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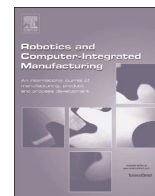
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## A framework for optimising product performance through feedback and reuse of in-service experience



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### ABSTRACT

Optimising performance of complex engineering artefacts, which are typically designed to have a useful life of several decades, becomes very difficult during in-service if lessons learnt are not used properly. The authors argue that performance of long-lived complex artefacts can be improved if adequate product in-service data is fed back to the early stages of the product life cycle. This paper discusses an inclusive life cycle approach to optimising product performance by using knowledge and experience gained during in-service. The problem is presented alongside a review of literature of relevant subject areas. A framework for in-service knowledge management is then presented and operationalised through an industrial case study. The framework is developed from the point of view of an integrated product and service provider. The findings from the case study demonstrate how in-service knowledge can be captured, fed back and reused for the design and manufacture stages of the product lifecycle. This enables designers to learn from in-service product performance by informing subsequent designs with in-service knowledge, and consequently improving the through-life product performance.

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### 1. Introduction

Engineering product development, in the late 20th century, has evolved from taking linear and sequential steps to a more integrated life cycle approach [1]. This was perhaps driven by the evolution in information technology (IT) which led to the emergence of concepts like computer-aided design and manufacture. These have been commonly used in product development and as a result, making the product development process more automated by requiring less human effort. This consequently reduces the development time and errors. Furthermore engineering artefacts are becoming even more complex, consisting of several major systems and/or sub-systems. These systems could be any combination of structural, mechanical, electrical, software or electro-mechanical components. Also, it is very likely that in practice, one or several sub-systems of such complex artefacts are designed and/or manufactured by different original equipment manufacturers (OEMs) [2]. When such an artefact is put into service, it is expected to perform according to its design requirements. However, if such requirements are not met either as a result of failure

or non-performance, it can be brought back to a running state through maintenance and repair or in some cases, through upgrades.

Ideally, the lessons learnt during the useful life of a product, in the form of in-service knowledge and experience, are expected to be used to improve subsequent designs of parts-of or the entire system. However, in practice, OEMs find it difficult to collect, feedback and reuse in-service knowledge for design improvements [3,4]. Also OEMs, who need to maintain regular contacts with customers so as to gain field and operational product knowledge, sometimes have misapprehensions about working environments, load and operating parameters which their product is subjected to [5].

This paper discusses how OEMs can continually optimise product performance by using knowledge and experience gained while their products are in-service. The paper also explores how experience gained in-service can be used to improve the design and manufacture of new products. This paper is an extended version of the conference paper titled: "A framework for optimising product performance through using field experience of in-service products to improve the design and manufacture stages of the product lifecycle", which was written previously by the authors and is now being re-written for the purpose of journal publication. This paper also draws upon previous literature in the life cycle knowledge management, through-life engineering, and

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product-service systems fields, through a taxonomic and captious review. The literature review is intended to provide theoretical underpinnings for this research focusing on the shift in product development paradigms and the challenges companies face with respect to in-service knowledge capture, feedback and reuse. A framework for in-service knowledge management, which was previously proposed in the conference paper [6], is developed further and then operationalised through an industrial case study. The primary aims of this paper include:

- Developing the in-service knowledge management framework.
- Operationalising the framework by demonstrating how it enables the capture, feedback and reuse of in-service data for through-life product optimisation.
- Apart from the primary aims, the paper also focuses on the following:
- Exploring the shift from traditional product development to a more integrated approach, which requires not just integrating product and services but also adopting a through-life or whole life cycle approach to knowledge and information management in each stage of the product life cycle.
- Identify the challenges that manufacturing companies face in managing and learning from life cycle knowledge, especially during the in-service stage.
- Explore the opportunities for manufacturing companies when they adopt new life cycle paradigms and what factors to consider, with respect to life cycle knowledge management, if such paradigms are adopted.

## 2. Product life cycle knowledge management

### 2.1. Overview

The concept “life cycle” is popularly used to describe the stages a living organism covers from the time of birth until death. Engineering artefacts go through a “lifelike” analogy similar to that of a living organism: Conception–Birth–Growth–Adulthood–Death [6]. In engineering practice abstract functional models, called life cycle models, are used to represent the conceptualisation of a need for an artefact (a system), its realisation, utilisation, evolution and disposal [7]. The generic product life cycle is shown in Fig. 1. Ideally, there exist some forms of iterative feedback loop between each life cycle stage, through which lessons from later stages can be used to improve upon decisions made and processes in earlier stages. This feedback loop exists in much more detail between the design and manufacture stages of the life cycle – through the use of product development philosophies such as Computer Integrated Manufacturing (CIM). Conversely, the feedback loop is less formal between the utilisation (in-service) stage and earlier stages of design and manufacture. Perhaps this is either due to the communication gaps that exist between design and service engineers or that in many cases, customers are usually unwilling to share product information during service [6]. The reasons for these, the authors argue, are because of the lack of an integrated through-life approach to delivering the product life cycle (especially during the utilisation stage), the different perspectives to the product life cycle that exists and other challenges surrounding both traditional and recent approaches to product development.

### 2.2. Different perspectives to the product life cycle

In [6], the different perspectives that exist in product life cycles as interpreted from the INCOSE systems engineering handbook [8] was described. Fig. 2 shows a representation of such perspectives compared with the generic life cycle model. If a single company is responsible for delivering all or most stages of the life cycle, it is easier to manage the feedback loops and interactions that exist between life cycle stages. If on the other hand, one or several stages of the life cycle are delivered by different companies, it becomes more difficult to fully implement and manage this feedback loop; it becomes even more complicated when a product consists of sub-systems that are designed and/or manufactured by several companies [6]. This is the case for most traditional manufacturing companies, who focus primarily on producing physical artefacts, while services, such as installation, maintenance, training, were seen as add-ons to the already developed and produced artefact [9].

Another aspect of the multiple life cycle perspectives is that it is common that the life cycle of the commercial high-tech manufacturer may repeat several cycles for every one cycle of a high-tech systems integrator when both life cycle perspectives are compared. The rationale behind this is that the life cycle stages of most complex integrated systems, such as aircrafts, power plants, marine systems, etc. run for longer periods with their useful life amounting to decades. However for the high-tech manufacturer, the life cycle time span is shorter with most of its life cycle stages coming before the operations (utilisation or in-service) stage of such complex integrated systems. This, as mentioned earlier, is because traditionally, manufacturers have primarily focused on the early stages of design/development and production while services are sold as add-ons in the utilisation stage. In some cases new sub-components of the system may have to be re-developed or provided as spares or design upgrades in order to keep the system running; hence repeating the production cycle several times before disposal of the system. Fig. 3 shows the analogy, combining the life cycle of the systems integrator (on the top of the figure) with that of the manufacturer – repeating itself several times. The in-service stage has deliberately been drawn with a longer arrow to indicating its longer time span. Therefore, in order for both the high-tech manufacturer and the systems integrator to fully optimise through-life product performance, they both have to understand how their respective life cycle stages interact [6].

In traditional product life cycle models, most products are designed and manufactured, by the OEM (high-tech manufacturer) and then sold to the customer who operates the product. Also, traditional life cycles currently have development, manufacturing and provision of products and services happening in separate processes [10] causing a disconnect between the early life cycle stages (product development and production) and the in-service stage. Another approach for manufacturers would be to adopt a more service oriented product life cycle business model as described in [9]. In such an approach, the manufacturer gets more involved in the utilisation stage providing support services and taking responsibility for the product during in-service [10].

Product life cycle and business models for companies have traditionally been based on a product delivery paradigm – i.e. making and selling products with little emphasis on after-sales support [11]. However, there is now a shift in paradigm where product and service offerings are integrated to deliver value to the



Fig. 1. Generic life cycle model [7].

Typical High-Tech Commercial Systems Integrator

Study Period				Implementation Period			Operations Period		
User Requirements Definition Phase	Concept Definition Phase	System Specification Phase	Acq Prep Phase	Source Select. Phase	Development Phase	Verification Phase	Deployment Phase	Operations and Maintenance Phase	Deactivation Phase

Typical High-Tech Commercial Manufacturer

Study Period			Implementation Period			Operations Period		
Product Requirements Phase	Product Definition Phase	Product Development Phase	Engr Model Phase	Internal Test Phase	External Test Phase	Full-Scale Production Phase	Manufacturing, Sales, and Support Phase	Deactivation Phase

ISO/IEC 15288

Concept Stage	Development Stage	Production Stage	Utilization Stage	Retirement Stage
			Support Stage	

Fig. 2. Life cycle perspectives, adopted from [8].

customers [12]. These are referred to as product service systems (PSS), described as a situation where a company fulfils functions and provide services to end-users without transferring ownership of the product to them [4]. This approach enables OEMs to be responsible for the whole-life of their products, conceiving, making and delivering products and services to meet customers' needs. Examples of companies which have adopted PSS in diverse applications include the likes of Rolls Royce, IBM, Xerox and Canon [4]. Rolls Royce for example, offers 'power by the hour' and 'Total Care' rather than just selling jet engines and spare parts to customers [9]. When the interaction that exists between the OEM and end-users is business-to-business, it can be referred to as industrial PSS or IPS<sup>2</sup> as described in [10]. The implication of the PSS paradigm is that through-life service support is of great importance [11].

Antecedent literature [4,10,11,13], suggest that the PSS paradigm presents companies with the opportunity of learning through the life of a product, having a broader scope and motivation to learn from their involvement in in-service activities [4]. These emphasise the need for good knowledge and information management (KIM) in PSS type companies even more than for traditional product offering companies. This is because of the nature of the business models PSS offer, which take on more

liability for the products by offering customers some form of guarantee in form of either guaranteed function, product availability or results [10].

2.3. Knowledge and information management through life

There are four key activities in KIM – the creation, mapping, retrieval, and use of knowledge [14]. Other researchers may describe these activities as three stages: knowledge capture, feedback and reuse. In early stages of the traditional life cycle, much of KIM is driven by the need to have a more efficient and cost effective product development process. The close links between design and manufacturing processes enable the manufacturing companies to adopt any of several manufacturing strategies such as, lean manufacturing, just-in-time, concurrent engineering, cellular manufacturing, agile manufacturing, responsive manufacturing, holonic manufacturing, distributed manufacturing, and collaborative manufacturing [6]. The use of computer aided tools during design and manufacturing aids not just the creation, mapping, retrieval and use of knowledge, but also eases the exchange of knowledge between design and productions teams. Computer Integrated Manufacturing (CIM) is one approach that companies have used to achieve this. CIM which was originally

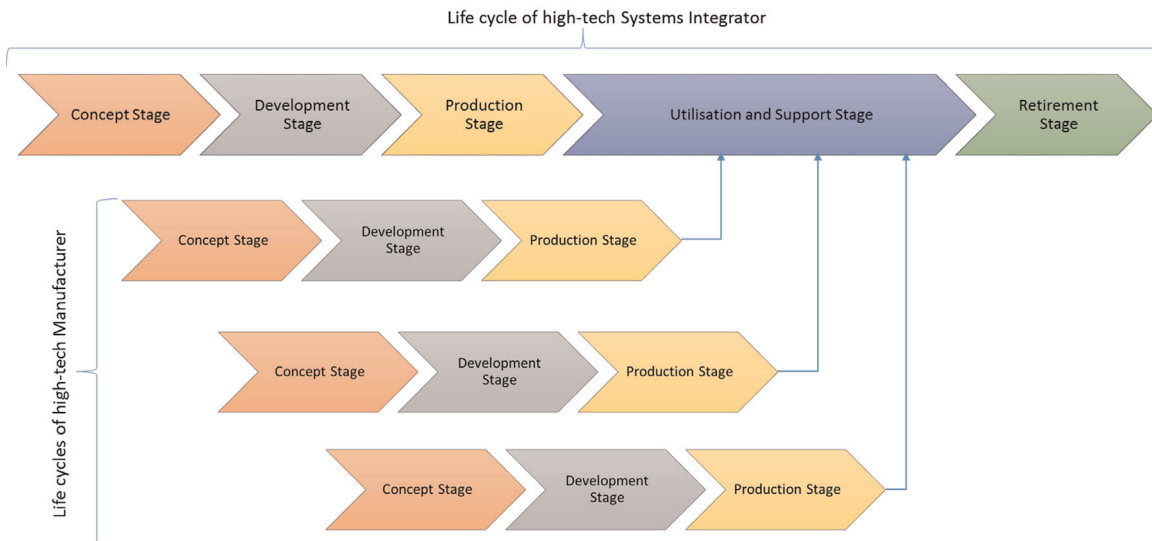


Fig. 3. Life cycles of a manufacturer and systems integrator.

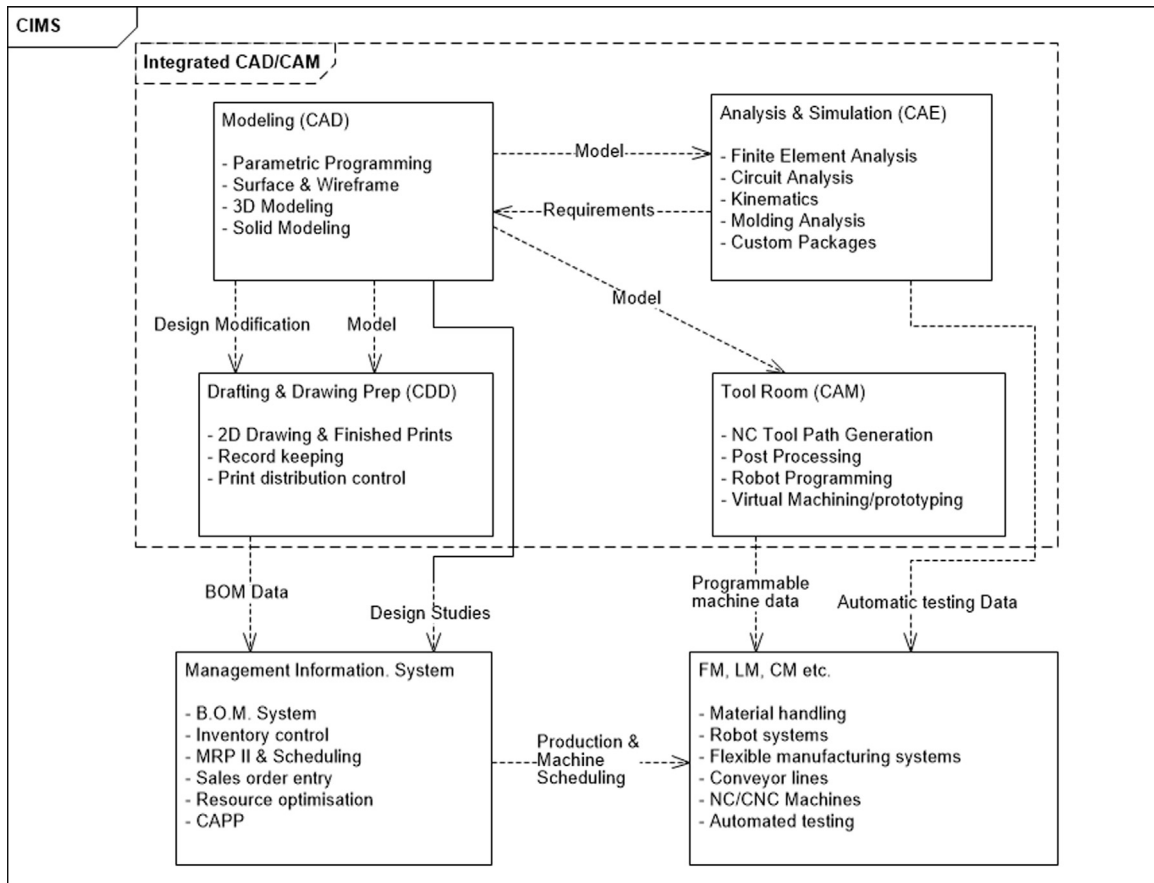


Fig. 4. Computer Integrated Manufacturing System (CIMS).

proposed by Dr. Joseph Harrington in 1973 in the seminal book entitled “Computer Integrated Manufacturing” [15], became well known in the 1980s [16] and is now popularly known as CIM systems (CIMS). CIMS integrates the IT and management systems, alongside all planning and control activities required for product development [17]. Hence, CIMS provides a supporting framework for decision making and managing both product development and KIM processes. Fig. 4 shows the interpretation, by [6] of CIMS from relevant literature [15–18] in the area of integrated design and manufacturing. This consists of the integrated computer-aided design, manufacture and engineering (CAD/CAM/CAE) as well as additional managerial, planning and control activities.

During in-service, KIM is mainly achieved through the use of a computerised maintenance management system (CMMS). This stores all the service requests, maintenance records, spare part consumption details and other operational records of the product (such as usage, environmental, and loading data). However, in traditional life cycle models, this is not integrated to other life cycle stages because CMMS are usually owned and maintained by either the customers or third party service providers making access to OEMs very difficult. Igba et al. [6] argue this is because, customers are either unwilling to share information with OEMs or due to the difficulty in getting third party providers to comply to OEMs standards. Furthermore, sensing technologies such as condition monitoring systems (CMS) and supervisory control and data acquisition (SCADA) systems can be used to monitor in-service product performance. These systems also require some form of KIM.

In summary, for traditional life cycle models, the independence of key stages prompts companies to have separate systems and processes for the key KIM activities, hence having separate CIMS,

CMMS, CMS and SCADA systems for KIM. Apart from this, due to the ease and power of computing, different departments and teams within the same organisation create bespoke tools and databases for their specific KIM needs. These together with the different systems for KIM gives rise to what Huby et al. [19] described as “Islands of data”. The next section seeks to address this challenge by proposing a framework for integrated KIM for the PSS life cycle.

### 3. In-service knowledge feedback and reuse (industrial case study)

This section presents an in-service KIM framework for PSS companies, which is operationalised through an industrial case study on gearbox in-service data feedback to design. The aspects of the framework that have been explored in the case study are in-service data capture, feedback and reuse, which make up the key activities of knowledge management proposed in [14].

#### 3.1. Literature review

Product design makes certain predictions about the manufacture and construction of the product [11]. Such assumptions could be the duration and cost of production processes, loads and tolerances, durability, to name a few. Therefore, it is important that the models designers use to make these predictions are accurate, which can only be validated by comparing predicted outcomes with actual outcomes [11], emphasising the need of in-service data feedback to designers to fulfil this purpose. Markeset and Kumar [3] argued that a product’s reliability, availability, maintainability



and safety (RAMS) characteristics during in-service are an important part of product quality since these characteristics determine if the product performs according to its original design specifications. Hence as Madu [20] suggests, product reliability is closely related to both product quality and the quality of the processes involved in delivering the product. During in-service, knowledge gained can be used for redesigning and reconfiguring the product [10], where the latter involves either extending or downgrading of product service contents or modules. A previous look at service knowledge and maintenance literature by [21] suggested that very few formal approaches of service knowledge capture and reuse exist. It was further noted in [21] that service and maintenance literature are tending towards intelligent monitoring, adopting techniques such as prognostics, diagnostics and health management, through CMS and SCADA technologies. However, these techniques do not include design feedback mechanisms [21]. Of relevance to this paper, from preliminary literature exploration in [2,6], is how companies currently learn from in-service experience to optimise their product performance and the future trends.

Manufacturing companies with traditional business models typically get most of their in-service information through warranty and spare parts data, customer's complaints and information from service personnel [3,6]. Unlike traditional life cycle business models, PSS types have the ability to collect information which was only accessible to the customer or by feedback from service personnel [10]. This offers companies with PSS models opportunities to learn from product usage by customers and use this knowledge for IPS<sup>2</sup> design or redesign process [10]. PSS also provides companies with the opportunity to develop increased intellectual knowledge [5], because they are in charge of all aspects of the life cycle, gaining control over the knowledge and competencies required for delivering the entire life cycle of the products. Also PSS companies are efficient and competitive only if their products are developed with features such as ease of maintenance, possibility of being upgraded, having built-in sensors for collecting in-use operational data and documenting maintenance activities [9]. However, previous PSS literature [10,22] indicate that the loops that exist between service and design personnel are more reactive than proactive. This suggests that just like traditional life cycle paradigms, companies with PSS models still face some challenges with respect to feedback and reuse of in-service data [10,11,13,21,23]. Also a previous case study on three companies done in [24] found that none of the companies actually learnt from in-service data feedback to inform new product developments.

In [23], a service knowledge reuse framework for engineering design was developed. They also identified the service issues and service knowledge that have an impact on product design, which was validated through industrial case study interviews with designers, service engineers and technicians. This led to the development of service ontology for a formal description of concepts which form the knowledge base. Baxter et al. [21] also developed a knowledge management framework to support PSS design, looking at knowledge collection, feedback and reuse for three core elements: design, manufacturing capability and service knowledge. Goh and McMahon [4] looked at improving in-service knowledge reuse by developing codification and classification techniques of in-service records making them more semantically meaningful, making statistical analysis and data mining easy and accurate.

The following conclusions with respect to in-service knowledge capture feedback and reuse have been drawn, as key themes that resonated across the literature reviewed for the purpose of this research:

- Most feedback to design and manufacturing only happened

after field failures had occurred [6] and that feedback processes are generally ad hoc and informal, although formal approaches like engineering change request exists [4].

- In-service data is usually being managed in stand-alone databases [2,19] making accessibility of data difficult for design engineers, in some cases engineers were not aware such data existed.
- Design engineers are most of the time remote from the problems experienced in the field by operations [4,14].
- Service personnel hardly take part in product development, and there is a lack of link between service and new product development teams [23].
- In-service knowledge capture, feedback and reuse has more focus in PSS companies who require data to continually optimise their product and service offerings [9,10].
- Motivational and organisational factors make in-service feedback problematic and difficult [4,25]. McMahon and Ball [13] termed this as the socio-technical challenges.

In summary, the reviewed literature have attempted to address the above listed issues, especially in [21,23], frameworks for service knowledge were developed. However, the work of [21,23] focused on developing ontologies for service knowledge feedback and identifying service issues and knowledge that have impact on product design. This article aims to take literature further by developing a framework for PSS KIM which encapsulates the flow of knowledge across the life cycle, conceptualises the systemic interactions between the different domains (i.e. design, production, service) in the life cycle, and finally identify the systemic interactions between the PSS companies, their customers, suppliers and third party service providers. This enables the PSS organisation in identifying the requirements and constraints necessary for the capturing, feedback and reuse of PSS life cycle data.

### 3.2. Research design

An action research approach was adopted by the authors, since the research is conducted in real-world environment in an industrial context and not in a laboratory [26] and since it seeks to contribute both to academic theory and practical actions [27]. Also the researcher, being embedded in the organisation, worked together with key stakeholders to explore and structure the problem – so as to develop a shared understanding, identify tools and techniques that will address the problem area, implement interventions that would meet the practical needs of the stakeholders and eventually reflecting on the process and outcomes. A case study was used to drive the problem solving process, and the method of data collection was done through field notes taken by the researcher during workshops, meetings and discussions between stakeholders. Some of the stakeholders involved in the process include: design engineers, service personnel, and quality and inspection specialists. Apart from taking field notes, the researcher also involved key stakeholders in the framework design right from the early stages so to get their inputs, as they are more conversant with the underlying processes and systems within their respective domains in the business. This was done via phone calls and email exchanges with stakeholders making it easy to get access to stakeholders who were remotely located.

### 3.3. Developing the framework

The framework was developed through an extensive stakeholder analysis so as to identify the suppliers, input, output, owners and users of PSS life cycle data and represent their interactions in a systematic way. The research methodology used to develop the framework integrates multi-perspective systems

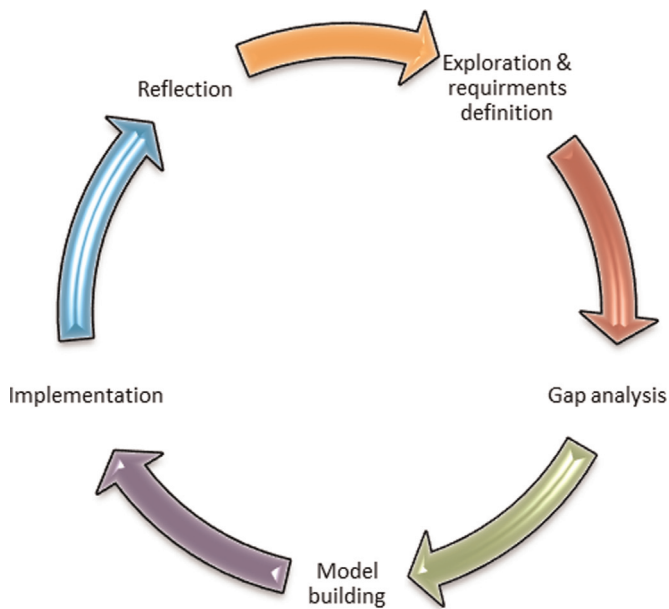


Fig. 5. methodology used to develop the framework.

within different domains i.e. design and in-service. The modelling process was done with a five staged methodology – exploration and requirements definition, gap analysis, model building, implementation and reflection (see Fig. 5). These stages are similar to the action research problem solving stages described in [28], but have been modified to suit the context of this research. This article will discuss the first four stages only. This is because the reflection stage is an ongoing continuous process which learns from the interventions (changes) made by the action research problem solving cycle and uses the lessons to either improve subsequent iterations of the problem solving cycle or as inputs for other problem situations. This is closely related to popular continuous improvement approaches where changes made are continuously monitored and improved.

### 3.3.1. Exploration and requirements definition

Bearing in mind the findings from [11,13,21,23,29,30], with respect to the various factors that need to be considered during feedback of service data for product design and redesign, this research sought validate these findings and develop them further. The exploration and requirements definition stage began by defining the requirements of the stakeholders involved in PSS life cycle data capture feedback and reuse. This was done during discussions with the stakeholders by asking key questions surrounding the key KIM activities. For example, design engineers who participated in the case study require better access to detailed and accurate field failure and maintenance data, however, service engineers require systems and processes that would not add extra time and effort if they need to supply more information to the design engineers. Some of the questions asked to the stakeholders in order to identify their requirements and needs include

- What kinds of in-service data do you need for design and redesign?
- Which kinds of in-service data do you currently use for design and redesign?
- How do you currently capture and feedback data?
- What kinds of data do you capture?
- How do you reuse in-service data?

By asking these questions the requirements and needs with

respect to each domain were identified. These, together with those identified in literature were noted and mapped into a value stream. This was achieved by a mapping technique used to define the suppliers, inputs, outputs and users of PSS life cycle knowledge, especially during in-service.

### 3.3.2. Gap analysis

A gap analysis was done to determine the current and future (ideal) states of the PSS life cycle KIM, i.e. “where we are” versus “where we would like to be”. Typically, the gaps identified from a gap analysis can be used to design the required action plans so as to meet the requirements and needs of stakeholders. The gap analysis was done by comparing current systems and processes within PSS life cycle data flow with ideal ones based on the requirements provided by the stakeholders. One of the primary gaps identified was the lack of integration of inter-domain systems and processes for PSS KIM. These include systems for storing design, manufacturing and maintenance data and their supporting processes, for example systems for CIMS and CMMS were not fully integrated and are managed in isolation by different domains. Other gaps, such as interoperability and varying semantics between data sources from different domains were identified and taken into consideration. These would be explained in detail in Section 4.

### 3.3.3. Model building

The data flow requirements and the identified gaps between domains were used as inputs for building the model for the PSS life cycle data framework. The model was constructed by combining two modelling methodologies—systems modelling language SysML and data flow model diagrams (DFDs). These two methods were deliberately chosen due to their respective modelling power. SysML is made up of domain-independent diagrams which corresponds to various aspects of systems modelling, such as, requirements, use case, behaviour, etc. [31]. DFDs are used to represent the flow data through information systems. Unlike DFDs, SysML have the ability to represent the interactions among sub-systems and between agents.

As a result, combining the strengths of both modelling techniques, the different system interactions and data flows were easily conceptualised. SysML use-case diagrams were used to capture the interactions between the various stakeholders (agents) of the respective domains, involved in the creating and reuse of PSS life cycle data. DFD objects were used to model the flow of PSS life cycle data within and across different domains and stakeholders. The main stakeholders (high level) in the framework are the PSS organisation, customer, sub-supplier and 3rd party service provider. This framework integrates the CIMS and CMMS into one centralised engineering database, owned and managed by the PSS organisation, which can create external databases to grant restricted access to sub-suppliers involved in product development and improvement processes. The original framework in [6] has been developed further in this case study, to reflect the PSS context and is shown in Fig. 6.

The framework shown in Fig. 6 is a simplified high-level representation which serves as a guide towards capturing the whole picture. The detailed interactions that may exist between several department functions within each enterprise (e.g. management, finance and engineering) will depend on the organisational structure and culture in each enterprise. It integrates existing systems (CIMS and CMMS) and processes from multiple domains into one unified framework. For example FRACAS “Failure Reporting and Corrective Action System” has been integrated with other maintenance processes and stored in one central maintenance database (which integrates with the operational and CIMS databases). FRACAS is systematic closed-loop process of

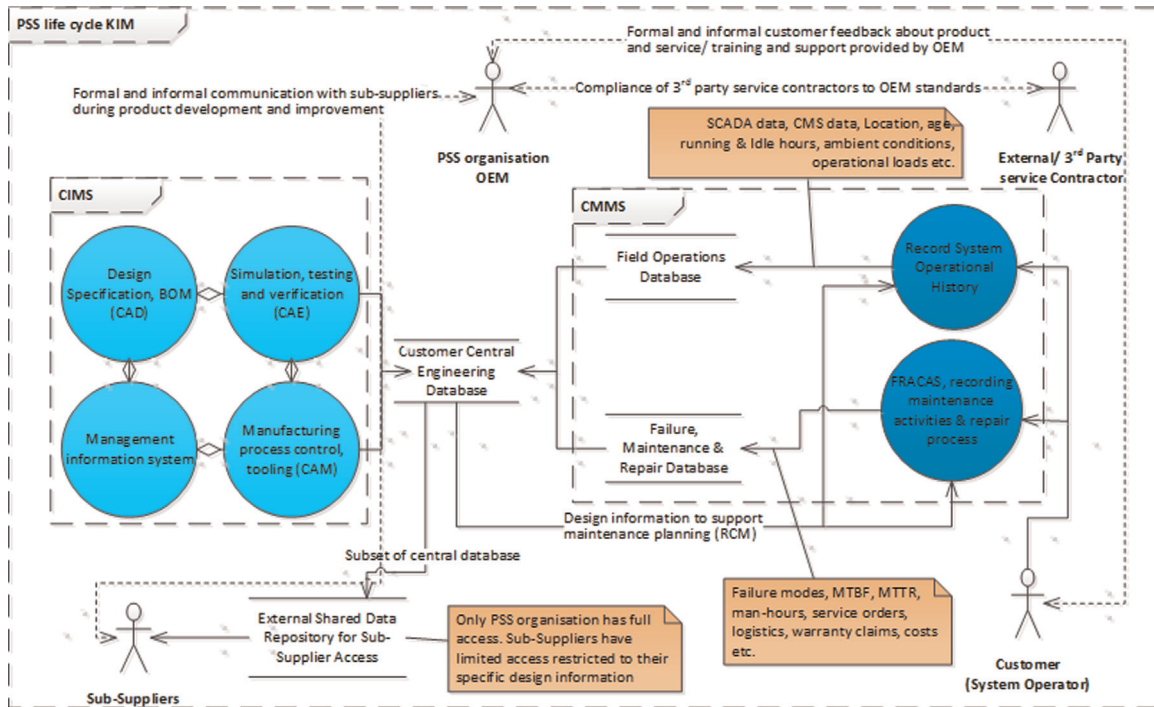


Fig. 6. Framework for in-service feedback in PSS KIM.

documenting and utilising field failure data and it is widely used in industry especially in military applications. However, as identified in [32] it lacks prioritised goals, it is unable to deal with complex organisational interaction and has poor data traceability – making it not structured and holistic enough when implemented in isolation. Hence, the framework helps to address these limitations.

The type and direction of the arrows indicate the type and direction of data flow respectively. The solid arrows represent the formal and codified data, which can be captured and stored using standard computer systems. However, the dotted arrows represent the more in-formal communication that may exist between the stakeholders. In-formal in this context implies that no formal and detailed documentation process for such data flow exists, e.g. service personnel, who work closely with customers, continually strive to build good relationships with them [24], hence gaining more personalised knowledge which is not codified formally and depends on the service personnel's individual experience. Hence for such knowledge to be reused for design process, the service personnel would have to take part in the design process itself [24] or be consulted.

### 3.3.4. Implementation and reflection

The framework gives a snapshot in time, of an ideal PSS life-cycle data flow. It can be operationalised by comparing the ideal PSS lifecycle data flow with the current state and identifying the areas of concerns and where improvements are needed. The ideal framework helps in decision making by answering the questions of what types of data need to be captured, who owns and has access to it, who uses the data and how can be reused. It was identified that there are generally two aspects of PSS life cycle data flow which need to be addressed in order to be able to optimise products throughout the PSS life cycle:

- The processes and supporting systems for in-service knowledge capture and feedback.
- The methodology and techniques for reuse of in-service knowledge.

These essentially cover the key activities of KIM described in [14], hence justifying the structure of the framework. The framework goes beyond the activities of KIM by closing the formal and informal gaps between design and in-service domains making it possible to speed up the process of learning across the entire PSS life cycle. This forms the basis of the life cycle optimisation of products. The two key aspects of PSS life cycle data flow, which influence the implementation of the framework, are discussed in the next section.

## 4. Results and discussion

This section discusses how the PSS life cycle KIM framework was operationalised, demonstrating how it can be used for in-service data capture, feedback and reuse.

### 4.1. Capture and feedback of in-service data

In-service feedback to an engineering organisation can be achieved via two different means [4,24]:

- The personalisation approach.
- Codification approach.

The personalisation approach deals with the transfer of knowledge through development of communities of practice and socio-technical models for enhancing company performance [33,34], emphasising an organisation's dynamic capabilities to learn in response to changing circumstances [4]. Service personnel who work closely with customers, building good relationships with them, acquire personalised individual experience which can be transferred to new product design [24]. The codification approach on the other hand, is simply concerned with making knowledge explicit by capturing it formally such that it can be reused afterwards. Data fed back through personalisation



approach is described as informal feedback in the PSS KIM framework, while codified data refers to formal feedback. The framework deals with formal feedback through helping organisations to understand the requirements, interactions and constraints needed to establish and integrate systems for PSS KIM in order for in-service information to be fed back. The integration is mainly done between already existing IT and engineering systems or through the acquisition of new IT systems. This also helps in identifying processes which can be integrated effectively such as FRACAS [32] and reliability-centred maintenance [35], otherwise, new processes might be developed. For informal feedback, the framework raises awareness for organisations about aspects of feedback that are typically ignored during product development. This is done by asking questions about what informal relationships the PSS organisation has with its customers and third party service providers, and how these relationships can be leveraged during product development or redesign. These informal relationships can then be formalised through the framework which already highlights the stakeholders and their interactions during the PSS life cycle.

Jagtap and Johnson [36] conducted series of questionnaire and interviews with designers and service engineers, from which they determined the common in-service information designers seek from maintenance documents. Also, as part of the “KIM project” in the UK [11,13,29], different categories of whole life information for engineering artefacts were identified from the results of a UK wide survey. From both surveys, the key in-service information that designers require include at least one of the following:

- Information related to component failure, operating conditions, maintenance, life cycle cost and warranty.
- Information about the performance of the artefact compared to how it was intended to perform, including planned and achieved reliability data.
- Information about the reparability and maintainability, including spare parts consumption, tooling and training off service personnel.

These largely correspond with the information required by the design engineers in this case study. However from this case study, it was also identified that the rationale behind key in-service decisions is also very important to design engineers. This is because, as many design engineers are not involved in in-service

operations, they are unaware of the context and constraints behind maintenance process. Hence, when service personnel take unconventional decisions during maintenance, designers might be unable to reuse such information if they do not know the rationale behind.

The process of codifying in-service knowledge can be either automated or a human assisted process. Automated techniques of codification are typically achieved through health monitoring systems, where sensors are installed with the product to monitor key parameters relating to the product’s health, performance and operation. These are easily integrated and fed back to design since they are stored in structured databases. However, there is still the need to pre-process, model and interpret raw sensor data before it can be reused by design engineers. The two automated techniques in this case study include CMS and SCADA, as described earlier. Apart from automated approaches many other valuable in-service information, as described in [36], are still generated through manual or semi-automated human efforts. These range from maintenance reports, service records, customer feedback, to name a few. This case study focused on the manual and semi-automated methods for collecting and feeding back in-service data. Three major aspects of in-service records capture and feedback were identified in this case study, which address some of the issues identified in literature [13,19,23,29], include

- (1) Moving from paper-based and PDF overhaul inspection reports to a tabular database structured representation of service records – here a web-based spreadsheet inspection tool (Fig. 7) was developed for the repair and overhaul disassembly inspection of gearboxes, replacing PDF and handwritten reports.
- (2) Implementing a structured classification of data with well-defined taxonomies for uniform data generation. This was achieved by adopting standardised database tabular format, for easy upload and retrieval to and from the central base respectively. Taxonomies for system, module, and component terminologies were also developed alongside with those for the failure modes and damages for each component, module and system. For example, Fig. 7 shows some of the component level taxonomies used for classification. Each serial component is identified with its serial number (for traceability) and the failure/damage modes are classified according to the type, location and severity of the damage.
- (3) Avoiding free text and erroneous data – in [19] it is illustrated

	Serial Number	Damage			Decision
Ring Gear	E789261	No Damage	No Damage	Not affected	Re-use
Sun Pinion	E789325	Moderate	Micro Pitting	in dedendum	Rework
Planet Gear 1	E789273	Severe	Tooth Fracture	on complete flank	Scrap
Planet Gear 1 Raceway		Severe	Scuffing	Not affected	Scrap
Planet Gear 2	E789273	Mild	Polishing	Not affected	Rework
Planet Gear 2 RaceWay		No Damage	No Damage	Not affected	Re-use
Planet Gear 3	E789273	Mild	Polishing	Not affected	Rework
Planet Gear 3 Raceway		No Damage	No Damage	Not affected	Re-use

Fig. 7. Online inspection tool for in-service data capture.

how free text can make people describe the same scenario differently. In their example, they showed a picture of a faulty tyre, which they indicated has the potential to be interpreted as: “a puncture”, “a flat tyre”, “a burst tyre” or “a punctured tyre”. Flat tyre in this example refers to a symptom while the others are different faults. Apart from describing things differently, there is a potential for spelling mistakes as well when using lots of free text. The use of drop down menus prevents service personnel from writing erroneous information and also avoids variation that might arise from entering free text. Apart from dropdown menus, checkboxes can be adopted. This replaces the checklists made using paper records. Dropdown menus and checkboxes semi-automate the data capture process, making it easier and faster to complete reports

Also important to consider in great detail, are the socio-technical aspects to in-service data feedback, just as [33,34,4,6,13] have described. These include both the aspect of general organisation learning [34] and those specific to learning more about products during service [4,6]. Personalised experience gained is one of the socio technical aspects to in-service data. Fundin and Bergman [24] pointed out in their case study that one of the ways through which personalised experience can be fed back to new product development is if experienced service personnel take part early in the design process. This is because they have better knowledge of the product and customers than the designers. Apart from managing the personalised experience other socio technical aspects which need to be considered include – social mechanisms such as communities of practice for informal knowledge transfer and developing skills and provision of training to relevant stakeholders involved in in-service knowledge capture and feedback.

#### 4.2. Reuse of in-service experience

With the current advancement in IT, organisations are not constrained by the ability to capture data but rather, being able to retain organise and interpret the information [13]. In fact

organisations can get overwhelmed with the quantity of data they have if not properly utilised. Hence data has no value if it is not used for a purpose [3] and information reuse occurs when information is assimilated and used in new applications, yielding useful insights and knowledge [4]. In-service data reuse can be aided by proper information classification technique, and statistical analysis and data mining [4]. The former uses taxonomy or classification to structure and organise in-service information making it easy to retrieve data. The use of similar terminologies between the product development and service teams is also a key for easy retrieval so that the design and manufacturing engineers do not need to worry about translating vocabularies before analysing in-service data. Statistical analysis and data mining are perhaps one of the most common ways by which information can be reused. Reliability, availability, maintainability, and safety (RAMS) statistics are one of the important measures by which design engineers can assess and learn from field performance. Some of the RAMS parameters which can be analysed from in-service data include: failure rates, mean time to failure-MTTF, mean time between failure-MTBF, mean repair time, degradation curve characteristics, Weibull parameters, etc. However, design engineers can get overwhelmed by complex statistics so it is better to keep it simple, using simple charts (bar, pie, Pareto) or dashboards with green, amber, and red indicators as straight forward reporting tools. Fig. 8 shows how the in-service data is reused in the framework for through-life product optimisation. Optimisation can be achieved in three ways:

- Optimisation via new designs and upgrades by learning from in-service data during product development
- Optimisation of maintenance processes, which can be achieved through classical RAMS techniques for maintenance planning.
- Optimisation of health monitoring systems by cross-correlating predictions made by such systems with failure and repair data so as to improve the predictive accuracy of sensors and algorithms.

As mentioned previously, another aspect of importance to in-

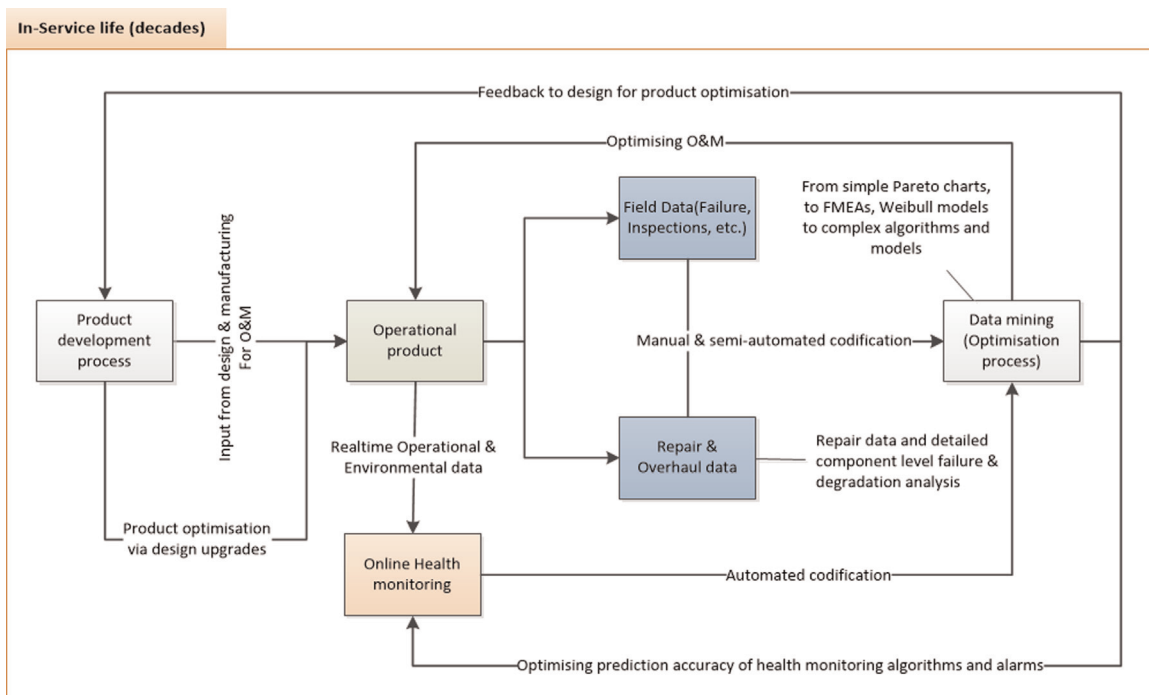


Fig. 8. Reuse of in-service data for through-life product optimisation [37].

service knowledge capture and feedback, which aids data reuse, is the capturing of context and rationale alongside the data itself. This is necessary because in-service data is typically reused by someone different from the person who captured the data. This is also very important for long-lived artefacts especially in the PSS context since data captured at a certain point of its service life can be reused several decades in the future. Capturing the context of in-service records has not been dealt with in literature in great detail. In this case study, one key aspect with respect to context of in-service records is the understanding of the “why?” behind a MRO (maintenance repair and overhaul) decisions. For instance, the decision to scrap a component during overhaul depends not only on how much degradation the component has experience but also on the feasibility of its repair (is it cheaper to repair or scrap?). The decision: “Why was it scrapped” needs to be captured so that the design engineer is aware of the reason behind the decision. This could apply to many other types of in-service records other than MRO data. Other ways through which context can be captured, which is commonly discussed in literature, include

- Creating metadata for each in-service record.
- Use of time and date stamps for time context recognition (as a decision valid today might not be valid years to come). It also helps in understanding the process and can help to link data from different sources for trending purpose, for example trending between operational data, environmental data and failure data.

As Ball et al. [11] argue, annotating elements of the original design with lessons learnt during in-service, without altering the original design information, can aid proper feedback to design. The authors agree with Ball et al. [11] and argue further that this can also aid information reuse. This is because design engineers are more familiar with the design environment, and if they can view in-service information in this environment, they can easily make changes to the design from in-service knowledge. One way by which this can be achieved is through the failure modes and effects analysis (FMEA) process. FMEA is a procedure used by design engineers to analyse a procedure by which each potential failure mode in a system, to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity [38]. If updated during the service life of the product, design engineers can compare the original design FMEA with the current version to see if design assumptions are valid during service, helping them make right decisions for redesign or upgrade of products.

Finally, once design engineers have access to in-service knowledge and experience, and are enabled towards re-using this information, the question that remains is how to know the right time to put a new system into service and the right time to begin the redesign for upgrades or new systems. There is not a straight forward answer to this question as the decision could be influenced by many factors such as the technical and financial feasibility, and also the ability to quantify the savings versus the investment costs. However, from a Systems Engineering and RAMS perspective, the time for redesigning and putting new systems or components into service can be determined through a holistic approach. This can be achieved by combining the systems engineering “Vee” product development model with the RAMS bathtub curve. Fig. 9 shows the relationship between both perspectives combined into a single model. The Vee model has been inverted to indicate the ideal times to begin redesign and commission a new product.

In the bathtub curve, the best time to start redesign or new system design, using in-service experience, is when the useful life of the operational system is about to end (just before wear out

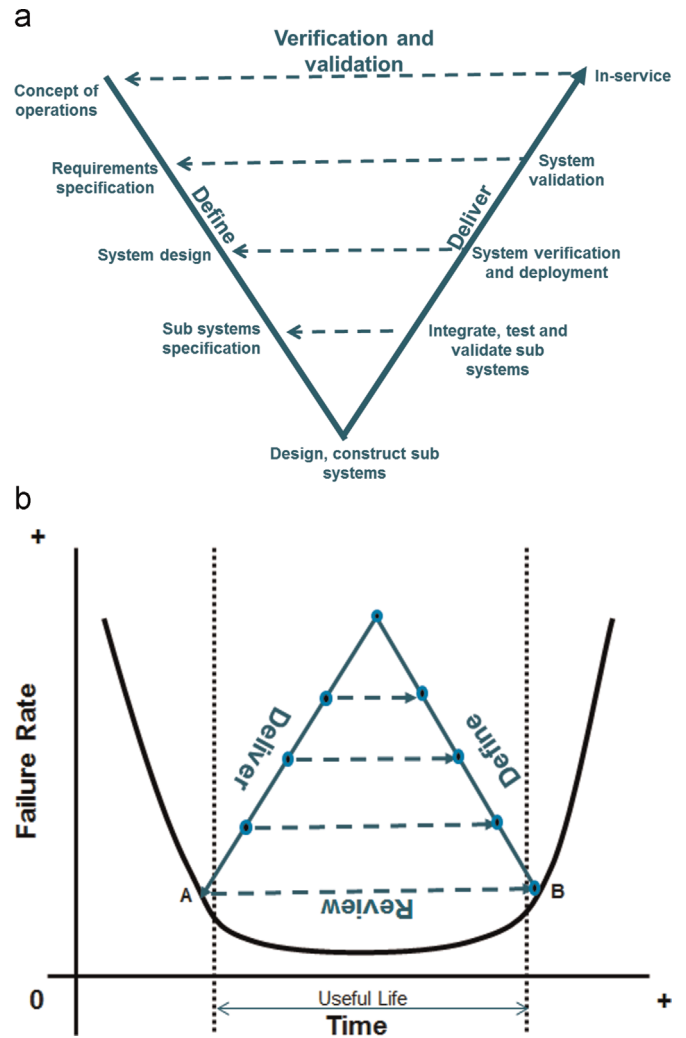


Fig. 9. (a) Systems engineering “Vee” model and (b) combined “Vee” and bathtub curve model.

begins, Point B). This implies that the “design phase” of the original Vee model should begin just before the useful life ends. Furthermore, the best time to commission a new system into service is just before its useful life phase (point A), where the burning-in failures have all been known and designed out. Here, the failure rate is within the constant and acceptable zone. This implies that the right end “deliver phase” of the original Vee model should end just before the beginning of the useful life of a new product. This is true for a new product which has been redesigned from in-service experience because it would have taken into account the burning-in failures which occurred in the previous design.

This model aligns the time at which a new system is delivered to the time the old one is decommissioned saving costs and time. This also applies to sub-system redesign. This model can be used for life extension plans where critical sub-systems can be redesigned at the end of the useful life to keep extending the life time of the system by shifting the bathtub curve more to the right. Even though in practice component and system failure rates do not perfectly follow a bathtub curve, there are other means by which this idealised optimisation technique can be achieved. One approach is by continuously trending the system degradation curves to know the threshold for when degradation would lead to substantial loss in product performance or availability [26].

## 5. Conclusion

This paper has explored how lessons learnt from in-service products can be used for new product development. It has established that companies with PSS type business models are in a unique position to learn from in-service knowledge and experience, but need to understand the various issues and challenges that surround KIM within their organisations. A framework for in-service KIM for PSS organisations was developed through and industrial case study and also by building upon previous literature. It was then operationalised by demonstrating how in-service data in PSS context can be captured and fed back to design and reused for through life product optimisation. Various ways through which optimisation can be achieved were also identified and the technique for determining the timing for through-life optimisation was presented. The case study has identified ways to address some of the key issues that need to be understood and resolved by PSS organisation for effective capture, feedback and reuse of in-service information for new product development.

This research is not without limitations, perhaps because the framework and case study were developed and applied in the PSS context, it might not be easily transferrable to companies who are only involved in product development and have no firm root in the in-service stage. This is because some of the hindering factors which prevent such companies from getting access to or reusing data are a complex combination of cultural, political and commercial, and are specific to individual organisations, hence beyond the scope of this research. Future research should perhaps explore how to quantify the financial benefits companies would stand to gain by adopting similar approaches to in-service KIM, since some companies are always reluctant to invest in new systems, processes and models if they do not have a clear idea of the financial benefits they stand to get.

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