenomena* will provide designers with an adequate high level view of the relationship between the system's structure, behaviour and function. By using this simplified representation, the complex model presented in figure 5.3 becomes much more manageable, as shown in figure 5.6.

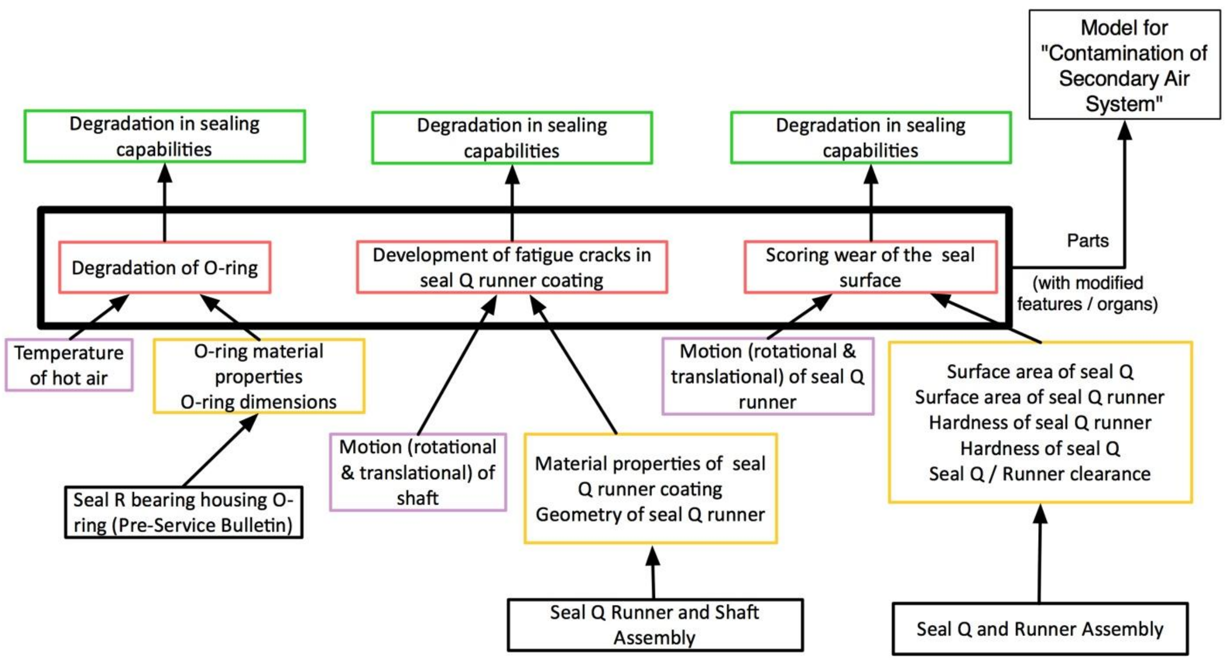

Figure 5.6 Simplified Representation of Complex Scenario

5.1.2 Communicating Product In-Use Information to Designers

As demonstrated in the previous section, the SAPPhIRE model can represent the causality of an event described by product in-use information sources. While this representation will support designers in their understanding of the behaviour of a system, there is much more product in-use information to be captured and to learn from than simply the constructs that make-up the model. For each construct, there exists related information that on the one hand allows for the identification of the construct, while on the other is necessary for completing in-depth analysis as to the causes and necessary corrective actions related to unwanted events. For example, as shown in figure 5.7, statistical data from inspection reports (6) can be associated to “Deviation beyond maximum allowable inner diameter”, showing the frequency with which this occurs on different products.

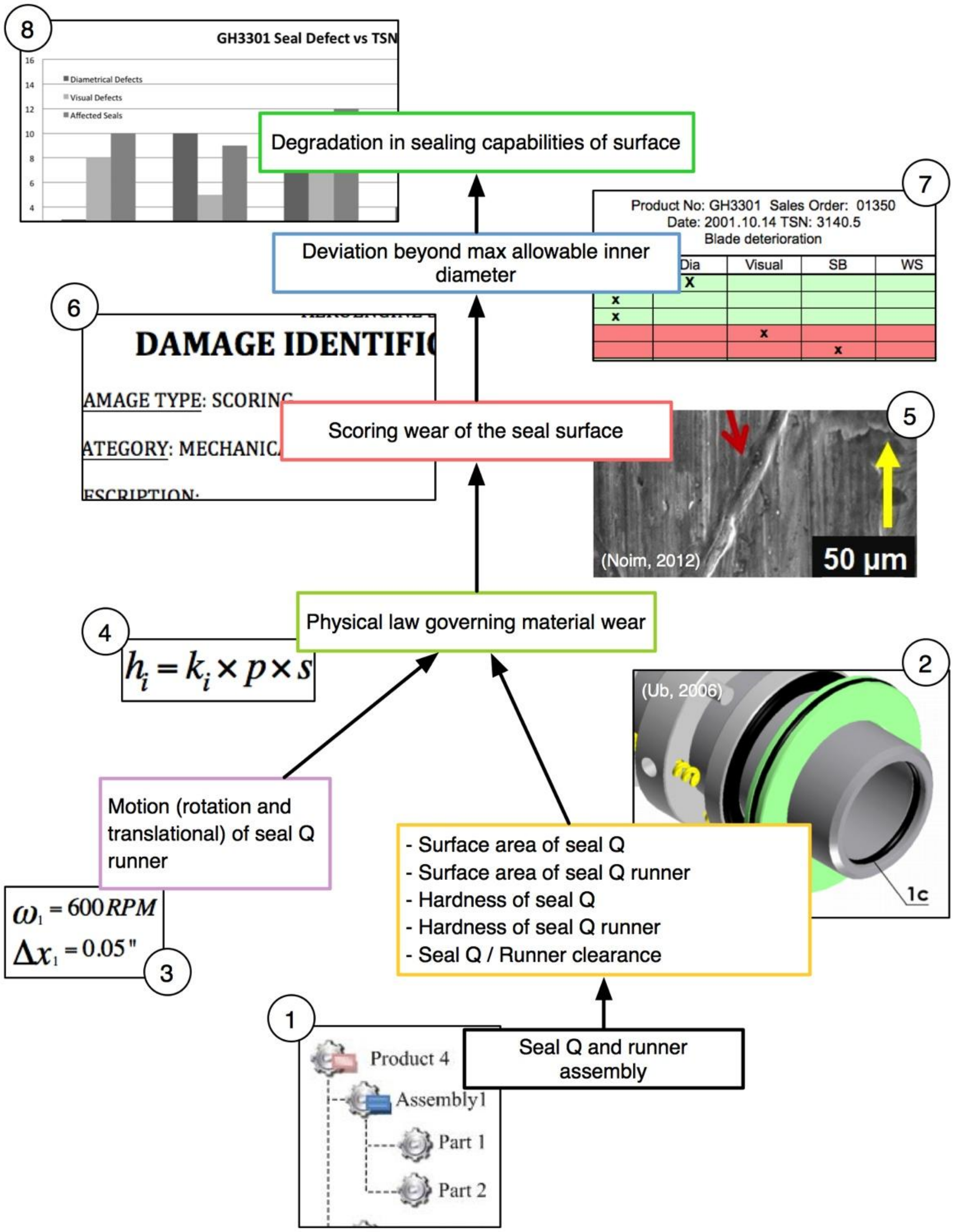

Figure 5.7 SAPPhIRE model with associated product in-use information (Noim210, 2012) (Castelnuovo, 2006)

Examples of the types of information that can be associated with the various constructs (1 to 8 in figure 5.7) are found in table 5.3. Note that while a majority of this information belongs to the product in-use category, some, such as the product structure, the CAD models, and the equations governing physical phenomena are more traditionally considered design information. As will be discussed subsequently, this combination of design and product in-use information can help facilitate the transfer of information between design and test or in-service personnel. Finally, it should be noted that the list of information types found in table 5.3 is not exhaustive, but is an example based on the typical information found when investigating the in-service behaviour of the seals in question. While this is similar to information observed when investigating the behaviour of other components, the precise information will vary depending on context.

Table 5-3 Examples of information associated with SAPPhIRE constructs (see Figure 5.7)

Number	**Type of information**
1	Product structure for in-service product configuration (or build)
2	CAD model of components of product
3	Dynamics information for component
4	Equation governing material wear
5	Photos of parts showing in-use condition
6	Identification guide for physical phenomena
7	Inspection data reporting precise change in state
8	Statistical data detailing occurrence rates for seal degradation

This association of information with the model constructs provides a richer understanding of the causality of in-use events, however the question remains as to how designers will actually access this information in a way that will support their work, and not increase their workload by demanding further time searching for information. At the most basic level, once causality is modeled using SAPPhIRE and the information is associated with the appropriate constructs, a graphical representation of the model along with links to the appropriate information sources can be provided to designers and other stakeholders in the development process.

As the model will be associated to this wide range of information, as well as to the event described by the causal chain itself, users can query the product in-use information using a variety of starting points. For example, one user could search for all events associated to a particular test build number, while another may search for all part numbers associated with a certain physical phenomena, such as blade untwist or surface wear. Providing straightforward, timely access to this type of information will directly answer the needs expressed by designers in the results of the previously described survey. This information management scenario is illustrated in figure 5.8.

While having the appropriate product in-use information linked to a graphical representation of product behaviour will make it easier to find relevant information, it is also possible to provide more direct access to designers. As previously noted, information such as design requirements, drawings, and product structures, which traditionally provide the basis for a designer's view of a product, can be related to the spatial dimensions of the SAPPhIRE model (i.e. the constructs related to product definition). This provides a direct link between the geometric definition of the product and its behavioural and temporal dimensions and is a logical entry point for designers to explore and learn from product in-use information. Furthermore, this will also benefit test and in-service engineers by facilitating efficient access to design information concerning the components under investigation or otherwise involved in a test or in-service event. Ideally, this would also help engineers understand the design rationale behind the product, thus contributing to the development of the proper corrective action.

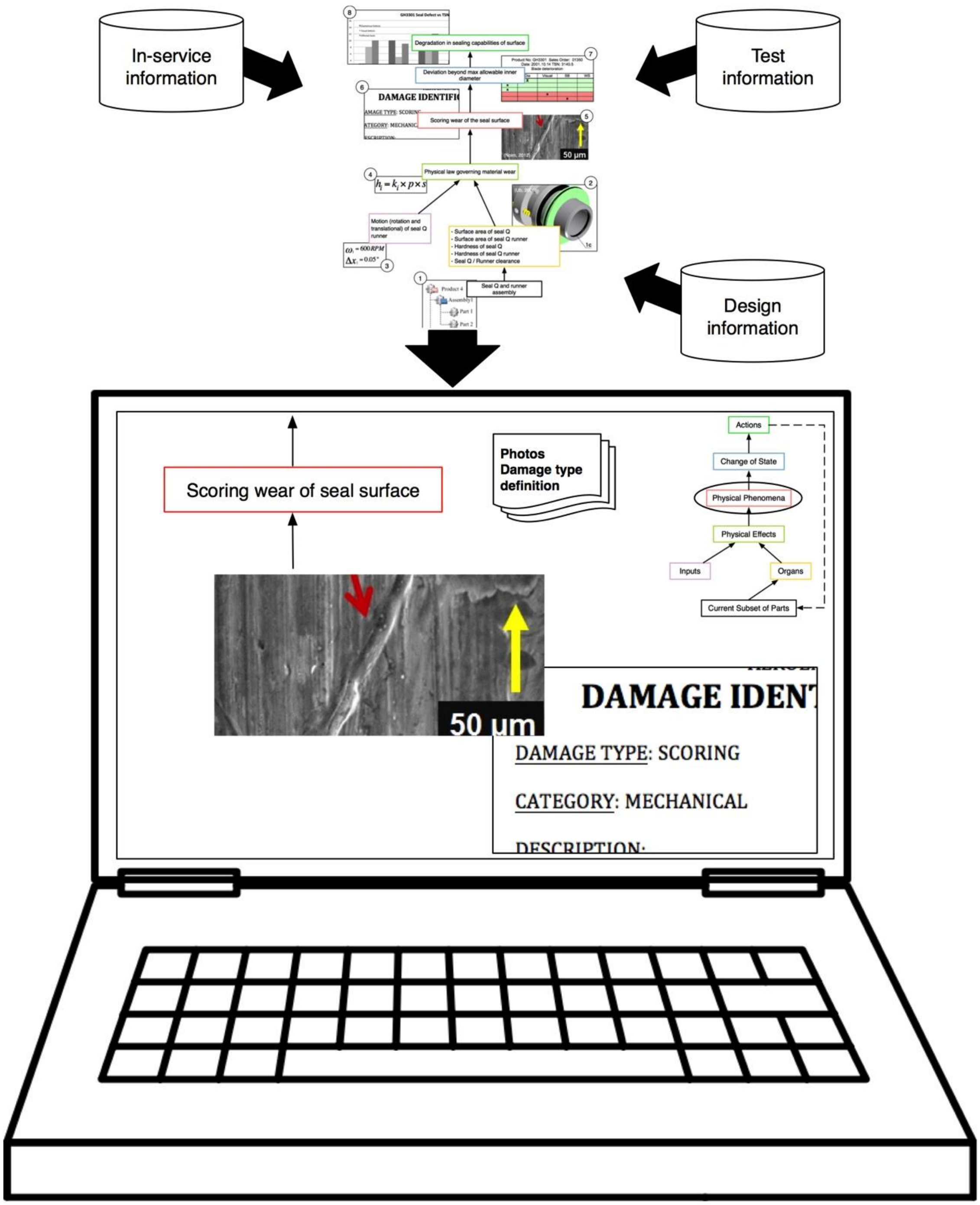

Figure 5.8 Designer-centered product in-use information sharing facilitated via SAPPhIRE model

5.1.3 An extended SAPPhIRE model for Product In-Use Information Management

While it has been demonstrated that the SAPPhIRE model as developed by Chakrabarti is applicable to the representation of product in-use information, certain shortcomings have been identified in analysing the results. This has led to a proposal for a modification to the model (Figure 5.9). This modified version has been termed the extended SAPPhIRE model as it has been developed in consideration of the information management and sharing requirements central to this research. To begin with, the terminology used in the original SAPPhIRE model does not match with that in common use in product development and PLM strategies. Certain clarifications were made to the terminology, including changing *organs* to *component features*, *physical effects* to *constitutive laws*, and *inputs* to *external inputs*.

Furthermore, the relation of *actions* to the rest of the model was unclear, as while the other constructs were clearly separate and distinct, *actions* are an interpretation of the *change of state* based on the intention of an outside observer, for example a user, an inspector or a designer. In fact, it is the *change of state* itself, which represents a physical effect on the *component features*, which are composed of the geometry, tolerances and material properties of the components, as well as external inputs, and not the actions. As a result, the *actions* construct has been replaced by *observation* This *observation* does not have a direct effect on the system, but rather the observer must make a conscious evaluation of whether the *change of state* observed requires *action*. If this is the case, the corrective action to the system requires a revision of the inputs and components to the model, which can entail a reconsideration of the relevant *constitutive laws*.

In order to represent the fact that the components of a model under consideration can form part of the components or inputs for the model of a connected system, an additional element has been added which states this explicitly. Finally, in order to differentiate feedback, whether it be towards the inputs, components or component features of a model, from the forward flow of information energy, the prior are represented using broken arrows, while the latter are represented by solid arrows.

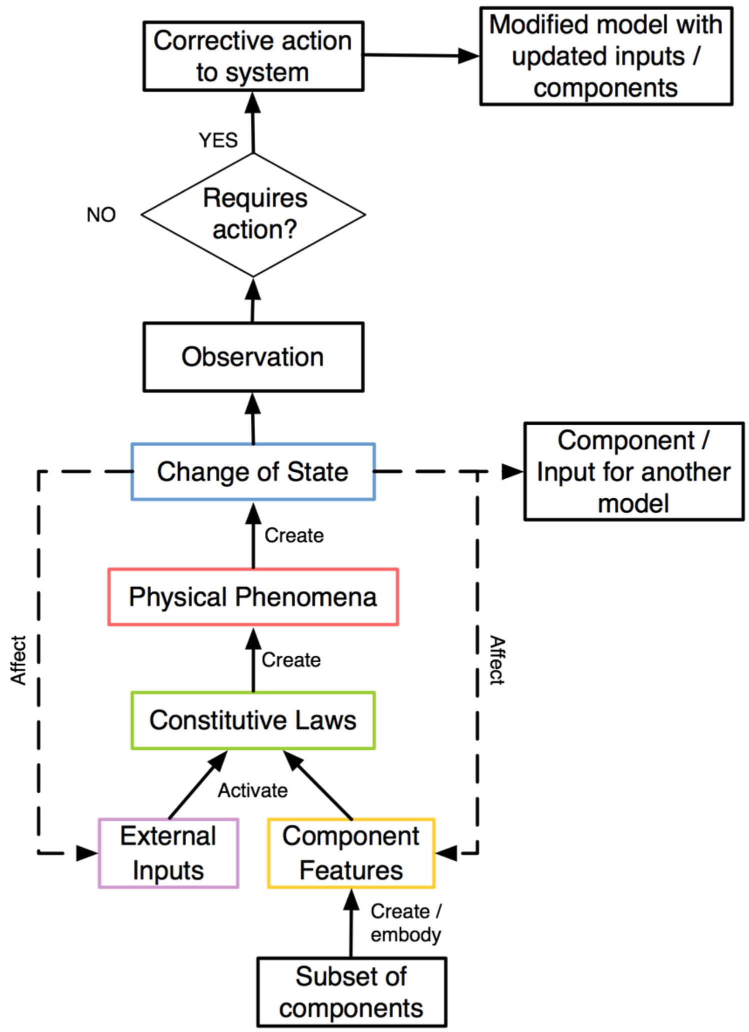

Figure 5.9 Extended SAPPhIRE Model

5.2 The extended SAPPhIRE model as a PLM framework

As discussed on section 1.3.4, the ability to represent spatial, behavioural, and temporal dimensions of the product is a requirement for the development of real product lifecycle information and engineering management systems. Current PLM systems manage information sharing based on the product structure, whether the structure is tailored to designers or other stakeholders in the product lifecycle. However, these structures remain fundamentally spatially centered, relying on an information structure that cannot easily take into account the behaviour of the product or its transition from one state to another over time, which is absolutely necessary in order to meet the requirements of a real PLM system. In comparison, the SAPPhIRE model has been shown to facilitate the management and sharing of not only spatial product information, but also that information pertaining to behavioural and temporal elements. Just as it has been demonstrated that these aspects of SAPPhIRE are beneficial when managing product in-use information, the same is true in regards to other types product lifecycle information. In this section, an argument can be developed for the use of the extended SAPPhIRE model as a framework for this real PLM.

Three examples are developed below, one based on the product in-use study presented earlier, and the others representing the evolution of the product during the design and manufacturing stages. While this proposal does not replace the need for current research into representations of domain specific information or the evolution of the product structure throughout the lifecycle, it can provide a model through which appropriate representations of the physical product can be related to product lifecycle information, while the extended SAPPhIRE model itself can represent the temporal aspect of the lifecycle. It should be noted, however, that the extended SAPPhIRE model is still in its preliminary stages and the examples developed below, in particular those related to the design and manufacturing lifecycle phases, are proposals and must be further investigated with actual case studies.

Figure 5.10 provides an example of the use of the extended SAPPhIRE model using the familiar example of the degradation of a seal. As can be seen, there are significant differences in the model compared to figure 5.2. Of particular note is the explicit inclusion of the link to the "oil leakage" model, which would be a system level model as opposed to the current subassembly level model. Furthermore, the observation of a degraded seal is not what leads automatically to a change in the physical characteristics of the system. Rather, the change of state will lead to a given change, and once this is observed, an external actor will determine whether actions leading to further modifications must take place. This more closely represents the reality of the evolution of the product throughout in-service lifecycle phase. A similar model can be created for the test phase. It should also be noted that product in-use information can be related to the new constructs. For example, at the point where a decision should be taken as to whether corrective action should be carried out, information sources detailing the necessary considerations to take into account can be associated to the model.

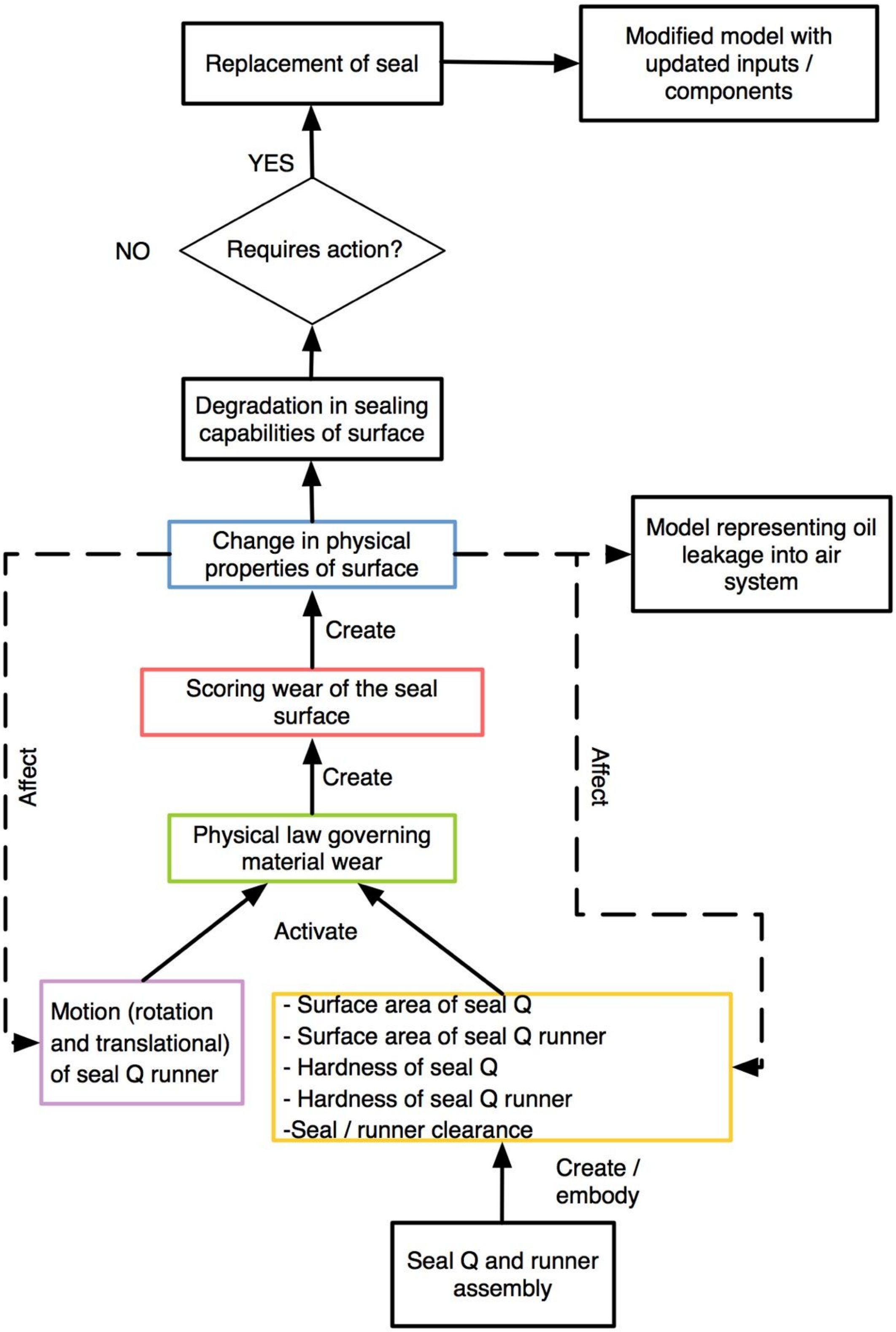

Figure 5.10 Extended SAPPhIRE model for PLM: In-Service

Figure 5.11 uses the extended SAPPhIRE model to represent a typical activity found within the design stage of the product lifecycle. In this case, an example related to the simulation of seal wear is given. While this is a hypothetical example, not one observed while working with the industrial partner, it is representative of the type of analyses completed during product design. In this case, some of the elements are familiar, such as the relevant features and the physical phenomena being observed. The major differences are related to the context in which the activities take place, which affects the information sources used to develop the model, as well as the actions taken by outside observers. In this case, the product definition is one version within the multiple iterations necessary when designing a product, and the spatial information is exactly that defined by the designers. While certain aspects can be informed through the study of product in-use information (for example the specific ways in which to model surface wear), the information used remains in the realm of product design. Furthermore, the action taken in this case will be to change the design, rather than to make a change to a physical product.

Finally, Figure 5.12 represents a scenario in which a discrepancy occurs during the assembly of a seal within a product. As can be seen, the model constructs once again exhibit relationships to the design and in-service extended SAPPhIRE models which also pertain to seals. Once again, however, the elements of the model reflect the current context. During assembly, the main concern is not the performance of the seal, but its physical interfaces with other components and their spatial requirements. When faced with a problem assembling the product, possible actions include modifying the assembly plans or the product itself, which would necessitate a design change.

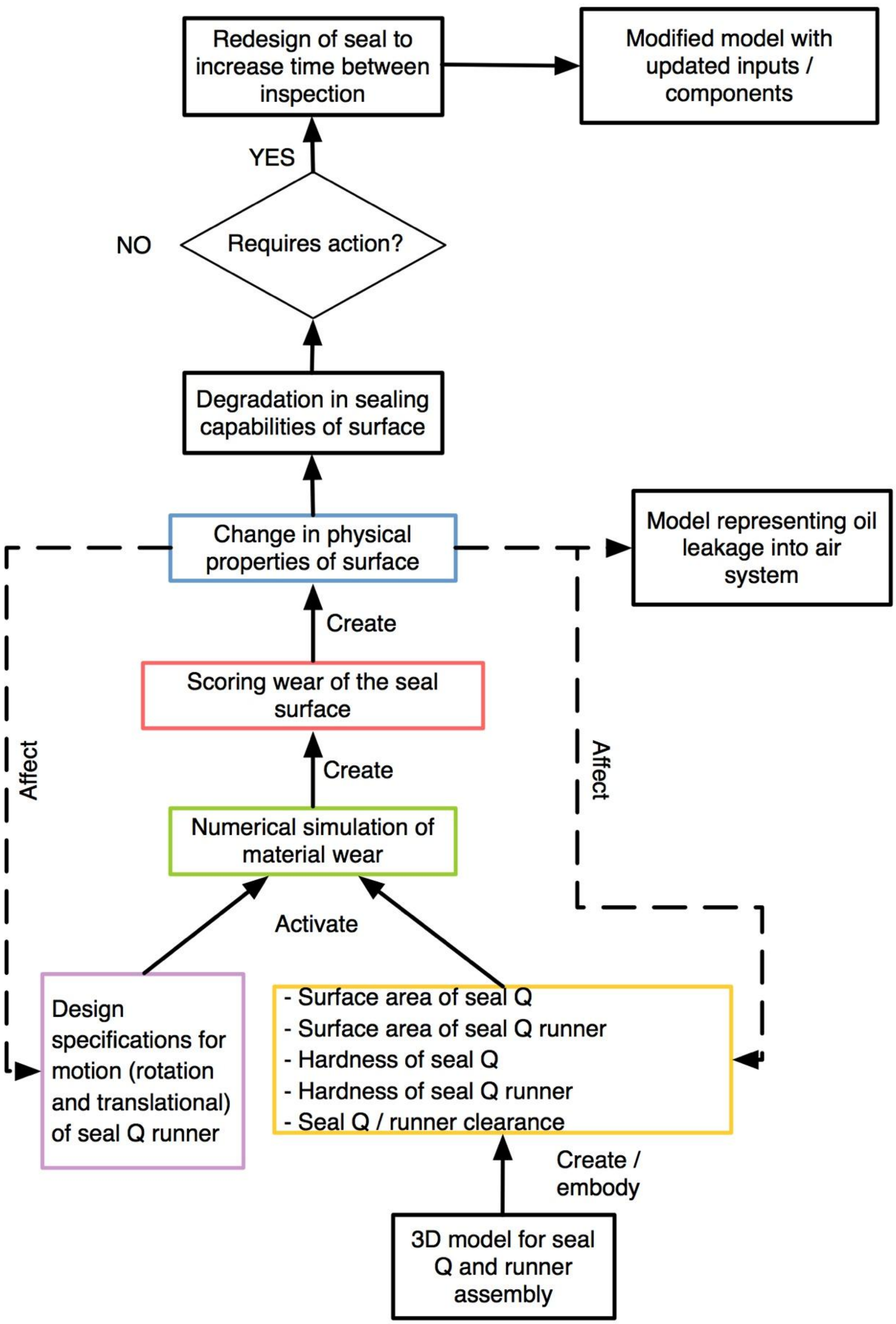

Figure 5.11 Extended SAPPhIRE model for PLM: Design

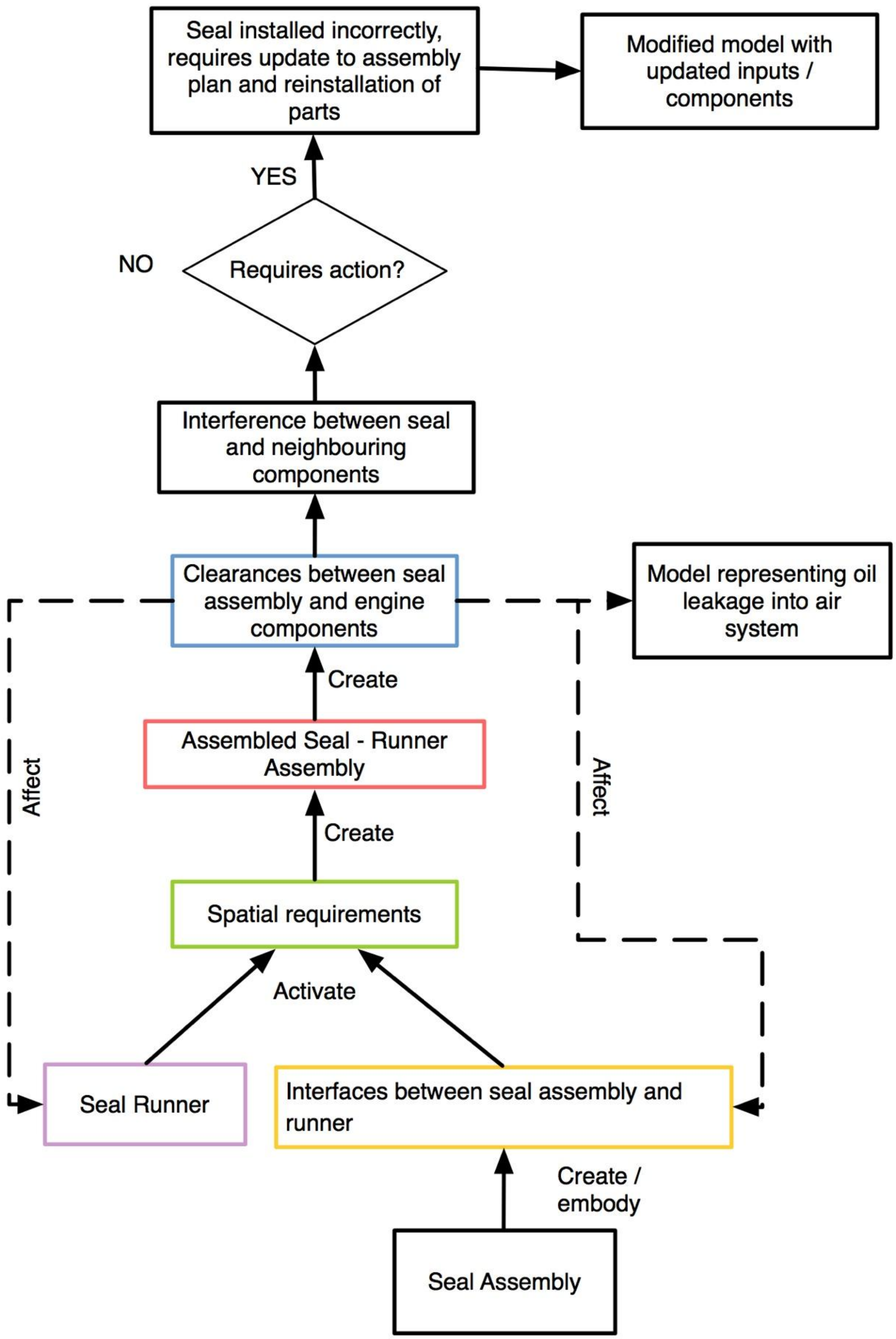

Figure 5.12 Extended SAPPhIRE model for PLM: Manufacturing

As can be seen, as the same component is traced throughout its lifecycle by means of the extended SAPPhIRE model, there are potential relationships between the elements making up these models from the design, manufacturing and in-service phases. For example, spatial requirements during assembly may be based on observations of what clearances are required once the product is in-service, which had been previously defined by an initial simulation during product design. However, the information included in a particular model must still be relevant to the context being considered. For example, the results of in-service inspections should not be mixed with design simulation results without specifying their source and the assumptions made in producing or collecting them. Further research will be needed to determine the most efficient ways to link these models together. Possible solutions include the results from one lifecycle phase being used directly as elements within subsequent models, or developing robust links between information collected at one stage and the relevant model constructs of other phases. For example, the previously described scenario where clearances are based not purely on simulations, but also on feedback from product in-use information.

5.3 Conclusion

In this chapter, it has been demonstrated how the SAPPhIRE model of causality can not only be used for the management of product in-use information, but has shown the potential for its applicability as a new strategy in the management of all product lifecycle and engineering information. By demonstrating the flexibility of the SAPPhIRE model by representing events at various levels of granularity, it can also be seen how this model is more robust than the other analyses presented in chapter 4. While this builds on the work of Jagtap (2008) and Chakrabarti et al. (2005), among others, it moves beyond what has come before by demonstrating, through detailed case studies, the possibility to manage both testing and in-service information as part of the newly proposed category of product in-use information.

By linking the causal chain description of events to the underlying product in-use information, the SAPPhIRE model can facilitate a deeper understanding, by designers as well as other stakeholders, of a product’s behaviour during both the testing and in-service lifecycle phases. While differences remain between testing and in-service information, mainly due to the context in which they were collected, by providing access to this information through a singular model, it is possible to overcome the information silos currently present in industry and facilitate information sharing. In turn, this access to information should support the design of more reliable products with lower long-term sustainment costs. Combined, these elements have demonstrated the most appropriate model and methodology to date for managing product in-use information within product development.

Finally, it has also been proposed, and demonstrated through detailed scenarios, that the extended SAPPhIRE model has applicability for the representation of a wide range of information created at various points throughout the product lifecycle. The scenarios presented point the way towards a new, robust means of managing the complete body of product lifecycle and engineering information. Further work should include the application of the extended SAPPhIRE model to real case studies based on industrial data from each stage of the product lifecycle to verify this proposal.

CONCLUSIONS & RECOMMENDATIONS

As a result of this research, a deeper understanding of development testing and in-service information has been achieved. The specific intent of this project is to determine the feasibility of the newly proposed category of product in-use information and to identify the most appropriate methodology, information structure and technology to ensure its efficient feedback and reuse throughout the product lifecycle. In the introduction, it was put forth that answering three questions could complete this objective:

1. To what extent are in-service and prototyping and testing information similar, with respect to their structure and content, and therefore able to be combined as product in-use information?
2. Is product in-use information currently treated as a coherent type of information during the design process?
3. How can product in-use information be further exploited to ensure the continued performance of a product and future products during the use phase of the product life cycle while reducing the associated sustainment costs?

The survey results and business cases developed have clarified the vital role this information can play throughout the product lifecycle. Furthermore, the in-depth review of in-service and testing information collected from the industrial partner has demonstrated that although there is a direct relationship between the two information types, they are currently managed completely separately. Therefore, chapters 1, 3 and 4 have answered question 2, demonstrating that product in-use information is not currently managed as such within industry, and this strategy has not been previously proposed within the literature.

Chapter 1 has also provided partial answers for questions 1 and 3, with the literature review indicating what similarities could potentially be found between testing and in-service information, as well as details of the proposals of other researchers for the management of product lifecycle and engineering information. While chapter 2 has not provided particular insights into product in-use information, it has explained how the current research will attempt to build on the existing body of design research in the area of information management, and in this way has contributed towards the overall quality of the final proposals.

Chapter 3 has also provided partial answers to questions 1 and 3, demonstrating the need for in-service information in design and defining those aspects which designers consider most important. By understanding this point of view, it was much easier to find the important similarities between in-service and testing information, namely those aspects describing product performance and behaviour under particular usage conditions.

Chapter 4 has provided the rest of the answer to question 1, demonstrating that testing and in-service information are indeed similar in enough important aspects to be considered as forming the basis of product in-use information. While the context under which information is gathered is an important consideration, the fact that both in-service and testing information essentially provide information allowing designers to model the causality of system, and how it relates to the systems structure, behaviour and functionality, indicates that they can both provide similar insights to designers, and therefore should be able to to be modelled in a similar fashion.

While several methodologies were considered, including a modified FMEA and a quantitative cost analysis, chapter 5 provided the answer to question 3 by demonstrating that a model that can natively represent the spatial, temporal and behavioural elements intrinsic to the product lifecycle, namely the SAPPhIRE model, is the most appropriate means of representing the causal chains described by product in-use information. Not only was it shown that the SAPPhIRE model could represent the causal chains found within product in-use information, but detailed case studies demonstrated how the model could be used as a starting point for the sharing and communication of this information among various groups of stakeholders, and in particular for the support of designers. This model has also been modified in order to represent product in-use information at various levels of granularity, allowing both in depth and high-level representations of simple and complex scenarios alike. Furthermore, the iSAPPhIRE model has been developed in order to tailor the SAPPhIRE model to the specific requirements of information management throughout the product development process in order to fully support designers through the ability to share and reuse product in-use information on subsequent development projects. This model has also been shown to have potential for use in managing information throughout the complete product lifecycle, although this work remains in its preliminary stages.

While these contributions are valuable additions to the current body of design research, it should be asked what implications do they have for the future management of product lifecycle and engineering information, both from academic and industrial standpoints?

From an academic point of view, further work should be completed examining how current, well accepted representations of the product and its evolution can be integrated within the extended SAPPhIRE model. For example, much work has been completed addressing the management of design and manufacturing information, with various frameworks developed for this purpose (Brissaud & Tichkiewitch, 2001; Huet et al., 2011). While extended SAPPhIRE provides an overarching model for the representation of product lifecycle and engineering information, there will continue to be a need for domain specific tools. For example, designers will still require the use of a properly configured product structure when designing a product. These should be integrated into an information management system where the extended SAPPhIRE model can link information from these various tools and provide a common means for accessing information that would otherwise be unavailable, or difficult to apply.

In terms of information management within industry, the conclusions of this thesis reinforce the need to focus on a combined information management strategy that does away with silos. While data mining and text-based searches will play a role in this, what is truly needed is a consistent information management philosophy which is constructed based on the needs of all those stakeholders who require access to this information. In particular, when it comes to supporting designers with product in-use information, it is necessary to develop an information management strategy that recognizes the realities not only of the designers but also those who are collecting the information. Therefore, while the designer survey presents valuable insight, a large study should be conducted to understand the context in which technicians or other engineers are collecting the information. By considering the information needs of stakeholders, the means of supporting these stakeholders, and the way in which the information is collected all from the beginning of the formation of an information management strategy, an organisation can be sure that they are creating a robust system which will ensure their competitiveness in the new integrated product-service marketplace.

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APPENDIX 1 – In-service information survey questionnaire

1. What is your specialization?
    a. A
    b. B
    c. C
    d. D
    e. E
    f. F
    g. G
    h. H

Note that the details of question 1 have been removed for confidentiality reasons

2. How many years of experience do you have with your current employer?
    a. Less than two years
    b. 2 to 5 years
    c. 5 to 10 years
    d. More than 10 years

3. For each type of in-service information, please indicate whether you currently use it in your work, or whether you believe you would benefit from using it.

    a. Reliability and failure rates
    b. Failure modes, causes and effects
    c. Photos of damaged components
    d. Scrap and repair rates
    e. Maintenance Requirements
    f. Inspection Data (after use)
    g. Service and Inspection Limits
    h. Service Center Lessons Learned
    i. Maintenance Cost (DMC in $/hr)
    j. Other, please specify

4. On average, how often do you currently use in-service information in your work?

    a. Daily
    b. Weekly
    c. Monthly
    d. Once or twice a year
    e. Once per Design Job
    f. Never

5. On average, how long does it take you to locate required in-service information?

    a. One hour or less
    b. One day or less
    c. One week or less
    d. More than one week, please specify

6. In your opinion, the in-service information you currently access is:

    a. Relevant to your daily work

    b. Up to date

    c. Complete

    d. Reliable

7. When searching for information, do you typically search by (select all which apply):

    a. Part Name

    b. Product Model

    c. Product Serial Number

    d. Part Number

    e. Part ATA Code (Air Transport Association)

    f. Damage Assessment

    g. Damage Type

    h. Date

    i. Author

    j. Time Since New

    k. Other, please specify