CHALLENGES IN DIGITAL FEEDBACK OF THROUGH-LIFE ENGINEERING SERVICE KNOWLEDGE TO PRODUCT DESIGN AND MANUFACTURE

Tariq Masood
Manufacturing Department, School of Applied Sciences, Cranfield University, UK
(Seconded at Life Cycle Engineering, Rolls-Royce plc, Derby, UK)
Email: Tariq.Masood@Cranfield.ac.uk

Rajkumar Roy
Head, Manufacturing Department, Cranfield University, UK and Director, The EPSRC Centre for Innovative Manufacturing in Through-life Engineering Services
Email: R.Roy@Cranfield.ac.uk

Andrew Harrison
Rolls-Royce Engineering Associate Fellow, Life Cycle Engineering, Rolls-Royce plc, Derby, UK
Email: Andrew.Harrison@Rolls-Royce.com

Stephen Gregson
Head of Engineering for Services Global Transformation Programme, Rolls-Royce plc, Derby, UK
Email: Stephen.Gregson@Rolls-Royce.com

Yuchun Xu
Manufacturing Department, Cranfield University, UK and The EPSRC Centre for Innovative Manufacturing in Through-life Engineering Services
Email: Yuchun.Xu@Cranfield.ac.uk

Carl Reeve
Engineering for Services Global Transformation Programme, Rolls-Royce plc, Derby, UK
Email: Carl.Reeve@Rolls-Royce.com

ABSTRACT

Even though knowledge management has been a subject of research for a long time, management of through-life service knowledge has started getting more attention quite recently. With the help of literature review and analysis, this paper identifies possible drivers to extend the product life cycle; presents definitions of “knowledge” and “service knowledge”, and identifies research gaps and challenges in digital feedback of through-life service knowledge to product design and manufacture. The paper presents a causal loop model to represent causes and effects of through-life service knowledge on product design and manufacture. A digital framework is presented to address challenges in digital feedback of through-life service knowledge to product design and manufacture. The digital framework is developed with the intention of developing a service knowledge backbone demonstrator application. Industrial experts have validated the initial framework. Detailed case studies shall be undertaken to enhance this framework in future.

KEYWORDS

Product design, digital feedback, design for service, through-life engineering service knowledge, manufacturing.

1. INTRODUCTION

The knowledge intensive industries (e.g. aerospace, construction) build complex and long-life products (e.g. aircrafts, engines, buildings) and tend to encourage the generation of very large amounts of information and knowledge within the overall 'design-use-upgrade' life cycle (Tang et al, 2010). The pressures have mounted in the airline industry since last decade, to reduce operating cost and improve service, whereas revenues are declining (Harrison, 2006). This tendency is because the in-service life is getting longer as a result of:

- The product-to-service shift, which is exemplified by Rolls-Royce's fleet service agreements (e.g. Trent XWB), aimed at reducing the risk and cost of long-term service and maintenance events to the customer, by providing a fixed cost per flight hour. This type of agreement provides a basis for continuity in service records resulting in increased documentation.
- Evolution of product service systems (PSS), especially technical or industrial PSS; and
- Emerging changes in technology.

The product-to-service shift has necessitated developing strong digital feedback links of through-life service with design and manufacturing stages of product life cycle. Digital feedback is necessary to transform tacit knowledge to explicit knowledge. However, there are challenges in achieving digital feedback of through-life service knowledge.

This paper presents recent advances in through-life service knowledge feedback to product design and manufacture. The scope of the paper is generic and covers the general body of literature. This paper presents a definition of knowledge in the industrial setting, distinguishing it from data, information and wisdom/action. It also presents definitions of service, service knowledge, and service knowledge management. Issues and barriers to knowledge reuse are also discussed. The paper presents current challenges in through-life service knowledge feedback to product design and manufacture. A service knowledge backbone (SKB) framework is proposed to overcome these challenges. A causal loop model (CLM) is also presented, which shows relationships between challenges and the SKB. Finally, the paper concludes with key recommendations for future research.

2. METHODOLOGY

The following steps are followed as part of the overall methodology for this paper (see Figure 1):

- Identifying challenges in digital feedback of through-life service knowledge (through literature);
- Identifying existing solutions to the challenges (through literature);
- Creating a digital framework to address the identified challenges;
- Developing a causal loop model incorporating the challenges and the digital framework; and
- Vetting of the digital framework using industrial experts.

Main sources used to identify challenges and solutions include journals and thesis available via Cranfield University's Search Point and CERES. Keywords used for different searches include but not limited to service knowledge feedback, product design, service knowledge management, manufacturing, and product life cycle.

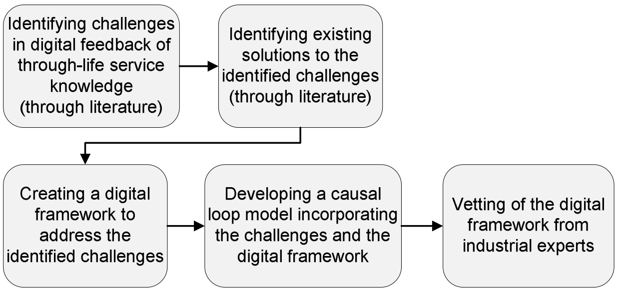

Figure 1 Methodology – Service knowledge feedback to product design and manufacture

3. RECENT ADVANCES IN SERVICE KNOWLEDGE MANAGEMENT

Knowledge management (KM) started gaining popularity when the concept of a *Knowledge Economy* was defined stating that the value of the organisation lies not within the commodities (product or service) that it produces, but within the knowledge applied within the organisation to produce it (Alavi and Leidner, 2001). Knowledge is defined in different ways and accepting this may be helpful to reduce further confusion. The hierarchy of data-information-knowledge-wisdom is most commonly referred to as a 'knowledge pyramid' (Hey, 2004). The shape of the hierarchy is representative of large amounts of data, that are refined creating smaller amounts of information, followed by further distillation to create knowledge and then to embed wisdom. Young et al (2005) defined *data* as text or numbers (Young et al, 2005). Data is the raw form of parameters e.g. signals going to cockpit instruments. According to Wilson (2002) and Young et al (2005), data becomes *information* when embedded in a relevant context (Wilson, 2002; Young, et al, 2005). Therefore, information is meaningful data. Examples may include air speed, altitude etc. Hey (2004) defined knowledge as subjective, personal and shaped by an individual's perceptions and experiences (Hey, 2004). Young et al (2005) defined knowledge as interpretation of information in order to assign meaning (Young, et al, 2005). Hence, it is information with understanding either within the human head, manually documented or computerised/automated e.g. pilot or autopilot.

A meaningful definition of knowledge in an industrial setting is 'actionable understanding'. The assertion is that industry functions on a return on investment basis. Therefore to warrant the investment of time or other resources in knowledge management there must be an equal or greater benefit returned for the activity to achieve sustainability. Therefore an industrial definition of knowledge (worth managing) must contain a reference to the potential for its value release.

ACTIONABLE UNDERSTANDING contains the two key characteristics: that it has to convey understanding and must be able to be acted upon (this implies it has intellectual property value and therefore has worth to the organisation justifying management above and beyond that extended to pure information). It also implies that it only really exists when contained in a human brain or other device where the understanding can be applied to an input to generate a decision. We could therefore assert that Knowledge does not exist on paper; it only becomes knowledge when it is interpreted by a human being or other active medium (such as a computer algorithm) where it is capable of influencing decisions and actions.

According to Ackoff (1989), *wisdom* is linked to the future, since it integrates design and vision, whereas the other pyramid levels are connected to the past, since they are related to known things. Hence, it is an extrapolative process, through which individuals differentiate between right and wrong, good or bad by extension of their understanding to different contexts. Figure 2 presents data, information, knowledge and wisdom across axes of understanding and context independence.

Knowledge can be typified broadly in terms of tacit or explicit. *Tacit knowledge* comes from experience and is quite unstructured and hard to communicate (Nonaka, 1994; Sobodu, 2002). *Explicit knowledge* is the one that can be transmitted in formal, systematic and well-structured language (Nonaka, 1994; Sobodu, 2002). The scope of this paper includes research that captures tacit knowledge and makes it explicit by externalizing through knowledge capture and re-use.

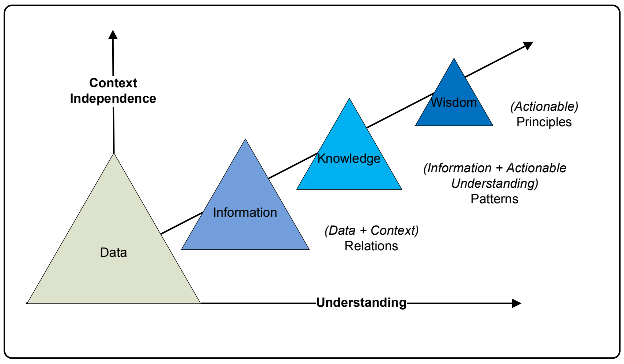

Figure 2 Data, Information, Knowledge and Wisdom

KM is defined as 'a crucial construct in understanding how humans convert information into thought and consequently into action' (Malhotra, 2001). KM is an activity for using information technology in order to systematically classify, store, and apply organisational and personal data and information so that: (1) quality and quantity of the creative knowledge within an organisation is promoted, (2) the feasibility of knowledge is improved, and (3) value is created for the organisation (Liang, 2002). Five key activities can be performed within the KM context in order to remain competitive: acquisition, selection, generation, internalisation and externalisation (Holsapple and Singh, 2001). The realisation of each stage is a pre-requisite for proceeding to the following stage, hence resulting in the externalisation of knowledge. A web based KM system for virtual electronics manufacturing enterprise is presented in (Chryssolouris et al, 2008).

Knowledge capture (or *knowledge elicitation*) is important as loss of knowledge commonly occurs when employees document investigations. When investigating new issues employees will generally look for similar issues that have occurred in the past, but documentation created for the prior solutions might not have captured the richness of knowledge actually applied in the decision making process. Hence, knowledge capture (elicitation) helps the organisation in retention of knowledge for future use (Sobodu, 2002).

Knowledge re-use (or feedback) is defined as sharing of best practice for people to resolve common technical issues (Markus, 2001). Weise (1996) defined knowledge re-use as sharing of information and documentation. The theory of knowledge re-use, presented by (Markus, 2001), emphasises on the role of knowledge management systems (KMS) and the repositories. The knowledge is systematically processed and stored, then re-used repeatedly when any similar situation arises.

Benefits of re-using knowledge to organisations include enhanced value of knowledge (Markus, 2001), capability to re-use knowledge (Baxter et al, 2008), common product characteristics (Baxter et al, 2008), reduced time to develop new products (Markus, 2001; Baxter et al, 2008), and reduced business costs (Markus, 2001). Organisations re-use knowledge to gain corporate competitive advantage (Ma, 2005). It is more cost effective to re-use knowledge that has already been created. Ma (2005) argued that the process of learning from past mistakes and successes can radically reduce design and related production costs. Masood et al (2011a) presented a framework for integrated use of design attributes, knowledge and uncertainty in aerospace sector.

Drawbacks of knowledge re-use include information overload (Ma, 2005; Tang et al, 2010), lack of ability to graduate the value of knowledge (Tang et al, 2010), loss of time and heavy search costs (Garud and Kumaraswamy, 2005), varying requirements of knowledge re-users (Markus, 2001), and knowledge re-users' unawareness of knowledge sources (Galup et al, 2003). Costs associated with introduction and maintenance of contextual KM environments and employees' mentality for knowledge sharing and re-use are two main barriers to knowledge re-use (Nunes et al, 2009).

Ontologies are another means of sharing and reusing information (Nunes et al, 2009). Kabilan (2007) described a key use of ontology as sharing of information between people, databases and applications. Gruber (1995) defined ontology as 'a representation of a conceptualisation' and as 'a formal specification of the concepts and terms of the information universe of a specific domain'. Ontologies aim at making implicit domain knowledge explicit (Kabilan, 2007). Hence, ontology is a form of knowledge representation (Doultsinou, 2010). However, ontology is not synonymous to knowledge base. A knowledge base is an ontology populated with data (Doultsinou, 2010). However, there is a blurred line where the ontology finishes and the knowledge base starts (Noy and McGuinness, 2001). Ontologies are used mainly for following reasons (Noy and McGuinness, 2001):

- Sharing common understanding of the structure of information among people or software agents
- Facilitating reuse of domain knowledge
- Making domain assumptions explicit
- Disconnecting domain knowledge from the operational knowledge
- Exploring domain knowledge.

The ontology is the basis for a context-aware content description of knowledge sources (Han and Park, 2009). The concept of ontology has been used and applied in areas, such as KM, knowledge acquisition, information retrieval and mining, and knowledge modelling. Ontologies can be categorised by three levels of abstraction i.e., upper, mid-level and domain (Semy et al, 2004). An upper ontology is independent of a particular domain and provides a framework; a mid-level ontology can be used as a link between abstract concepts used in the upper and domain ontologies; and domain ontology specifies concepts related to a particular domain.

Knowledge Management Systems (KMS) are IT-based systems developed to sustain and improve the organisational processes of knowledge creation, storage/retrieval, transfer, and application (Alavi and Leidner, 2001). The following are the major classes of KMS:

- Informational Knowledge Systems, which primarily store and manage knowledge on a potential use basis. Examples may include databases and directories.
- Knowledge Management Tools, which try to simplify the access or provide direction to knowledge and information within KMS by decreasing the amount of time needed for the user. Examples may include search tools or portal applications.
- Dynamic Knowledge Systems, which elicit timely, on demand and in context of information and knowledge from people when someone else demands it. Examples may include KM help desks.

4. DIGITAL FEEDBACK OF THROUGH-LIFE SERVICE KNOWLEDGE TO PRODUCT DESIGN AND MANUFACTURE

The study of Service Knowledge Management (SKM) is relatively novice in reported literature. However, its popularity is growing among academics and industry peers. To define SKM, service needs to be defined first. The United Nations provided a broad definition of services, as *"Services are not separate entities over which ownership rights can be established (United Nations, 2002). They cannot be traded separately from their production. Services are heterogeneous outputs produced to order and typically consist of changes in the condition of the consuming units realised by the activities of the producers at the* *demand of the customers. By the time their production is completed they must have been provided to the consumers".* Overall, services are defined as activities, benefits, and satisfaction that create returns directly or in relation to the sale of goods (Kamponpan, 2007). The characteristics of service include intangibility, inseparability, heterogeneity, perish ability and ownership.

Maintenance is a major service activity, which is required for a variety of products having mechanical, electrical or hydraulic systems for example. The aim of a maintenance service should be an increase in customer functionality that may be achieved through increased availability, which in turn boosts the equipment reliability and cuts down their repairing time (Viles et al, 2007). Broad maintenance types and strategies include preventive maintenance, corrective maintenance and predictive maintenance. An approach to operational aircraft maintenance planning is presented in (Papakostas et al, 2010).

Servitization includes innovation of capabilities and processes within an organisation that can lead to a better value creation through a change from selling products to selling *product-service systems (PSS)* (Neely, 2008). Servitization literature makes a significant distinction among four concepts: PSS, servitization, servitized organisation and global value system (Neely, 2008). PSS originated in Scandinavia in the late 1990s and can be defined as a marketable set of products and services capable of jointly fulfilling user needs, while delivering value in use (Meier et al, 2010; Annamalai et al, 2011). The product/service ratio in this set can vary, either in terms of function fulfilment or economic value (Mont, 2002). Technical PSS is defined as PSS having following characteristics (Roy and Cheruvu, 2009):

- A physical product core (e.g. aero engine) enhanced and customised by a mainly non-physical service shell (e.g. maintenance, training, operation, disposal)
- Relatively higher monetary value and importance of the physical PSS core, and
- 'Business to business' relation between PSS manufacturers and customers (Aurich et al, 2006).

It is observed that the term industrial PSS is also used in the same sense as technical-PSS in literature (Roy and Cheruvu, 2009).

Service Knowledge (SK) can be defined as *"the amalgamation of processed information, which is required by service personnel for the execution of their activities (i.e. planned and unplanned maintenance, service exchange, product repair and overhaul, retrofitting and upgrades, training) stored by them to be re-used when needed. Experience of service personnel, gained through their tasks, should also be integrated into SK" (Doultsinou, 2010).* This is true only in a traditional organisation where service is an isolated activity relative to the product design. In PSS service knowledge is of equal if not more value to the product and service design teams as they have the greatest flexibility to turn the understanding gained from service use into action to improve future designs. The service delivery team can only use service knowledge to recover to the intrinsic performance level that is designed into the system. The designer has the power to fundamentally change the baseline performance.

SKM deals with SK capture and re-use to support product design and service engineering. Product design has been categorised in the literature as original or adaptive (Mountney, 2009). An original design is a completely new solution and product. An adaptive design will satisfy an existing requirement by providing a solution in a new way, therefore requiring new or substantial changes to existing components and possibly assemblies. Adaptive design may also be applied to incremental improvement to an existing solution to meet a new requirement. There are three major stages to the product design process:

- Concept Design Stage – concerned with the product function. During this stage, the intended functions of the product and potential solutions to achieve them are explored;
- Preliminary Design Stage – concerned with the relationship between function and form. The requirements and functions finalised during the concept stage are transformed into an initial engineering general arrangement (i.e. a physical representation) during this stage; and
- Detailed Design Stage – concerned with the detail form of every component in the product. The arrangement from the preliminary stage is optimised and finalised, each part is fully defined (including geometric dimensions and tolerances), the final material selection takes place and the product is assessed for technical and economic viability. The necessary documentation is also created to enable the product to be produced and maintained.

Design for Manufacture (DfM) methodology aims at the design of products that are easier to manufacture by assessing their manufacturability during early design stages. 'Manufacturability' can be defined as process capability to meet the product attributes. Extension of DfM is Design for Manufacture and Assembly (DfMA), which aims at the design of products that are easier to manufacture and assemble. DfMA methodology aims to enable greater thought around production and assembly requirements before the detailed design stage (Boothroyd et al, 2002). Process selection in mechanical engineering design has been considered in the literature, where the main driver for the selection is cost assuming all relevant technologies are available (Lovatt and Shercliff, 1998). Nowack (1997) reported on assessment of 'manufacturability' during early design stages and provided guidelines. Assembly process templates for the automotive industry are presented in (Papakostas et al, 2010).

DfS is a design process that aims to reduce maintenance costs at the design stage by supporting product design with service information. The knowledge pyramid is important to designers in this context. In literature, several authors discussed certain aspects of service information that are beneficial to designers. Norman (1988) mentioned that past operating experience could contribute towards forecast reliability/availability that also depends on the sample size. Jones and Hayes (1997) discussed the value of collecting field failure information and during a product's life, and the analysis of this data to assess the product's reliability. Petkova (2003) described the flow of in-service information back to the manufacturer (within the context of consumer electronics industry) and stressed the significance of the failure root causes for the improvement of product quality. In order to benefit the DfS process, identification of information types is important. Constructive in-service information in product design includes: in-service component life, failure types, failure causes, deterioration mechanisms regarding various components, the occurrence rate and impact of these mechanisms, reliability data and spare's cost (Jagtap et al, 2007). The service information that designers are interested in is linked with the following (Jagtap et al, 2007):

- Failure mechanisms (e.g. failure mode);
- Maintainability (e.g. accessibility);
- Reliability (e.g. Weibull analysis of reliability);
- Service instructions (e.g. inspection recommendations);
- Operating data (e.g. difference of various performance parameters with operator);
- Component cost (e.g. repair cost);
- Design information (e.g. technical diagrams); and
- Component life (e.g. average life).

Availability of in-service information can help in reducing maintenance costs, prediction of product reliability/availability, evaluation of product reliability in the field, maintenance optimisation, reliability improvement of future products and fulfilment of the maintainability and reliability requirements (Jagtap et al, 2007).

Mapping service knowledge and design requirements is very important for efficient SKM. Baxter et al (2009b) concluded that there is a clear design bias in the manufacturing knowledge literature and that service research is severely lacking and service (operation) is under represented in the manufacturing knowledge domain. Service knowledge is important, particularly in wake of shifting nature of production and service (Baxter et al, 2009a). Hence, there is a research gap and further research is recommended.

Current industrial practice to inform design functions mainly include face-to-face communications (i.e. design review meetings, etc), communities of practice sessions, group or individual emails, and file-folders on local PCs or LAN (for storage purposes). These forms of communication have their pros and cons e.g. face-to-face meetings are very good means of knowledge transfer, and telephone/email communications deliver required knowledge quickly. However, these forms of communication are not well-structured so that to use knowledge in a longer term as and when required. Also, search capabilities are very poor in current forms of communication, which are utmost necessary to find relevant knowledge quickly and at right time. In order to address these drawbacks, digital feedback is required. Digital feedback may be provided through structured knowledgebase systems that have capabilities of uploading, searching, prioritising and reporting. Hence, it is important to develop digital feedback links between through-life engineering service knowledge and design in future research to support the product (e.g. maintenance) and the customer. These links may be additional to the links between service knowledge and manufacturing, which also may have commonalities amongst them. A clear set of requirements specification for through-life engineering service knowledge, its capture and representation (data/information systems), and re-use methodologies are required to fulfil such requirements. SKM related research initiatives have been undertaken in recent past including but not limited to IPAS, DATUM, IITKM, HIPARSYS, X-Media, SILOET, SAMULET, SKB (Masood et al, 2011b). Some of these are still on-going e.g. SILOET, SAMULET and SKB. Current service knowledge feedback challenges are discussed in the following section.

4.1. CURRENT CHALLENGES

Following current challenges in feedback of through-life engineering service knowledge are identified from the literature review and analysis presented in this paper:

Challenge 1: Feedback to Product Design: Service Engineering is a core part of the product life cycle, but there is a lack of focus on effectively feeding back service knowledge to product design stages. There is a lack of available structured methodologies for capturing and structuring service knowledge in order to map service knowledge onto design requirements. The challenge here is to devise an effective methodology to capture service knowledge gained from previous learning (possibly in a structured way) and then re-use by feedback to conceptual and detailed product design stages so that new/revised product design incorporates the new learning. The future work may include: (1) Development of a representation of the service knowledge that can be used by design engineers to improve product design; (2) Identification of service knowledge required by product design engineers at conceptual and detailed design stages; and (3) Development of an effective methodology to re-use service knowledge for product design and service engineering stages.

Challenge 2: Feedback to Manufacturing: Service knowledge is important for manufacturing and assembly life cycle stages to improve its processes when fed back through new/revised product design based upon previous service experience. This may also include considerations of repair margins as required by repair engineers through new/revised product designs incorporating such considerations. The challenges here are two fold: (1) to feed back through-life service knowledge gained from previous service events, root cause analysis, etc where repair engineers may say that more margins are needed while design engineers may argue against it; and (2) to feedback from manufacturing/assembly to design engineers in order to optimise their manufacturing/assembly processes where they may ask designers to revise features, profiles or contours etc for alternatives for which they may have required fixtures and tooling etc. In both cases, establishing an effective feedback loop is challenging.

Challenge 3: Feedback to Service/Repair Engineering: Service knowledge is important for service/repair engineering functions of an organisation, especially for its uses in root cause analysis and problem solving, mitigation of operational risks, improving repair policies, recommendations of repair margins, etc.

Challenge 4: Use of Through-Life Engineering Service Knowledge in Reducing Product Life Cycle Cost: The knowledge of previous service experience could help reduce product life cycle cost by giving priority to mitigate risks imposed on those product commodities, which exhibit high costs.

Challenge 5: Corporate Definition of Through-Life Engineering Service Knowledge: There are many definitions of service knowledge that define how knowledge is managed and used. However, the suitability for a specific knowledge type in a specific situation varies accordingly. Through-Life Service knowledge has earlier been defined as an actionable understanding. This definition does not apply to only through-life service knowledge but has a broader scope and defines 'service knowledge' as discussed earlier in this paper. However, getting a corporate level consensus on this definition may be challenging, especially in large global organisations.

A digital framework is proposed in the following to address service knowledge feedback challenges.

5. SERVICE KNOWLEDGE BACKBONE (SKB) FRAMEWORK

In order to address the challenges of through-life service knowledge feedback to product design and manufacture as discussed in the prescript, a service knowledge backbone (SKB) framework is proposed in Figure 3.

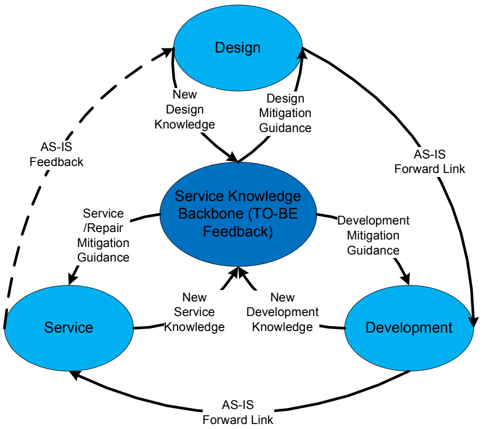

Figure 3: SKB Framework

The SKB framework proposes to develop a through-life service knowledge base of deterioration mechanisms from the service stage of the product life cycle with a feedback link to product design features. The present link between engineering service stage and product design stage is either weak or takes a long time to acquire required levels of knowledge necessary to undertake design modifications. It is proposed here that risk mitigation guidance should be uploaded to the service knowledge base whenever investigations into new service events are complete. It is important to derive key mitigation guidance from high impact service events, which might have gone through root cause analysis, functional analysis and risk mitigation in terms of what must be done, should be done, could be done and not to do things. Such risk mitigation guidance should first inform product design engineers (at concept, preliminary and detailed design stages) as most deterioration mechanisms could be prevented or reduced at the design stages. The SKB Framework provides an interface to the communities of practice, where new knowledge (design, development or service) is uploaded when available and in return the stakeholders (design, development or service) can get ‘actionable understanding’ in terms of mitigation guidance (design, development or service/repair). This framework places particular emphasis upon strengthening the weaker AS-IS link between service and design.

Causal loop models (CLMs) can represent causal effects of activities (Forrester, 1961; Sterman, 2000). This type of modelling helps identify aspects of complexities and dynamics can be modelled through this technique (Masood, 2009; Masood et al, 2010; Masood and Weston, 2011). Implementation of CLM has been reported in several case studies either standalone or as part of integrated approaches (Masood, 2009; Zhen et al, 2009). The causes and effects of establishing SKB on feedback of through-life service knowledge to product design and manufacture is presented as a CLM in Figure 4. The CLM is mapped across design, development and service stages of product life cycle. The design stage includes conceptual, preliminary and detailed product design. The development stage includes product engineering, manufacturing, assembly and testing. The service stage includes product service, repair and maintenance. Here links between causes and effects are represented across product life cycle stages and have positive or negative links representing increasing or decreasing effects of related causes. The main idea revolves around providing an enhanced SKB, and seeing effects of different causes linked to this. For example, if service knowledge capture is improved, it has a positive effect in enhancing SKB, which results in affecting positively on improving conceptual and detailed design characteristics. On the other hand, it could also result in increasing cost of service knowledge capture and maintaining SKB, which further increases life cycle cost. The CLM further suggests that improved design could result in positively affecting on improving manufacturing (fixtures, tooling, inspection, quality). The overall effect could lead to reduce maintenance burden and frequency of occurrence in effect reducing operational disruption, which could lead to reduce number of maintenance and repair events. However, too much rear view mirror approach to risk management may detract from forward looking. The CLM also suggests that life cycle cost could be reduced as an overall effect of the presented feedback loops, however a balanced view of benefits and costs need to be considered.

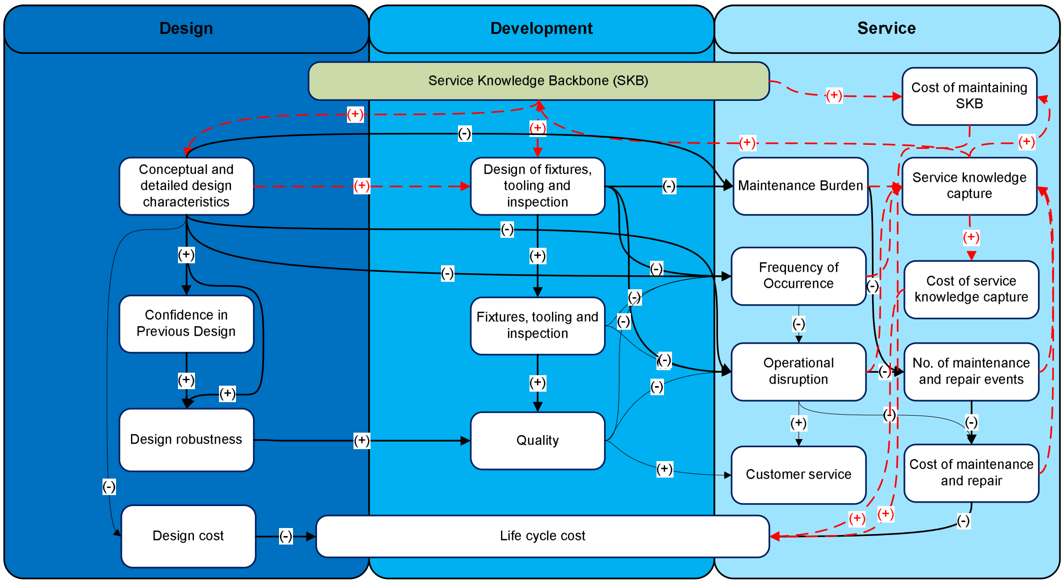

Figure 4: Causal loop model: Through-life engineering service knowledge feedback to product design and manufacture

6. CONCLUSIONS

A state-of-the-art literature review and analysis on through-life service knowledge feedback to product design and manufacture is presented in this paper. It is emphasised to define knowledge as "**ACTIONABLE UNDERSTANDING**" in an industrial setting. The following through-life service knowledge feedback challenges are discussed in the paper:

- Feedback of through-life service knowledge to product design, manufacturing and service/repair engineering;
- Use of through-life service knowledge in reducing product life cycle cost; and
- Defining and implementing a corporate definition of service knowledge.

A Service Knowledge Base (SKB) framework is proposed to address the challenges of through-life service knowledge feedback. A Causal Loop Model (CLM) is also presented, which is drawn across product life cycle stages of design, development and service. Feedback of through-life service knowledge to product design (conceptual/preliminary/detailed), manufacturing/ assembly, and service/repair engineering are modelled in this CLM. The CLM presented increasing or decreasing links between causes and effects associated with provision of an enhanced SKB. It is proposed through this CLM that the through-life service knowledge feedback challenges could be overcome by establishing an enhanced SKB. For future research, it is recommended to develop further methodologies for effectively capturing, representing, and re-using through-life service knowledge to support product design and manufacture. It is also recommended that such frameworks be demonstrated through application development and industrial case studies.

7. ACKNOWLEDGMENTS

The authors acknowledge Rolls-Royce plc, EPSRC and TSB, UK for providing funds to Knowledge Transfer Partnership Program No. 7767 on SKB. KT-Box Project partners are also acknowledged for sponsoring the SKB project.

REFERENCES

Ackoff, R.L., "From data to wisdom", *Journal of Applied Systems Analysis,* Vol. 16, No. 1, 1989, pp 3-9.

Alavi, M. and D.E. Leidner, "Review: Knowledge management and knowledge management systems: Conceptual foundations and research issues", *MIS quarterly,* Vol. 25, No. 1, 2001, pp 107-136.

Annamalai, G., R. Hussain, et al, "An Ontology for Product-Service Systems", *Functional Thinking for Value Creation*, 2011, pp 231-236.

Aurich, J.C., C. Fuchs, et al, "Life cycle oriented design of technical Product-Service Systems", *Journal of Cleaner Production,* Vol. 14, No. 17, 2006, pp 1480-1494.

Baxter, D., J. Gao, et al, "A framework to integrate design knowledge reuse and requirements management in engineering design", *Robotics and Computer-Integrated Manufacturing,* Vol. 24, No. 4, 2008, pp 585-593.

Baxter, D., R. Roy, et al, "A knowledge management framework to support product-service systems design", *International Journal of Computer Integrated Manufacturing,* Vol. 22, No. 12, 2009a, pp 1073-1088.

Baxter, D., R. Roy, et al, "Managing knowledge within the manufacturing enterprise: an overview" *International Journal of Manufacturing Technology and Management,* Vol. 18, No. 2, 2009b, pp 183-209.

Boothroyd, G., P. Dewhurst, et al, "Product design for manufacture and assembly", M. Dekker, 2002.

Chryssolouris, G., S. Makris, et al, "Knowledge Management in a Virtual Enterprise - Web Based Systems for Electronics Manufacturing", "Methods and Tools for Effective Knowledge Life-Cycle-Management", A. Bernard and S. Tichkiewitch, Springer, 2008, pp 107-126.

Doultsinou, A., "Service knowledge capture and re-use to support product design", School of Applied Sciences, Cranfield University, Cranfield, PhD Thesis, 2010, p 377.

Forrester, J.W., "Industrial Dynamics", MIT Press, Cambridge, MA, 1961.

Galup, S.D., R. Dattero, et al, "The enterprise knowledge dictionary", *Knowledge Management Research Practice,* Vol. 1, No. 2, 2003, pp 95-101.

Garud, R. and A. Kumaraswamy, "Vicious and virtuous circles in the management of knowledge: The case of Infosys Technologies", *MIS Quarterly,* Vol. 29, No. 1, 2005, pp 9-33.

Gruber, T.R, "Toward principles for the design of ontologies used for knowledge sharing", *International Journal of Human and Computer Studies,* Vol. 43, 1995, pp 907-928.

Han, K.H. and J.W. Park, "Process-centered knowledge model and enterprise ontology for the development of knowledge management system", *Expert Systems with Applications,* Vol. 36, No. 4, 2009, pp 7441-7447.

Harrison, A., "Design for Service: Harmonising Product Design With a Service Strategy*", ASME Turbo Expo 2006: Power for Land, Sea, and Air (GT2006)*, American Society of Mechanical Engineers, Barcelona, Spain, 2006, pp 135-143.

Hey, J., "The data, information, knowledge, wisdom chain: The metaphorical link", *Relatório técnico, Intergovernmental Oceanographic Commission (UNESCO)* (Journal Article), 2004.

Holsapple, C.W. and M. Singh, "The knowledge chain model: activities for competitiveness", *Expert Systems with Applications,* Vol. 20, No. 1, 2001, pp 77-98.

Jagtap, S., A.L. Johnson, et al, "In-service information required by engineering designers", *16th International Conference on Engineering Design (ICED'07)*, The Design Society, 2007.

Jones, J. and J. Hayes, "Use of a field failure database for improvement of product reliability", *Reliability Engineering & System Safety,* Vol. 55, No. 2, 1997, pp 131-134.

Kabilan, V., "Ontology for Information Systems (O4IS) Design Methodology", The Royal Institute of Technology, PhD Thesis, 2007.

Kamponpan, L., "Service supply chains", Cranfield University, Cranfield, MSc Thesis, 2007.

Liang, T.-P. "Theory and practice of electronic commerce", Taipei, Taiwan, Hwa-Tai Publishing, 2002.

Lovatt, A.M. and H.R. Shercliff, "Manufacturing process selection in engineering design Part 1: the role of process selection", *Materials and Design,* Vol. 19, No. 5-6, 1998, pp 205-215.

Ma, W., "Factors affecting knowledge reuse: a framework for study", National Sun Yat-sen University, Taiwan, MSc Thesis, 2005.

Malhotra, Y., "Expert systems for knowledge management: crossing the chasm between information processing and sense making", *Expert Systems with Applications,* Vol. 20, No. 1, 2001, pp 7-16.

Markus, M.L., "Toward a Theory of Knowledge Reuse: Types of Knowledge Reuse Situations and Factors in Reuse Success", *Journal of Management Information Systems, Vol.* 18, No. 1, 2001, pp. 57-93.

Masood, T., "Enhanced Integrated Modelling Approach to Reconfiguring Manufacturing Enterprises", Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, PhD Thesis, 2009, p 314.

Masood, T., J.A. Erkoyuncu, et al, "A digital decision making framework integrating design attributes, knowledge and uncertainty in aerospace sector", *7th International Conference on Digital Enterprise Technology (DET)*, Athens, Greece, 2011a, pp 1-9.

Masood, T., R. Roy, et al, "Service knowledge feedback to product design: Recent advances, challenges and future trends", *Cranfield University & Rolls-Royce,* Not submitted journal article, 2011b, pp 1-31.

Masood, T. and R. Weston, "An integrated modelling approach in support of next generation reconfigurable manufacturing systems", *International Journal of Computer Aided Engineering and Technology,* Vol. 3, No. 3-4, 2011, pp 372-398.

Masood, T., R. Weston, et al, "A computer integrated unified modelling approach to responsive manufacturing", *International Journal of Industrial and Systems Engineering,* Vol. 5, No. 3, 2010, pp 287-312.

Meier, H., R. Roy, et al, "Industrial Product-Service Systems-IPS2", *CIRP Annals-Manufacturing Technology*, Vol. 59, No. 2, 2010, pp 607-627.

Mont, O.K. "Clarifying the concept of product-service system", *Journal of Cleaner Production,* Vol. 10, No. 3, 2002, pp 237-245.

Mountney, S.L., "Acquisition and sharing of innovative manufacturing knowledge for preliminary design", School of Applied Sciences, Cranfield University, Cranfield, PhD Thesis, 2009.

Neely, A., "Exploring the financial consequences of the servitization of manufacturing", *Operations Management Research,* Vol. 1, No. 2, 2008, pp 103-118.

Nonaka, I., "A dynamic theory of organizational knowledge creation", *Organization Science,* Vol. 5, No. 1, 1994, pp 14-37.

Norman, D., "Incorporating operational experience and design changes in availability forecasts", *Reliability Engineering and System Safety,* Vol. 20, 1988, pp 245-261.

Nowack, M.L., "Design guideline support for manufacturability", University of Cambridge, Cambridge, PhD Thesis, 1997.

Noy, N.F. and D.L. McGuinness, "Ontology Development 101: A Guide to Creating Your First Ontology", 2001, Accessed 2010.

Nunes, V.T., F.M. Santoro, et al, "A context-based model for Knowledge Management embodied in work processes", *Information Sciences,* Vol. 179, No. 15, 2009, pp 2538-2554.

Papakostas, N., K. Efthymiou, et al, "Assembly Process Templates for the Automotive Industry", *3rd CIRP Conference on Assembly Technologies and Systems (CATS 10)*, Trondheim, Norway, 2010, pp 151-156.

Papakostas, N., P. Papachatzakis, et al, "An approach to operational aircraft maintenance planning", *International Journal of Decision Support Systems,* Vol. 48, No. 4, 2010, pp 604-612.

Petkova, V.T., "An analysis of field feedback in consumer electronics industry", Endhoven University of Technology, Netherlands, PhD Thesis, 2003.

Roy, R. and K.S. Cheruvu, "A competitive framework for industrial product-service systems", *International Journal of Internet Manufacturing and Services,* Vol. 2, No. 1, 2009, pp 4-29.

Semy, S.K., M.K. Pulvermacher, et al, "Toward the use of an upper ontology for US government and US military domains: An evaluation", MITRE CORP, BEDFORD MA, 2004.

Sobodu, O., "Knowledge Capture and Representation in Design and Manufacture", School of Industrial and Manufacturing Science, Cranfield University, Cranfield, MSc, 2002.

Sterman, J.D., "Business dynamics: systems thinking and modelling for a complex world", McGraw-Hill, 2000.

Tang, L., Y. Zhao, et al, "Codification vs personalisation: A study of the information evaluation practice between aerospace and construction industries", *International Journal of Information Management,* Vol. 30, No. 4, 2010, pp 315-325.

United Nations, “Manual on statistics of international trade in services”, United Nations Publications, New York, 2002, pp 1-190, <http://www.oecd.org/dataoecd/32/45/2404428.pdf>

Viles, E., D. Puente, et al, "Improving the corrective maintenance of an electronic system for trains", *Journal of Quality in Maintenance Engineering,* Vol. 13, No. 1, 2007, pp 75-87.

Weise, R.H., "Representing the corporation: strategies for legal counsel", USA, Aspen Law & Business Publishers, 1996.

Wilson, T.D., "The nonsense of knowledge management" *Information Research,* Vol. 8, No. 1, 2002.

Young, B., A.F. Cutting-Decelle, et al, "Sharing Manufacturing Information and Knowledge in Design Decision and Support", *Advances in Integrated Design and Manufacturing in Mechanical Engineering* (Journal Article): 2005, pp 173-185.

Zhen, M., T. Masood, et al, "A structured modelling approach to simulating dynamic behaviours in complex organisations", *Production Planning & Control: The Management of Operations,* Vol. 20, No. 6, 2009, pp 496 - 509.