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Product Life Cycle Information Management in the Electronics Supply Chain

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Abstract

Information availability and data transparency are key requirements from manufacturers when supporting products throughout the life cycle, for example when implementing product service systems. The application of embedded wireless technologies into printed circuit boards (PCBs) can help bridging current knowledge gaps and to minimise both technical and financial risk through reduced product downtime, improved quality of tracking and enhanced end-of-life decision making. The application of embedded RFID into PCBs for life cycle monitoring of electronic products to support Product Service Systems is discussed in this paper.

Keywords: Product service system, RFID, knowledge management, risk

1 Introduction

The Product Service System (PSS) is a well-documented sustainable business model and represents a growing area of research that supports the recognised strategic theme of sustainable manufacturing [1]. Under the PSS paradigm companies sell a “service” rather than a product [2]. Manufacturers offering a “service” or a “function” may have a superior selling proposition compared to classical product sales. As shown in Figure 1, product information such as location, status and health, use history and materials/component contents needs to be gathered and updated throughout the whole life cycle. This product information can then be used by the service provider to create company knowledge (to feed back to the design e.g. design for manufacturing (DfM), design for recycling (DfR), design for maintenance) on customer preferences and behaviour, service plans (pre-emptive and scheduled) and costing when bidding for new products.

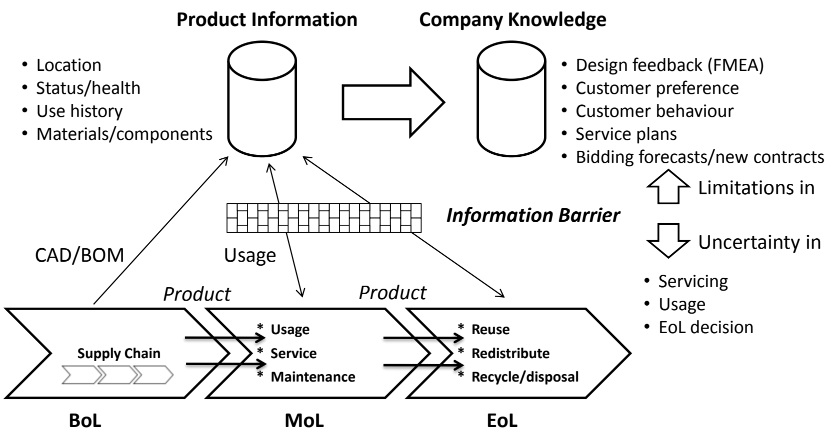

Figure 1: Illustration of the information barriers in the middle of life (MoL) and end of life (EoL) in product service systems.

Product information is not always available during the life cycle of a product [3]. Information flow in the beginning of life (BoL) of the product is closely monitored within industrial companies in the supply chain. Currently tracking data in the middle of life (MoL) and end of life (EoL) is normally not available. These product information barriers cause limitations in extracting knowledge at the OEMs (e.g. when to schedule services, which cost model to use, what the user preferences are). As a result uncertainties are introduced in the product service system, which influences servicing, use-phase of the product and EoL decision making and increases the risk of ownership for the OEM.

A more detailed and continuous view of a product in real-time is needed throughout the whole product life cycle in order to support a sustainable service provision model. The research assertion made in this paper is that risk limitation techniques must be established as a requirement for PSS to be profitably implemented. Risk limitation is needed to maximise operating time as a charged “service per unit basis”, i.e. cost per hour of operation [4] by: i) Shorter time from order to service; ii) Reduced downtimes during use phases; iii) Increased lifetime; and iv) Increased reuse value. It is shown that Product Centric Data (PCD) is crucial to achieve these objectives and that a wireless embedded device, for example a radio frequency identification (RFID) device, can offer enhanced visibility of PCD by overcoming the information barrier within the supply chain during MoL and EoL. It is shown that these results enable the reduction of risk by lowering the amount of uncertainty of life cycle related data. In the approach adopted by the authors, contrary to traditional usage of RFID tagging systems as described for example in [4], RFID tags are embedded into the product (i.e. into the Printed Circuit Board (PCB) of an electronic product) of high value, low volume products and information is gathered and stored into the product throughout its life cycle. Product centric data can be obtained at all stages of the life cycle, starting at the printed circuit board (PCB) manufacturer and can be readily made available to stakeholders even in cases where no global network and connections to central databases are available. The embedding of the RFID tag into the PCB also enables the information to be physically attached, that is impossible to remove or change and which can be used to ensure the authenticity of the product and associated data.

In section 2, an overview of where risks and uncertainties occur in a product service system is described and the literature reviewed on current life cycle monitoring systems. In section 3 the specific risks in a product service system in the electronic domain are highlighted followed by details of how a life cycle monitoring device (e.g. embedded RFID) can be embedded into the structure of a PCB in section 4. Finally in section 5, use cases are described where such embedded devices can reduce risk in a product service system for electronic products.

2 Product service systems risks and uncertainties

Much research work has been done regarding PSS's including definition [1] configurations of a PSS business, and applications as discussed in [5]. In these applications focus has been on costing implications and tools to support a PSS business model, the design issues associated with a PSS, life cycle considerations [6] and supply chain management and logistical issues [7].

The PSS model is attractive for high value items and capital goods that have high inherent value. As shown in Figure 2, the main customer benefit is the "service" supplied by the product (e.g. a vehicle power-train or a jet engine) [8]. In addition the customers also benefit from a reliable service and reduced investment. The major difference to conventional business approaches is in a use-oriented product service system, customers pay for equipment availability and ownership of the product stays with the original equipment manufacturer (OEM) [9].

Resulting from this change in ownership the OEM's major interest is to increase the operation time of the product, which leads to logistical activities and product life cycle servicing [10], which are crucial for the development of a successful PSS strategy. Customer locations, product return planning, and service / maintenance plans are among a wide range of logistical issues which must be addressed in order to support the successful delivery of a PSS.

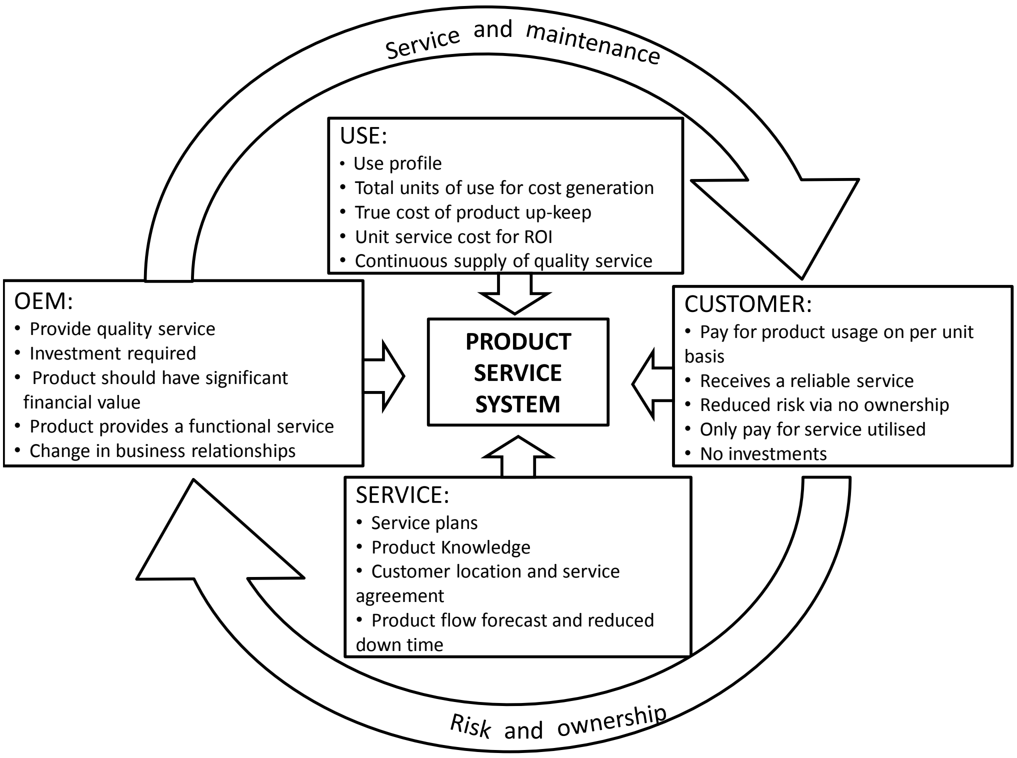

Figure 2: The main characteristics of a product service system.

Risk mitigation can be observed as a consequence of the changed ownership from customer to producer [1]. Equipment availability EA as defined by [11] is a function of mean time between failure (MTBF) and mean time to repair (MTTR) as

$$EA = MTBF / (MTBF + MTTR) \tag{1}$$

As a consequence, MTBF has to be increased while MTTR should be decreased to a minimum. Information about the product and its performance is of paramount importance to achieve these objectives. The barriers for implementing a PSS model have previously been analysed [15] with the conclusion that the most common barrier is a lack of strategic planning. However additional major barriers include the lack of ideal information systems and the lack of PCD throughout a product's complete life cycle.

2.1 Risk due to PSS

2.1.1 Risk and uncertainty definition

Uncertainty generates risk and is founded in poor or missing information [12]. As shown in Figure 3, uncertainty is characterised as "not predictable" and could be either a threat or an opportunity. Examples of uncertainty are MTBF, MTTR, EoL value and currency rates. Risk is defined as the threat of loss (financial [9], reputation quality [1], time [12], and opportunity) from an unwanted event, with uncertainty being the possible reason for the negative event. Risks can be either predictable or unpredictable. Risk for a PSS could be for example, the risk that life cycle costs are higher than the revenue from contracted price per equipment availability. Through the introduction of available, transparent, and accurate product centric data, focused on improving communication it is hypothesised that both uncertainty and therefore risk can be minimised.

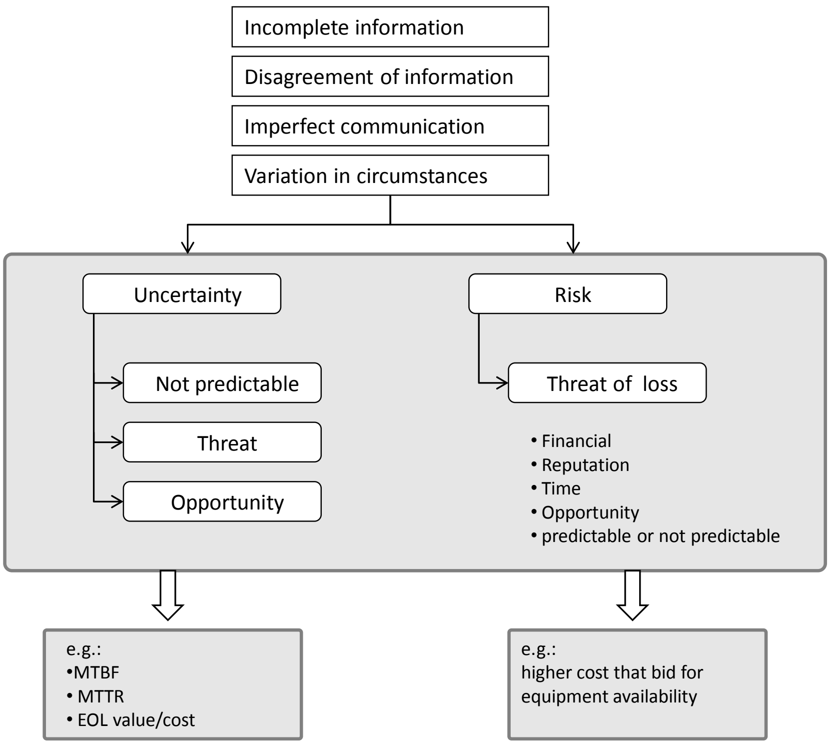

Figure 3: Uncertainty and risk definition derived from [12]

In addition to the perceived risk, there is also the element of uncertainty, which is related to factors such as cost estimates, time scales and work flow [12]. Uncertainty in cost estimates creates a risk resulting from a lack of return on investment to the business through capital needs [9]. Furthermore, the issues with generating a healthy return on investment, cash flow forecasting, and general concerns over profit generation [13], uncertainty and risk, are inhibiting the uptake of PSSs by manufacturers [1].

2.1.2 Risk quantification and classification

Risk measures have been defined in literature in several different ways [14], [15]. The common starting point is to establish both the probability, and the severity of consequence of the risk occurring [16].

Risk (R) can be described by a set of i risk elements, which consist of the risk scenario (S_i), probability (P_i) and consequence (x_i) as shown in equation (2), which was adapted from Kaplan et. al [15].

$$R = \{\langle S_i, P_i, x_i(u) \rangle\} \quad (2)$$

In addition, consequence $x(u)$ is typically a function of uncertainty u. The risk elements can be calculated and visualised in a risk matrix as shown in Figure 4, where the consequence is shown versus the probability of occurrence of each risk element.

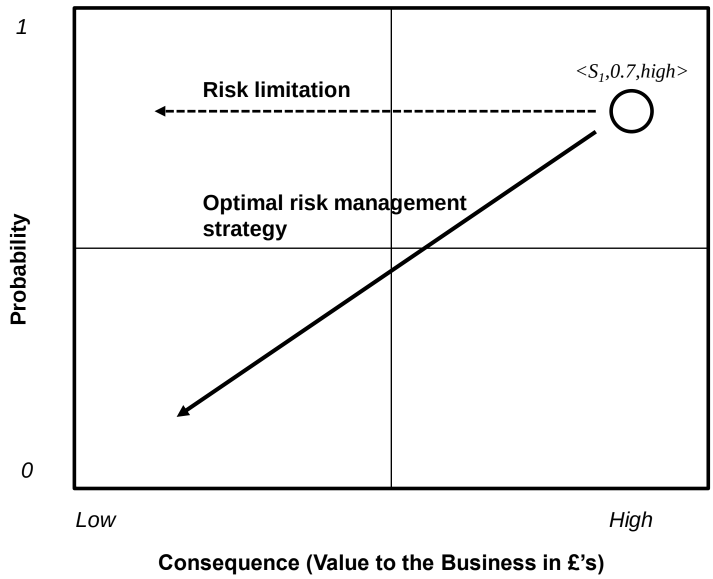

Figure 4: Risk management strategy and risk limitation illustrated in the risk matrix.

Risk management strategies typically aim to mitigate risk elements from the top right quadrant to the lower left quadrant [16].

The probability of an occurrence cannot be affected by the proposed embedded information system. However, the availability of information could limit the consequence of the occurrence via reduced uncertainty of required information. Therefore risk limitation (i.e. movements of risk sets horizontally to the left), rather than full mitigation, where also probabilities would be reduced, is discussed in this paper. Risk limitation can be achieved via the timely availability of product life cycle information, which is directly stored within the product.

2.1.3 Life cycle information

Life cycle information is central to PSS implementation. Furthermore performance data collected during customer usage can help to provide a better understanding of the product during its life, to enable optimisation of servicing and maintenance plans, improve overall product quality and wear characteristics and hence the increase value of the service supplied. With product ownership and subsequent investments being the responsibility of the OEM, quality and reliability are key to reducing running costs, retain brand reputation and to maximising return on investment. To fully supporting this fully, system data transparency, consistency, correctness and validity is critical.

2.2 Cash flow in a PSS

A typical cash flow profile throughout the life cycle of a product is shown in Figure 5. Contrary to usual product sale cash flows, positive cash flow (revenue) is dependent on the equipment's availability in the use-phase or middle of life (MoL). To increase profitability of a PSS a company has to decrease non-operating times i.e. time to service delivery and mean time to repair or service. Costs during the time to service delivery arise from manufacturing, distribution and installation and delivery.

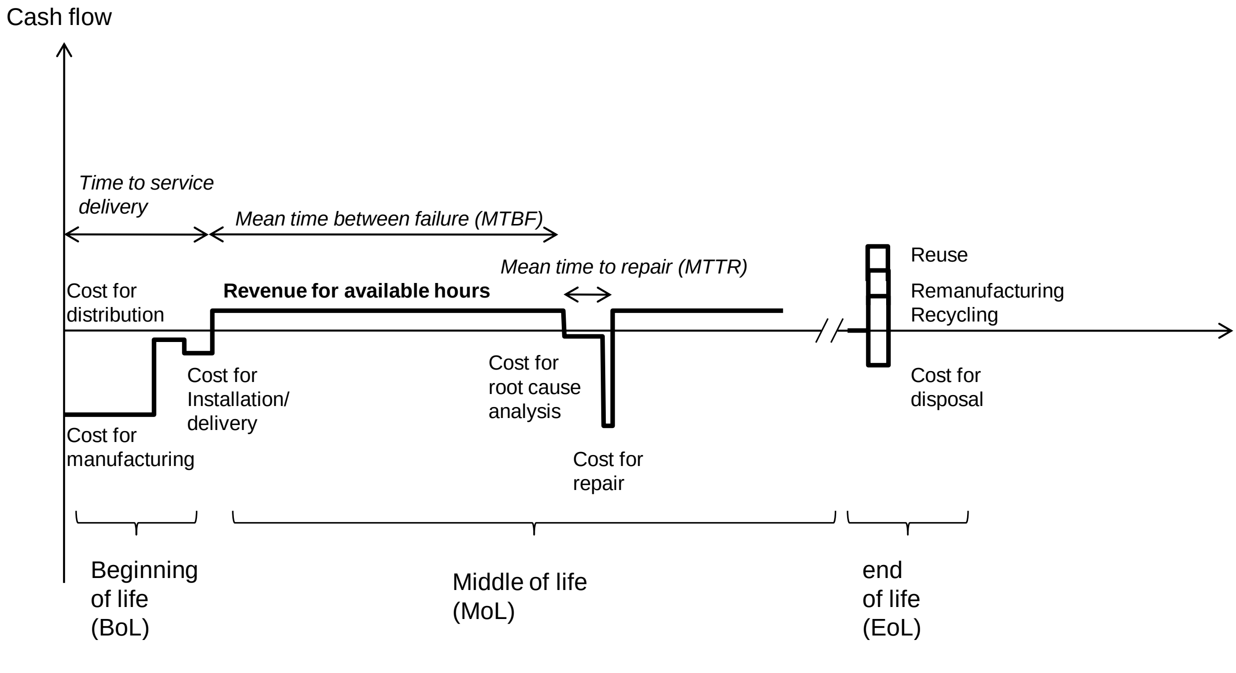

Figure 5: Cash flow in a product service system for high value low volume electronic products.

These costs can be predicted from manufacturing experience. However, costs incurred during the use phase of a product / service include those for root cause analysis and repair, which occur during servicing and maintenance. Uncertainties exist here, as MTBF and MTTR are also strongly dependent on the scenarios and the efficiency in responding to events (e.g. failures). The need for improvements in life cycle monitoring to enable and timely more accurately and timely prediction of these variables is vital for PSS adaptation [13].

2.3 RFID systems

Radio Frequency Identification (RFID) systems consist of three major parts [17], [18]: 1) RFID tag, i.e. a memory chip, which can store a unique number and typically 512 bits of user defined data and which can be interrogated wirelessly, 2) an RFID reader capably of communicating with the RFID tag, and 3) an application software (typically linked to a database system) which interprets, analyses and visualises the RFID data.

The working principle of passive RFID-labels is illustrated in Figure 5. Energy is transmitted wirelessly to the RFID tag, which is scavenged by the RFID-label's antenna [19]. The scavenged energy is rectified and powers the RFID-chip [20]. Information is modulated on the energy fields, which powers the tag. The chip is then able to process the information and responds to the RFID reader by modulating the energy fields, which are back-scattered from the RFID-label to the RFID reader.

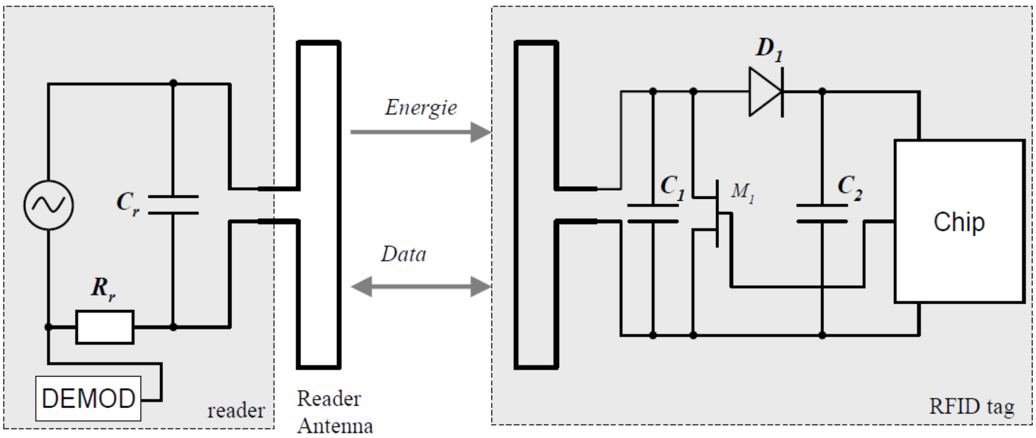

Figure 6: Working principle of a passive RFID tag.

RFID systems have been used in various different industries (e.g. aerospace [21], automotive [22], health care [23], retail) and during different life cycle stages to: 1) trace products through the supply chain, 2) trace quality information, 3) enhance logistics operations, 4) monitor products / animals and 5) prevent counterfeiting of products.

An overview of different application areas can be found in the literature e.g. by Ngai et al. [18] or Chao et al. [24].

2.4 Life cycle monitoring

Life cycle monitoring systems have been proposed as solutions capable of closing the information gap of product centric data across the supply chain between BoL and MoL. A possible system structure for a life cycle monitoring system is presented in Figure 7.

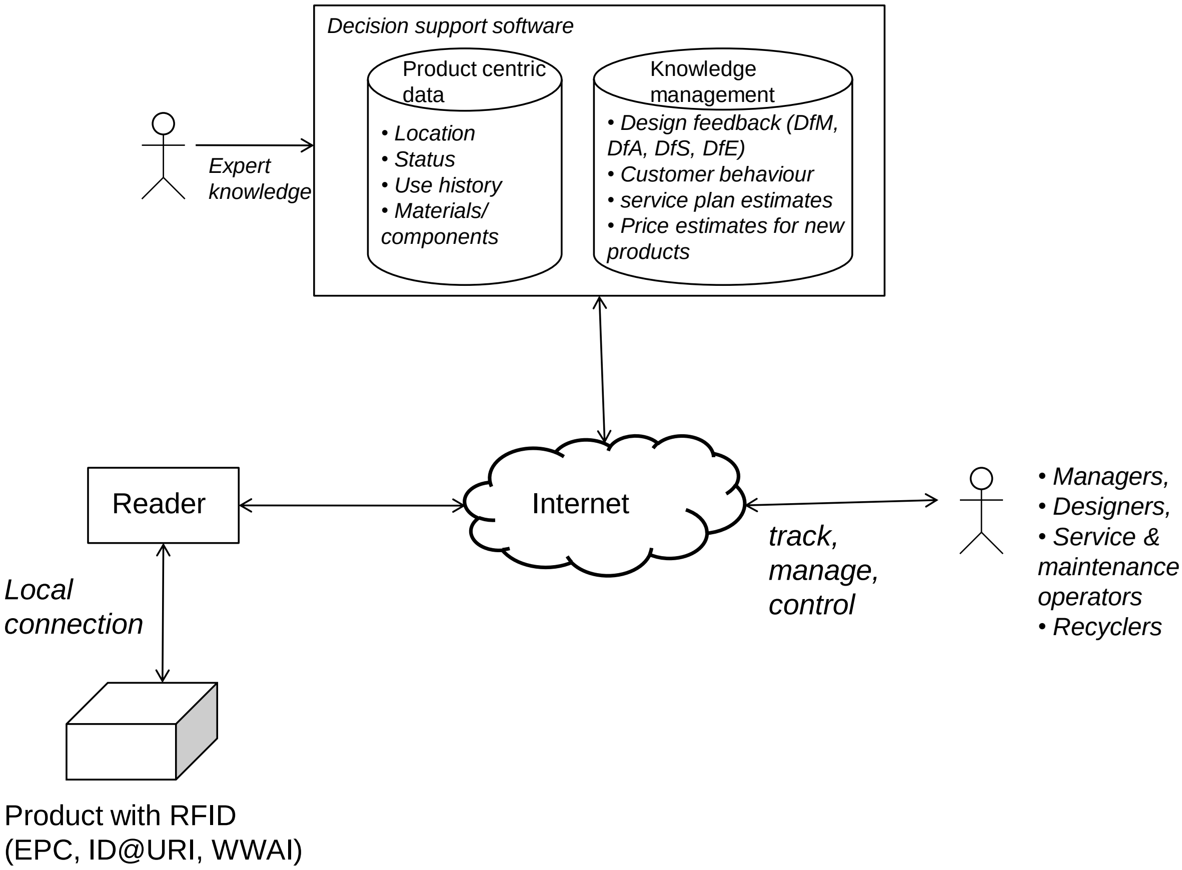

Figure 7: Life cycle management system.

Within this system each product is uniquely identified with an RFID or Barcode, which is interrogated by a reader. Relevant information is linked via an Electronic Product Code (EPC), ID@URI or World Wide Article Information (WWAI) to a specific product. Electronic product code (EPC) is a global standard, which assigns unique numbers to manufacturers and product groups. A unique serial number is stored in the RFID chip and a networked database system links data to this number [17]. ID@URI stores a unique web link to a location in the RFID chip, where relevant data can be accessed. The WWAI scheme uses a peer-to-peer based look-up service to relevant data. A comparison of these identification techniques are presented by Främling et al. [25].

Key elements of decision support software systems are databases that combine product specific information, expert knowledge and aggregated product information in the form of a knowledge management database. A configuration relevant for PSS integration composed of a local connection to the product, an internet connection to the knowledge system, data and information flows and the decision support software is described in [10]. This integrated product life cycle system should enable managers, designers, service maintenance operators and recyclers to "*track, manage, control any time and at any place a product*" [10] and overcome the information gap between the BoL, MoL and EoL.

A similar approach has been presented by Yang [3] where the concept of an intelligent product is used to develop a method for realizing a product service system. The product is equipped with an intelligent data unit (IDU) which acquires the life cycle data [26]. The communication architecture of the knowledge management system is referred to as the communication support infrastructure, while the knowledge support system is termed the Service Enabler. Yang [3] suggests using such a system for remote diagnostics, remote monitoring and use pattern analysis.

These centralised systems [3] assume that all data relevant to the specific product is transferred and updated in the remote central decision support software databases. Although the OEM holds the ownership throughout the life cycle of the product, information is generated in different stages, by different stake holders e.g. in the supplier network, at the user, at the repair facilities. This implies that the partners that create (and use) product data, require interconnected IT systems between partners and OEM. An information backbone is described in [21] that can be established across company borders to update ERP systems. Alternatively the adaption of advantages of e-hubs as a mean of interchanging information between companies is analysed in [27].

In the automotive industry, information inter-connectivity has led to the establishment of the Automotive Network Exchange (ANX) business-to-business virtual private network [28], which is accessible only to certified members [29]. This network allows the direct exchange of information between certified suppliers and OEMs.

3. The risk for OEMs in the electronic domain

Original equipment manufacturers in the electronics manufacturing domain in Europe, in particular in the UK, generally manufacture low volume and high value products since the high volume, low variety products have migrated to manufacturers in the low wage economies. As illustrated in Figure 8, high quality requirements such as reliability, safety, serviceability, recyclability need to be fulfilled. Operations, documents and components for aerospace and defence customers must be treated as confidential. Mounting pressure to increase reuse value as demanded by customers and governments (e.g. the WEEE directive) is also impacting on life cycle support and profitability.

These constraints and requirements lead to logistical, quality, confidentiality, recycling and customer considerations that need to be addressed in the product service system for an electronic product. Product return plans need to be established to account for maintenance and overhaul, repair or disposal at the end of life. It is necessary to know the customer / product location and the status of the product to make decisions on time and content of the product service or maintenance. High quality production and demands for reduced down times require fast root-cause analysis in the event of failure. As such, information flow needs to be integrated across the enterprises spanning the supply chain. Product manufacturing history and visibility of the product within the supply chain is essential to fulfil these demands. At the end of life the reuse value also needs to be optimised (e.g. by determining the value of components and amount of useful life remaining in the product) and regulations (e.g. WEEE, RoHS) require compliance.

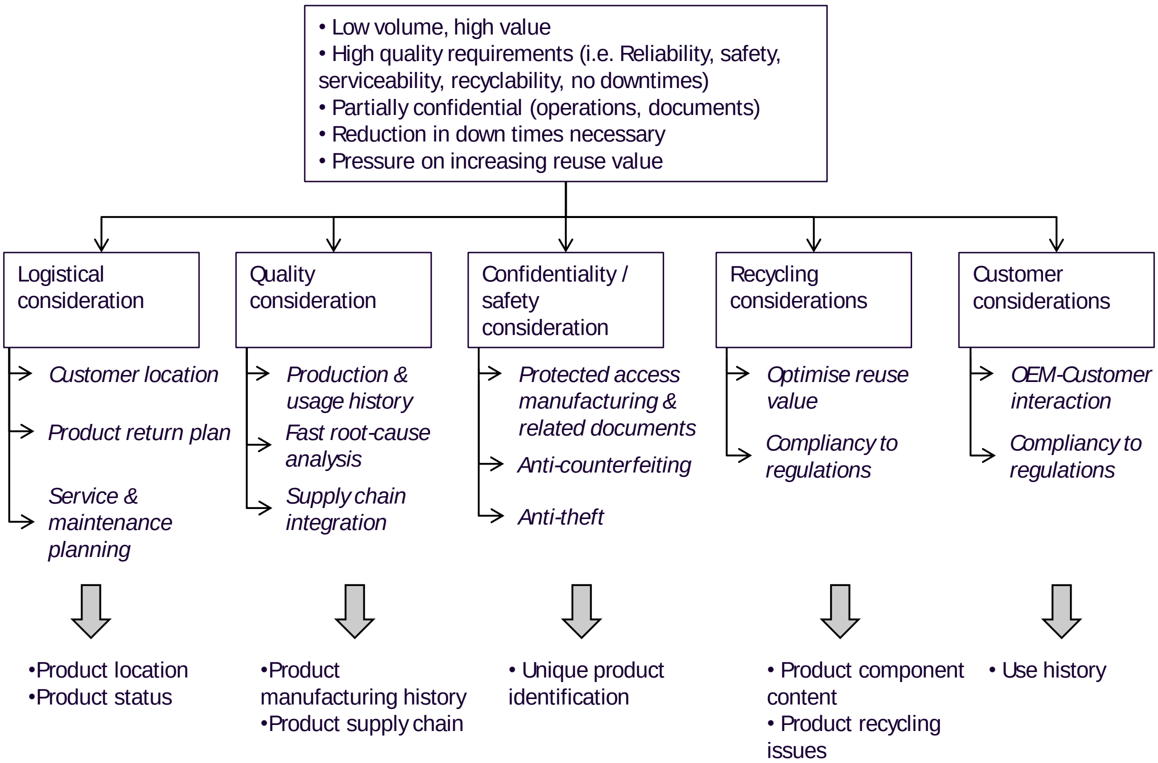

Figure 8: Influences on a product service system in the electronic product domain.

The issues described above lead to a requirement for product centric information including location, status, manufacturing history, supply chain, components, recycling and use history, which is needed for a product service system. Uncertainty and risk arises since this information is not always available for all stakeholders at all locations and times. An overview of these parameters and the risk that develops due to the uncertainty of availability is shown in Table 1. Along with an assessment of the influence this uncertainty has on the PSS proposition is also derived.

The risk of long reaction times to customer requests occurs if the location in production is not known. Interviews with manufacturing experts in the electronic manufacturing domain have revealed that the exact location of work in progress

(WIP) is often uncertain. Customer requests requiring engineering changes or halts in production to address the root causes of field failures can represent severe problems for low volume production or new product introduction (NPI) processes. The influence of delayed reaction to customer requests on the PSS system can be seen in a longer time to service delivery and a longer MTTR.

Manufacturing processes or products usage outside specification is a risk, which can result from uncertain information flow in the supply chain. Often specifications or manufacturing results from one supply chain partner have to be passed onto the subsequent supply chain partner. The usage of experience instead of defined specifications due to lack of information could result in shorter MTBF.

Table 1: Uncertain product data and consequential risk

	Uncertain parameter	Developed risk	Influence on PSS system
Logistics	• Location in production	• Long reaction time to customer requests	• Longer time to service delivery & longer MTTR
	• Information flow in the supply chain	• Missing information forces use of default parameters/ mistreatment of product	• Shorter MTBF
Quality	• Aggregation of manufacturing data (e.g. birth history)	• Time loss in root cause analysis if not available	• Longer MTTR
	• Status of product	• If not available no optimal service plan	• Higher cost to repair/ Longer MTTR
Confidentiality/ Authenticity	• Authenticity of ID/ components	• Usage of non original components or products	• Lower MTTR
Recycling	• Material / component content	• Loss of reuse value	• lower revenue or cost at EOL treatment
Network	• Availability of network communication	• No access to product data and decision support software	•

Time loss in root-cause analysis is a risk that can be related to the uncertainty of availability of aggregated manufacturing data (e.g. birth history) and support for the capture of operational data and working environment monitoring. The time required to locate that could highlight the causes of errors during production or from field returns could lead to higher costs to repair and longer MTTR.

Confidentiality and the need to authenticate original products and components are essential to a PSS. Usage of non original components and products could lead to lower MTTR but also to unresolved liability issues and warranty responsibilities.

Reduced revenue or disposal costs at the end of life of an electronic product is a potential risk if decisions around recycle, reuse or remanufacture cannot be made due to lack of qualitative data. A qualified decision has to be made on the optimal route at the end of life. Loss of reuse value and increased environmental impact resulting from inappropriate EoL decisions could result in lower total revenue for the OEM in the PSS business proposition.

Finally, if distributed networked data systems are used to integrate the product centric data, there exists the risk that relevant information would be not available if network connectivity was lost of unavailable. If there was no capability for autonomous storage of information this would have a severe impact on the associated OEM risk in supporting the PSS.

4. Embedding of RFID system

To increase product visibility throughout the life cycle and to decrease the risk associated with data unavailability, an RFID tag could be embedded with the product at the PCB manufacturer during the initial stages of the electronics manufacturing supply chain (see Figure 8). In this case each board can be traced and information acquired and stored from the beginning of the life cycle of the product.

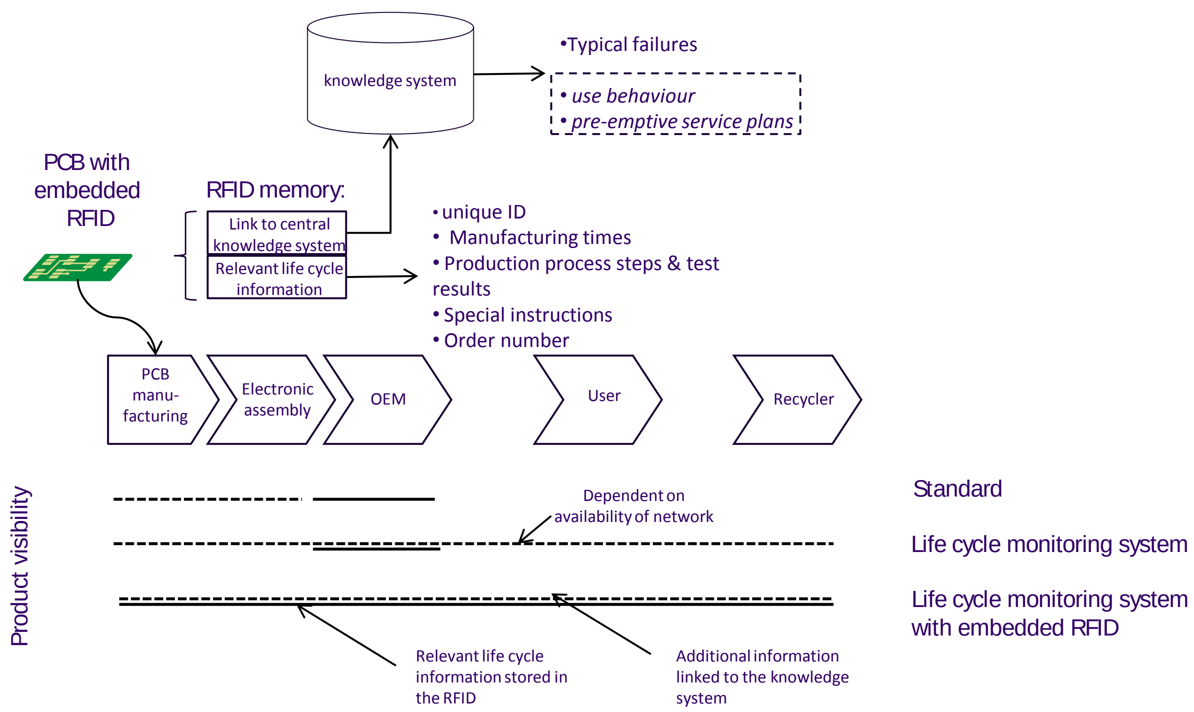

Figure 9: Increase of life cycle product visibility by embedding an RFID tag into the structure of a PCB.

The RFID memory has to be structured, such that relevant information can be added at subsequent life cycle phases. Experts within the electronic manufacturing domain have requested the storage of a unique ID, manufacturing times, production process steps and test results, special instruction and the order number in the limited RFID memory. In addition, provision is required for URL link a central data bases to update stored and additional data at the OEM. This integrated knowledge system would include typical failures, signatures and usage along with monitoring capability part of pre-emptive service plans obviously requiring class 3 RFID devices capable of supporting sensors (e.g. temperature, acceleration, orientation).

By embedding the RFID into the PCB it is physically embedded in the product and stored information travels with the product through the supply chain and throughout the product lifecycle to the user and the recycler.

Original equipment manufacturers standard manufacturing systems (e.g. manufacturing execution systems (MES), Product life cycle management (PLM) and production planning systems (PPS)) typically support product visibility only within the company boundaries. Visibility throughout the supply chain (dashed lines in Figure 9) is possible only if integrated IT systems are adopted.

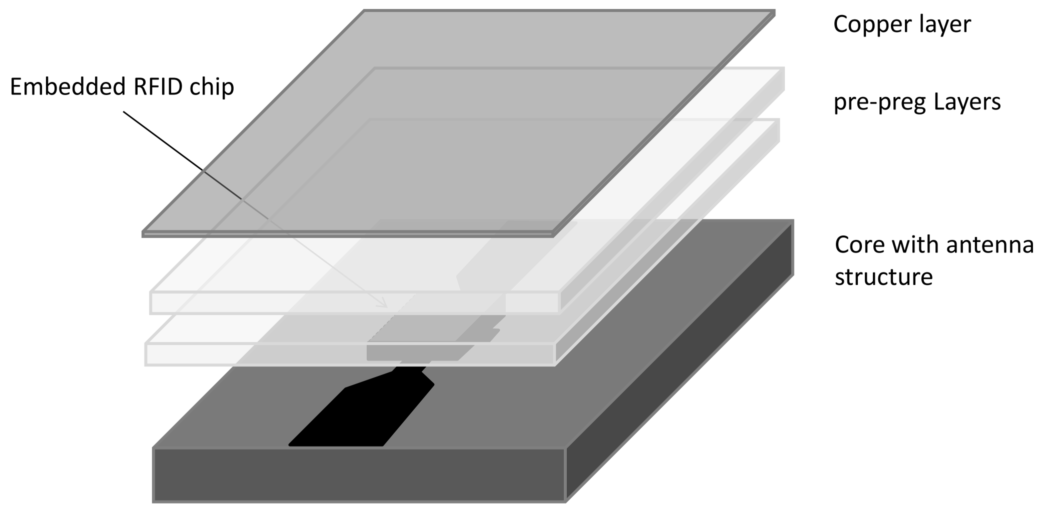

Figure 10: Structure of embedding an RFID tag in between the structure of a printed circuit board.

New life cycle monitoring system approaches, as discussed above, have been proposed to overcome the information boundary between the supply chain and the end user and recycler. However, an IT system or network access needs to be available to allow full product visibility. The uncertainty of network availability introduces a risk of losing visibility during the product life cycle. In contrast, the proposed system with an embedded RFID tag offers ready visibility of relevant product data across the whole life cycle of the product. Only additional operational data is reliant on network connectivity, whilst relevant data is directly accessible from the product itself.

The process of embedding RFID tags into the structure of the PCB is detailed in [30]. In summary, the RFID tag is placed onto an inner surface of a multi-layer board on which the antenna structure has been etched. The multi-layer structure forms a rigid stack of dielectric and conductive layers. After the PCB bonding process the embedded RFID tag is completely encapsulated. A cross-section of the embedded tag is shown in Figure 11.

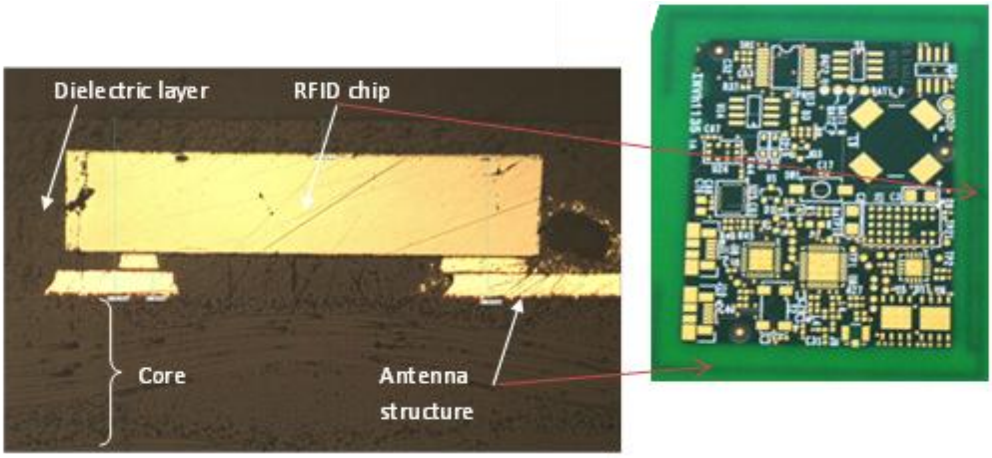

Figure 11: Cross-section of an embedded component in the structure of a printed circuit board.

5. Use cases

Use cases have been analysed in the electronics manufacturing domain with an embedded RFID tag (Higgs-3 supplied by Alien Technologies), in which life cycle data was stored into it, as shown in Figure 9.

The use cases involve

1) Logistical considerations
2) Quality considerations and
3) Recycling considerations

A front end graphical user interface (GUI) has been developed, using the Visual .NET platform to enable the contents of the embedded tag's memory to be visualised along the additional / knowledge linked to the tagged PCB via an embedded URL. A typical window proforma is show in Figure 12.

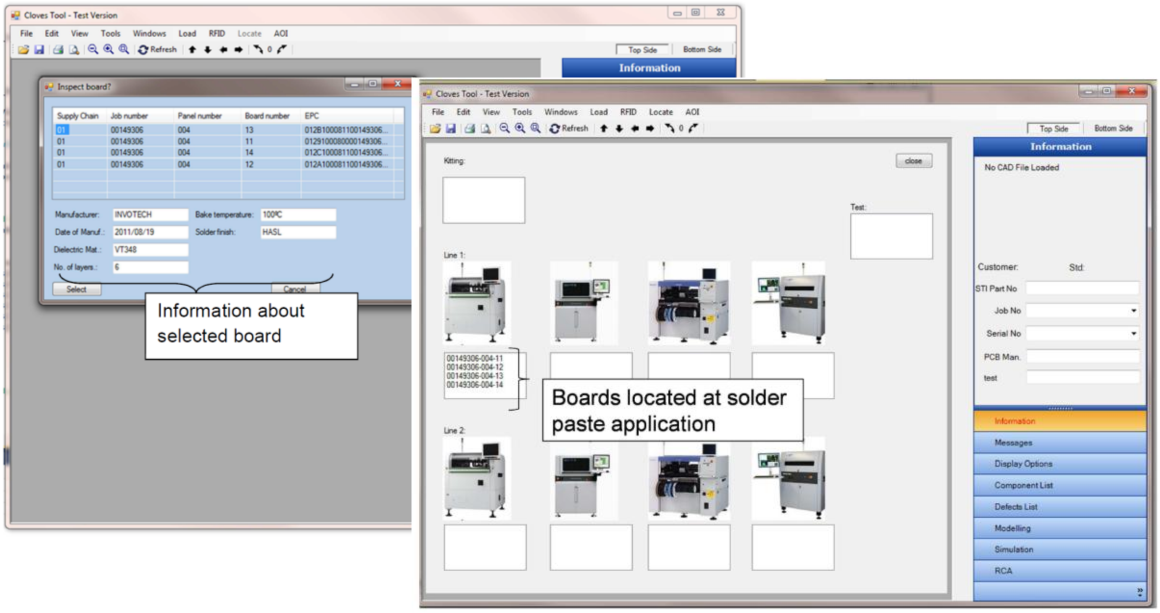

Figure 12: Visualisation software for life cycle monitoring applications.

The system offers the functionality to register the PCB (e.g. unique identification and any special requirements such as baking requirements), store PCB test results and display manufacturing process data in the PCB "memory". Additionally GUI tabs enable the location of the PCB to be determined via triangulation of signal strengths observed at in-plant antenna locations and the PCB registry to be queried.

5.1 Logistical considerations

Information flow and product flow are considered as important logistical considerations of a PSS. Typical business activities within goods inwards of an electronic manufacturer (i.e. the interface in the supply chain between PCB manufacturing and electronic assembly) are illustrated in Figure 13. After the PCB has entered the facility at goods inwards it is passed to the PCB Storage and Moisture control activities. Initial treatment of the PCB (i.e. baking temperature, baking time, temperature ramp rates) has to be decided at this stage. Optimal parameter selection is based on expert knowledge and depends on the technologies used in the PCB (e.g. number of layers, usage of micro vias, specifics of the organic materials).

As this decision is based on human experience and knowledge it is prone to variability which could lead to failures such as delamination or breaks in track interconnections (e.g. micro vias) baking temperature is too high. An embedded RFID tag, which stored the temperature specifications in the product, could reduce this risk of error as the relevant information can be read automatically from the tag's memory.

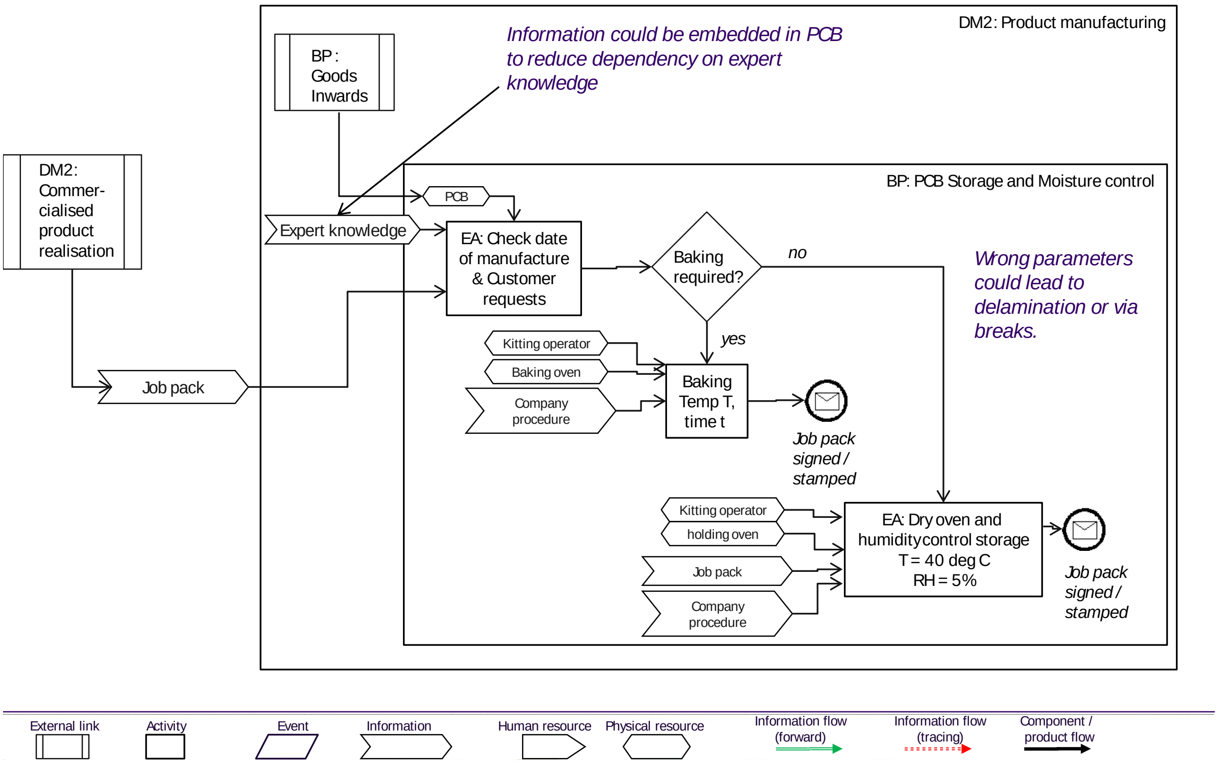

Figure 13: Logistical considerations in the electronic product domain.

5.2 Quality considerations

High quality products are essential to survive in a global market. This is especially important when supplying a product service system in which the OEM retains ownership of the product. Although manufacturing processes are continuously improved, statistical variations and changes (e.g. due to input material variability, wear, operator variability, new technologies) in these processes will be such that the probability of in-process failures can never be reduced to zero. As failures cannot be excluded completely it is essential that root-cause analysis and repair have to take place within a minimum amount of time to minimise the effect on reduced uptime of the product.

A typical corrective action business process and its impact on time and cash flow in a product service system is shown in Figure 14. The time to repair can be divided into three phases:

1. Reaction time from occurrence of the failure to when it is reported to the relevant manufacturer in the supply chain;
2. Time for root cause analysis;
3. Time for repair.

The *reaction time* is influenced by how quickly information can be passed from the user to the OEM and then to the responsible manufacturer/service provider. Currently this information flow is not standardised and often involves manual searches using the ERP or PLM software systems at the OEM. With the manufacturer names and order numbers directly embedded in the product it is possible to assign the information directly to the responsible supplier via a simple examination of the product 'on board' memory.

A major part of root-cause analysis is gathering of relevant manufacturing information about the product under investigation. The typical business activities include: 1) assign and hand over problem description to actionee (EA1.1); 2) finding the job pack and review the job pack (note, the job pack contains the order number of the product, bill of materials and special instructions, EA1.2, see Figure 14); 3) finding the route card (note, the route card is a list of the performed process steps and test results, which are signed off by the operators, a route card is mandatory in safety critical applications, EA1.3); 4) find additional product documentation (e.g. EA1.4); and finally, 5) undertake root-cause analysis (EA1.5). Currently however, the majority of information is stored on paper and has to be located before any corrective action is taken.

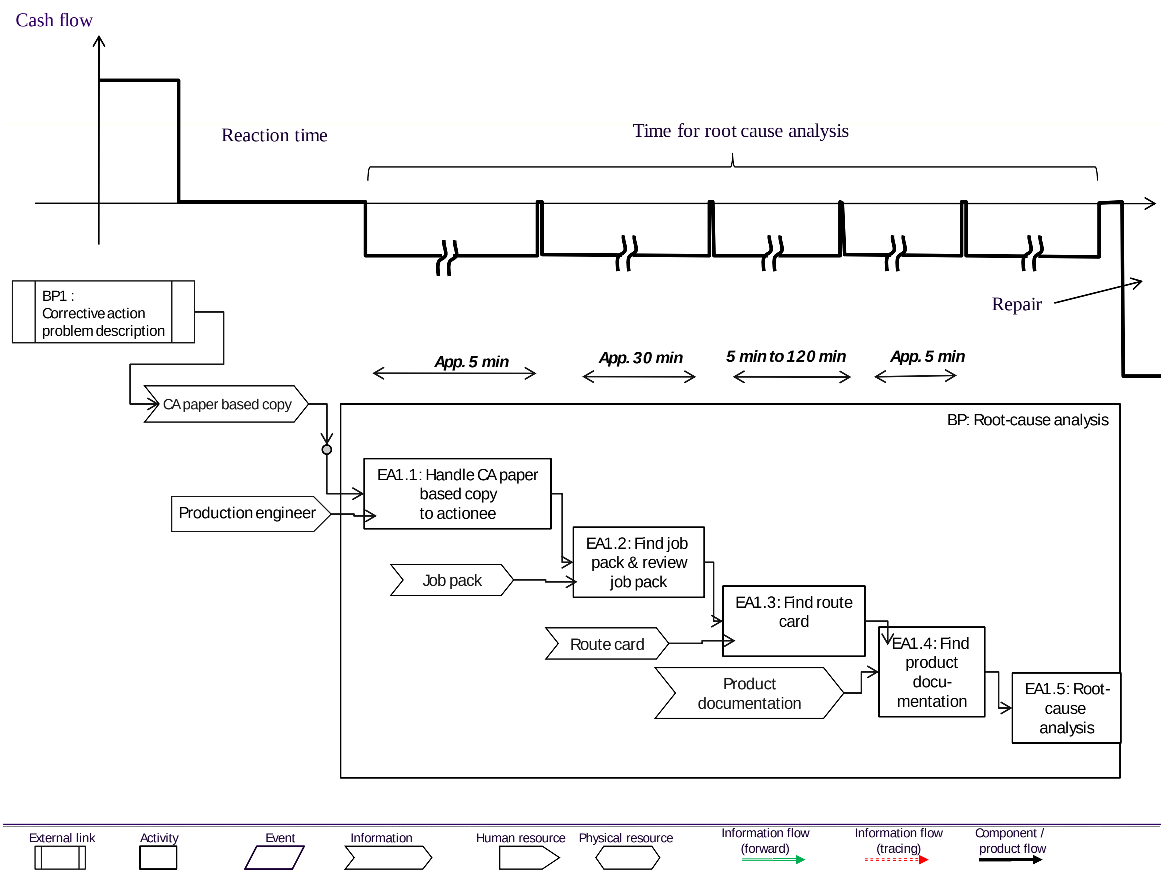

Figure 14: Cash-flow implications during a typical root cause analysis process.

The typical times for these activities, which involve finding relevant product data, are in the range between 45 and 160 minutes (see Figure 14). It has been demonstrated in preliminary tests that with life cycle information embedded in the product, it is possible to directly access these data via a simple read of the tag, which reduces this time to the interrogation time of the embedded RFID.

Additionally, since the information is embedded into the product, the information is accessible at the customer site, which could allow direct intervention and without shipping the product back to the relevant supplier.

5.3 Recycling considerations

End of life responsibilities in a PSS could result in either a cost for recycling or revenue if materials are reused, components reused, product remanufactured or redeployed [1]. An examples EoL decision based process utilising embedded RFID tags has been described by the authors in [31], using a laptop with embedded lifecycle and usage information to test the feasibility of the system. Information was readable from the RFID tag even though the electronics were situated within the casing of the laptop. The decision making at goods inwards, repair and refurbishment could be optimised due to the availability of data.

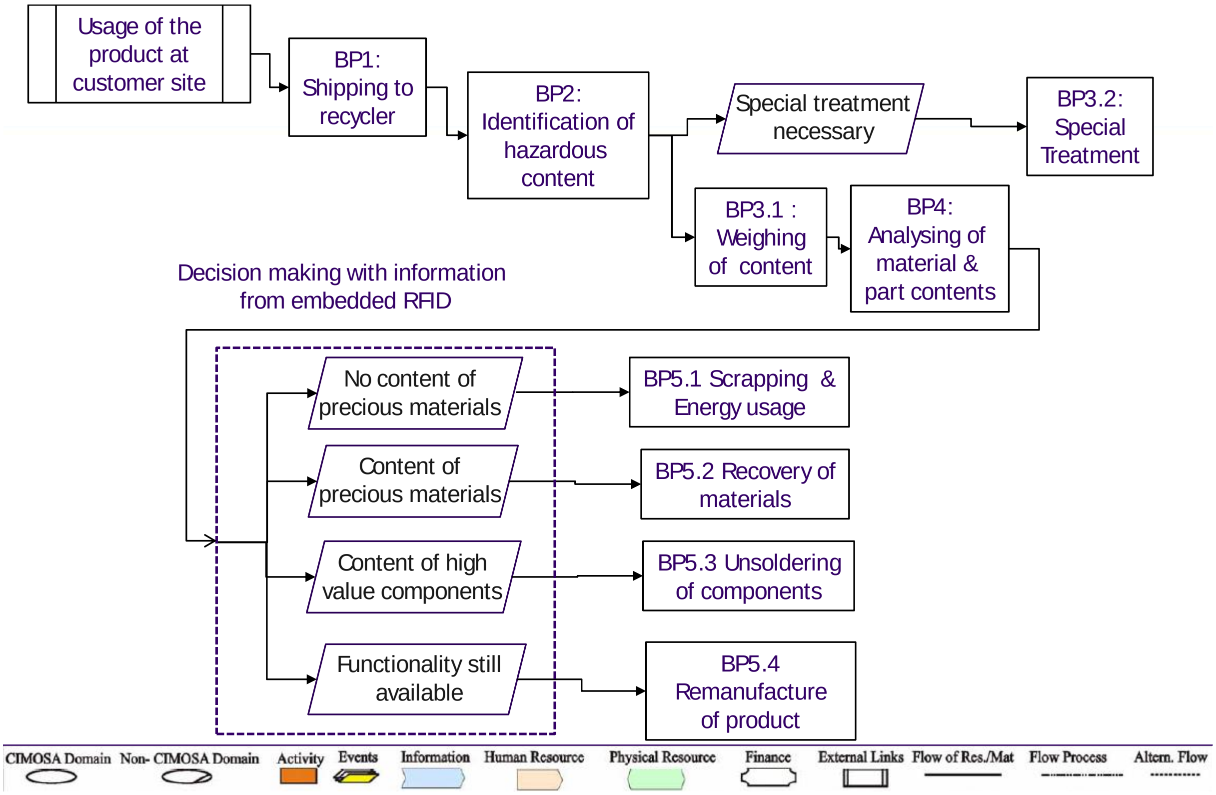

Figure 15: Typical decision making process at the end-of-life of an electronic product.

A schematic of such a decision process has been illustrated in Figure 14 above, where the resultant EoL process determined for a specific product has been based upon a sequence of business processes, the product use data, and the inherent functionality/material content of the product.

5.4 Conclusion to the use cases

The risk limitation for each risk scenario described in the above use cases is illustrated in Figure 16.

Failures of the PCB due to incorrect baking temperature can be nearly totally avoided. This could result in the reduction of the consequence as the amount of the PCB, which could be as high as thousands of pound sterling.

Secondly, the availability of product related information can reduce the reaction time during root-cause analysis significantly (typically 45 to 160). This results in less resource usage and less Mean Time To Repair, which results in reduction in revenue loss in product service system.

Lastly, the product information can be used at the end-of-life of the product to optimise the recycling options. As a result, end-of-life disposal costs can be changed into opportunities. This can be achieved by remanufacturing, reusing of the product or recycling of component and creating a positive revenue stream back to the OEM.

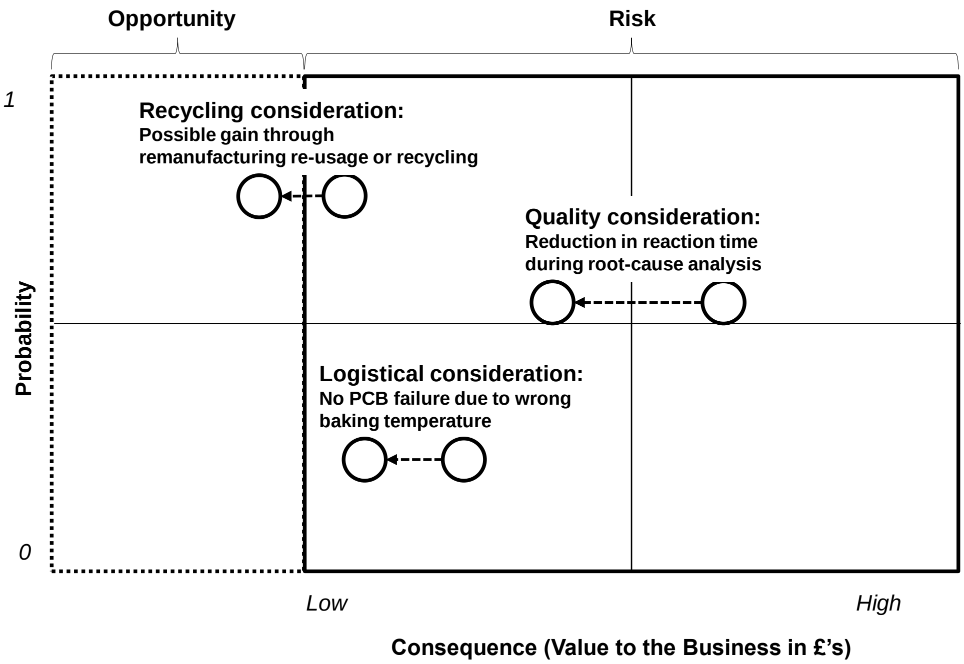

Figure 16:Risk limitations of the use cases, illustrated in the risk matrix.

6 Conclusion and further developments

It has been demonstrated in this paper that embedding of an RFID tag within the structure of the PCB could reduce and limit risks of a product service system within the electronics manufacturing domain by embedding life cycle relevant information such as:

- unique ID;
- manufacturing times;
- production process steps and test results;
- special instruction;
- order number;

In addition, both the risks and uncertainties associated with a PSS have been discussed, and the current data and knowledge gap has been identified. The full lifecycle of the product has been considered, and various key data requirements have been identified. These include: logistical information, quality control and assurance, EoL determination and processing, and product security.

Table 2: Limitation of risks by embedding information into a PCB

	Developed risk	Limitation of risk
Logistics	• Missing information forces use of default parameters/ mistreatment of product	• Automatic reading of instructions (i.e. baking temperature) prevents human error or missing information in paper based system
Quality	• Time loss in root cause analysis if not available	• MTTR reduced by 45 min up to 160 min
Confidentiality/ Authenticity	• Usage of non original components or products	• Identification and data physically embedded into the product. The chip cannot be changed or altered without damaging the product. Data is password protected and not accessible to unauthorised people.
Recycling	• Loss of reuse value	• Marking of relevant or high value components prevents from loss of reuse value.
Network	• No access to product data and decision support software	• Relevant data is embedded into the product and travels with the product. Inaccessibility is reduced to RFID to reader communication. Failures in RFID to reader communication have been shown to be very low.

The paper has addressed how each of these different requirements may be supported by the adoption of secure product intelligence, in the form of embedded RFID tags, and this claim has been supported via the description of a product case study. How a developed risk is reduced by the availability of information directly stored within the product is summaries in Table 2.

A second generation tag has been developed that consists of a high memory RFID chip, external interface to sensors and a microcontroller. This embedded wireless device will enable operational usage behaviour to be monitored including as:

- Usage time and use frequency;
- Use environment (e.g. temperature and humidity);
- Mechanical shocks (e.g. acceleration and turn rates).

7. Acknowledgement

The authors wish to express their gratitude to the project partners for their collaboration. This work is supported by the Technology Strategy Board (TSB) and the Engineering and Physical Sciences Research Council (EPSRC) under the INBOARD (award TP11/HVM/6/I/AB138G) and EMBLEM research proposals.

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Curriculum Vitae

Axel Bindel is a Research Associate at Loughborough University. His research focuses on embedded wireless components, distributed systems and lifecycle monitoring systems. He graduated with a Dipl.-Ing. in Electrical Engineering and Information Technology in 2006 from University of Stuttgart. From 2006 to 2009 he worked for Fraunhofer TEG where he led the research group *Integration of Electronic Systems,* which focused on contract research and consultancy in the field of integrated electronics mainly for the automotive, automation and machine building industry. In 2009 he joined Loughborough University for an industry led collaborative research project in whole life cycle monitoring system with RFID.

Dr Emma Rosamond is lecturer in Sustainable Design and Manufacturing at Loughborough University. Emma graduated as PhD at Loughborough University, focused on prototype design and design methodologies. On completion of her PhD in 2006, Emma joined Pera Innovation, as a project manager in the Recycling Practice - managing UK and European research collaborating projects. She was appointed as the position of Team Leader of the Environmental Practice, and was involved in coordinating research projects, both research and industrial proposals, project contracts and industrial collaborations. In 2009 Emma returned to Loughborough University as a senior research associate in the area of sustainable manufacturing, and in January 2010, Emma was appointed as a lecturer.

Paul Conway is Professor of Manufacturing Processes at Loughborough University, where he heads the Interconnection research Group that has been serving the electronics manufacturing sector since 1989 in contract research, consultancy and training. He is also Academic Director of the UK's Innovative *electronics* Manufacturing Research Centre, established in 2004 by the Engineering and Physical Sciences Research Council. His research interest in process simulation for product and process design and optimisation, materials processing, lead free technologies and optoelectronic packaging.

Dr Andrew West CEng FIMechE is Professor of Intelligent Systems, leader of the Distributed Systems Research Group and founder member of the Manufacturing Systems Integration Research Institute at Loughborough University. His main research focus has been on the lifecycle engineering (e.g. requirements, specification, design, analysis, implementation, maintenance and reuse) of intelligent, distributed, component-based control and monitoring systems. Interests and activities have focussed on a number of areas but are centred on research into the development of the control, monitoring and evaluation of the next generation of manufacturing systems based upon distributed control (i.e. software and hardware) components.

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Date: 31st October 2011

To: Journal of Sports Engineering Manufacture
Proceedings of the Institution of Mechanical Engineers – Part B

Dear Editor:

Enclosed is a paper, entitled: *"*Product Life Cycle Information Management in Electronics Supply chain*"*

Could you please accept this paper as a candidate for publication in the Proceedings of the Institution of Mechanical Engineers – Part B?

The main theme of this article is the application of embedded RFID into PCBs for life cycle monitoring of electronic products to support Product Service Systems is discussed in this paper.

The article documents the authors' approach to help bridging current knowledge gaps in the electronic manufacturing supply chain and to minimise both technical and financial risk through reduced product downtime, improved quality of tracking and enhanced end-of-life decision making.

This paper is our original unpublished work and is not under consideration for publication with any other journals.

Yours Sincerely,

Axel Bindel
Corresponding author

Product Life Cycle Information Management in the Electronics Supply Chain

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Abstract

Information availability and data transparency are key requirements from manufacturers when supporting products throughout the life cycle, for example when implementing product service systems. The application of embedded wireless technologies into printed circuit boards (PCBs) can help bridging current knowledge gaps and to minimise both technical and financial risk through reduced product downtime, improved quality of tracking and enhanced end-of-life decision making. The application of embedded RFID into PCBs for life cycle monitoring of electronic products to support Product Service Systems is discussed in this paper.

Keywords: Product service system, RFID, knowledge management, risk

1 Introduction

The Product Service System (PSS) is a well-documented sustainable business model and represents a growing area of research that supports the recognised strategic theme of sustainable manufacturing [1]. Under the PSS paradigm companies sell a “service” rather than a product [2]. Manufacturers offering a “service” or a “function” may have a superior selling proposition compared to classical product sales. As shown in Figure 1, product information such as location, status and health, use history and materials/component contents needs to be gathered and updated throughout the whole life cycle. This product information can then be used by the service provider to create company knowledge (to feed back to the design e.g. design for manufacturing (DfM), design for recycling (DfR), design for maintenance) on customer preferences and behaviour, service plans (pre-emptive and scheduled) and costing when bidding for new products.

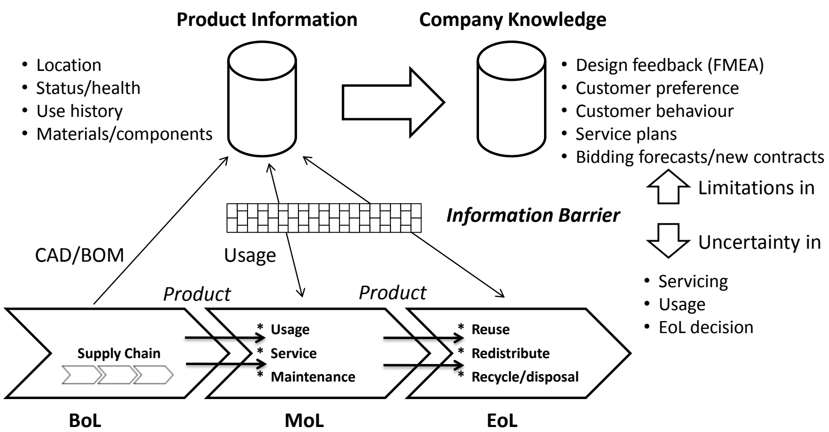

Figure 1: Illustration of the information barriers in the middle of life (MoL) and end of life (EoL) in product service systems.

Product information is not always available during the life cycle of a product [3]. Information flow in the beginning of life (BoL) of the product is closely monitored within industrial companies in the supply chain. Currently tracking data in the middle of life (MoL) and end of life (EoL) is normally not available. These product information barriers cause limitations in extracting knowledge at the OEMs (e.g. when to schedule services, which cost model to use, what the user preferences are). As a result uncertainties are introduced in the product service system, which influences servicing, use-phase of the product and EoL decision making and increases the risk of ownership for the OEM.

A more detailed and continuous view of a product in real-time is needed throughout the whole product life cycle in order to support a sustainable service provision model. The research assertion made in this paper is that risk limitation techniques must be established as a requirement for PSS to be profitably implemented. Risk limitation is needed to maximise operating time as a charged “service per unit basis”, i.e. cost per hour of operation [4] by: i) Shorter time from order to service; ii) Reduced downtimes during use phases; iii) Increased lifetime; and iv) Increased reuse value. It is shown that Product Centric Data (PCD) is crucial to achieve these objectives and that a wireless embedded device, for example a radio frequency identification (RFID) device, can offer enhanced visibility of PCD by overcoming the information barrier within the supply chain during MoL and EoL. It is shown that these results enable the reduction of risk by lowering the amount of uncertainty of life cycle related data. In the approach adopted by the authors, contrary to traditional usage of RFID tagging systems as described for example in [4], RFID tags are embedded into the product (i.e. into the Printed Circuit Board (PCB) of an electronic product) of high value, low volume products and information is gathered and stored into the product throughout its life cycle. Product centric data can be obtained at all stages of the life cycle, starting at the printed circuit board (PCB) manufacturer and can be readily made available to stakeholders even in cases where no global network and connections to central databases are available. The embedding of the RFID tag into the PCB also enables the information to be physically attached, that is impossible to remove or change and which can be used to ensure the authenticity of the product and associated data.

In section 2, an overview of where risks and uncertainties occur in a product service system is described and the literature reviewed on current life cycle monitoring systems. In section 3 the specific risks in a product service system in the electronic domain are highlighted followed by details of how a life cycle monitoring device (e.g. embedded RFID) can be embedded into the structure of a PCB in section 4. Finally in section 5, use cases are described where such embedded devices can reduce risk in a product service system for electronic products.

2 Product service systems risks and uncertainties

Much research work has been done regarding PSS's including definition [1] configurations of a PSS business, and applications as discussed in Mont (2006). In these applications focus has been on costing implications and tools to support a PSS business model, the design issues associated with a PSS, life cycle considerations [5-7] and supply chain management and logistical issues [8-10].

The PSS model is attractive for high value items and capital goods that have high inherent value. As shown in Figure 2, the main customer benefit is the "service" supplied by the product (e.g. a vehicle power-train or a jet engine) [11]. In addition the customers also benefit from a reliable service and reduced investment. The major difference to conventional business approaches is in a use-oriented product service system, customers pay for equipment availability and ownership of the product stays with the original equipment manufacturer (OEM) [12].

Resulting from this change in ownership the OEM's major interest is to increase the operation time of the product, which leads to logistical activities and product life cycle servicing [13], which are crucial for the development of a successful PSS strategy. Customer locations, product return planning, and service / maintenance plans are among a wide range of logistical issues which must be addressed in order to support the successful delivery of a PSS.

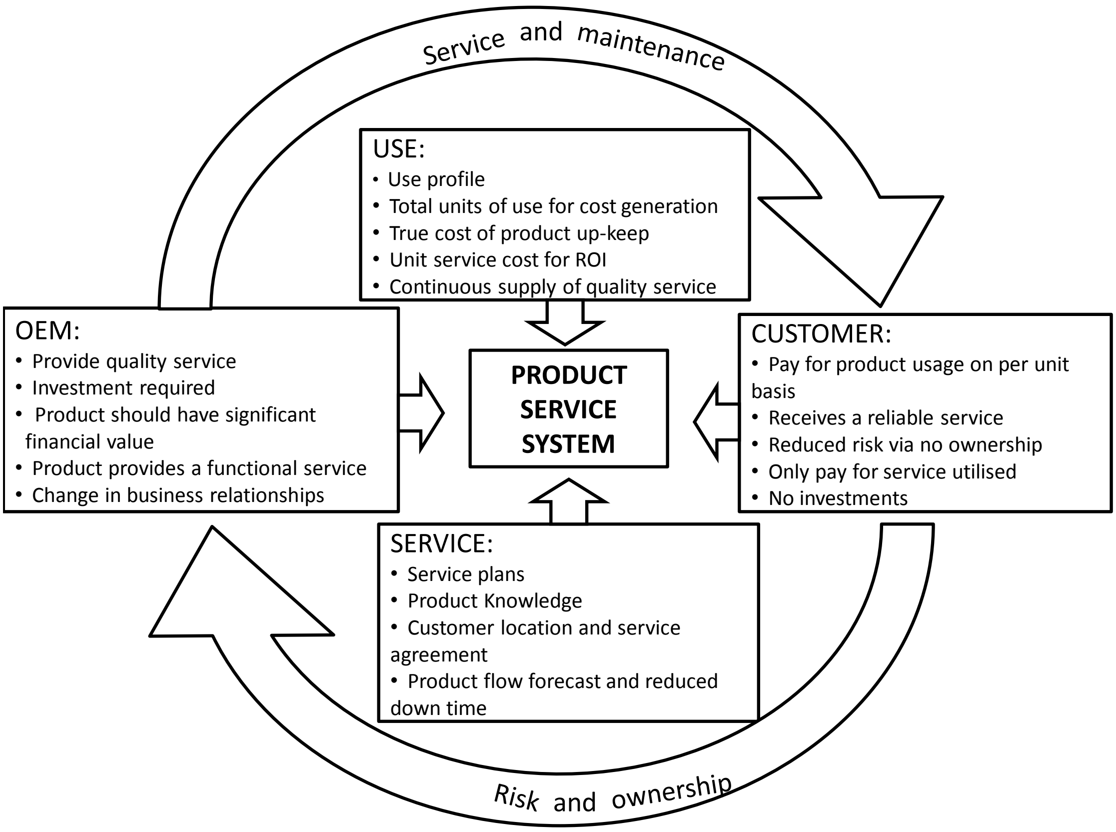

Figure 2: The main characteristics of a product service system.

Risk mitigation can be observed as a consequence of the changed ownership from customer to producer [1]. Equipment availability *EA* as defined by [14] is a function of mean time between failure (MTBF) and mean time to repair (MTTR) as

$$EA = MTBF / (MTBF + MTTR) \tag{1}$$

As a consequence, MTBF has to be increased while MTTR should be decreased to a minimum. Information about the product and its performance is of paramount importance to achieve these objectives. The barriers for implementing a PSS model have previously been analysed [15] with the conclusion that the most common barrier is a lack of strategic planning. However additional major barriers include the lack of ideal information systems and the lack of PCD throughout a product's complete life cycle.

2.1 Risk due to PSS

Uncertainty generates risk and is founded in poor or missing information [16]. As shown in Figure 3, uncertainty is characterised as "not predictable" and could be either a threat or an opportunity. Examples of uncertainty are MTBF, MTTR, EoL value and currency rates. Risk is defined as the threat of loss (financial [12], reputation quality [1], time [16], and opportunity) from an unwanted event, with uncertainty being the possible reason for the negative event. Risks can be either predictable or unpredictable. Risk for a PSS could be for example, the risk that life cycle costs are higher than the revenue from contracted price per equipment availability. Through the introduction of available, transparent, and accurate product centric data, focused on improving communication it is hypothesised that both uncertainty and therefore risk can be minimised.

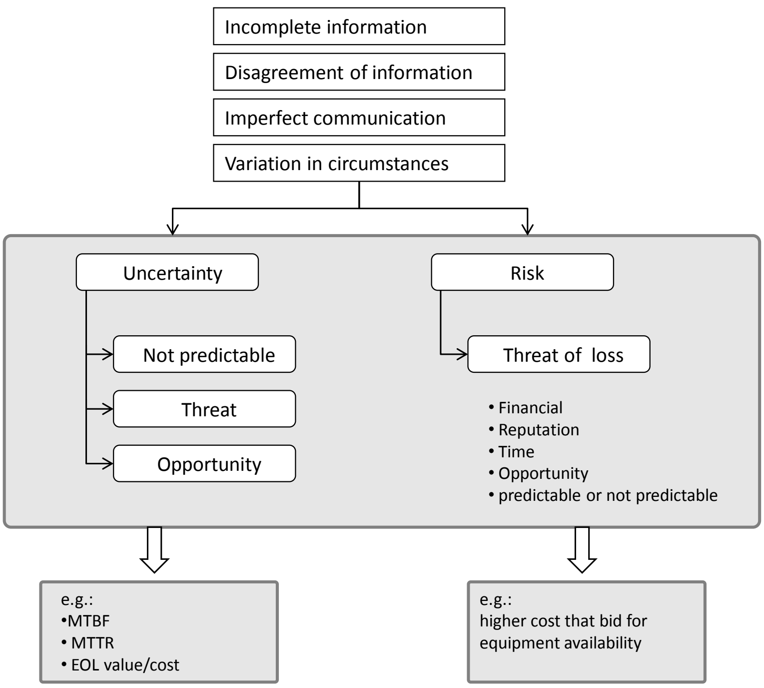

Figure 3: Uncertainty and risk definition derived from [11]

In addition to the perceived risk, there is also the element of uncertainty, which is related to factors such as cost estimates, time scales and work flow [16]. Uncertainty in cost estimates creates a risk resulting from a lack of return on investment to the business through capital needs (Tukker, 2004). Furthermore, associated the issues with generating a healthy return on investment, cash flow forecasting, and general concerns over profit generation [17], uncertainty and risk are inhibiting the uptake of PSSs by manufacturers [1].

Life cycle information is central to PSS implementation. Furthermore performance data collected during customer usage can help to provide a better understanding of the product during its life, to enable optimisation of servicing and maintenance plans, improve overall product quality and wear characteristics and hence the increase value of the service supplied. With product ownership and subsequent investments being the responsibility of the OEM, quality and reliability are key to reducing running costs, retain brand reputation and to maximising return on investment. To fully supporting this fully, system data transparency, consistency, correctness and validity is critical.

2.2 Cash flow in a PSS

A typical cash flow profile throughout the life cycle of a product is shown in Figure 4. Contrary to usual product sale cash flows, positive cash flow (revenue) is dependent on the equipment's availability in the use-phase or middle of life (MoL).

To increase profitability of a PSS a company has to decrease non-operating times i.e. time to service delivery and mean time to repair or service. Costs during the time to service delivery arise from manufacturing, distribution and installation and delivery.

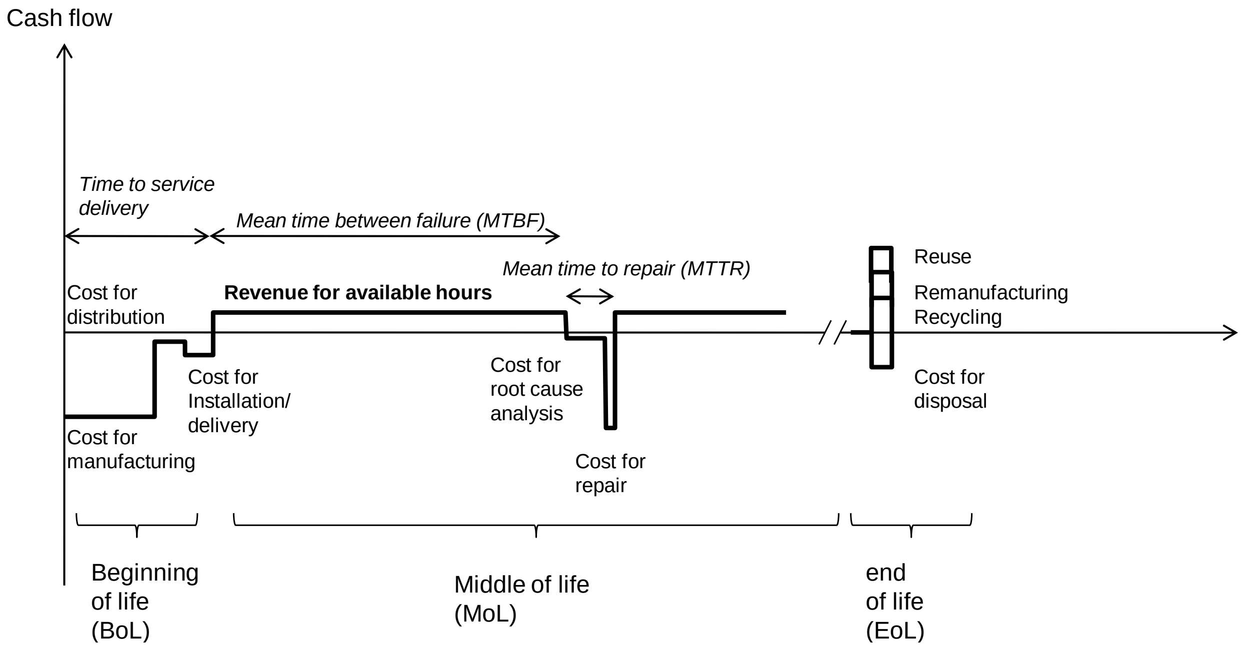

Figure 4: Cash flow in a product service system for high value low volume electronic products.

These costs can be predicted from manufacturing experience. However, costs incurred during the use phase of a product / service include those for root cause analysis and repair, which occur during servicing and maintenance. Uncertainties exist here, as MTBF and MTTR are also strongly dependent on the scenarios and the efficiency in responding to events (e.g. failures). The need for improvements in life cycle monitoring to enable and timely more accurately and timely prediction of these variables is vital for PSS adaptation [12].

2.3 Life cycle monitoring

Life cycle monitoring systems have been proposed as solutions capable of closing the information gap of product centric data across the supply chain between BoL and MoL. A possible system structure for a life cycle monitoring system is presented in Figure 5.

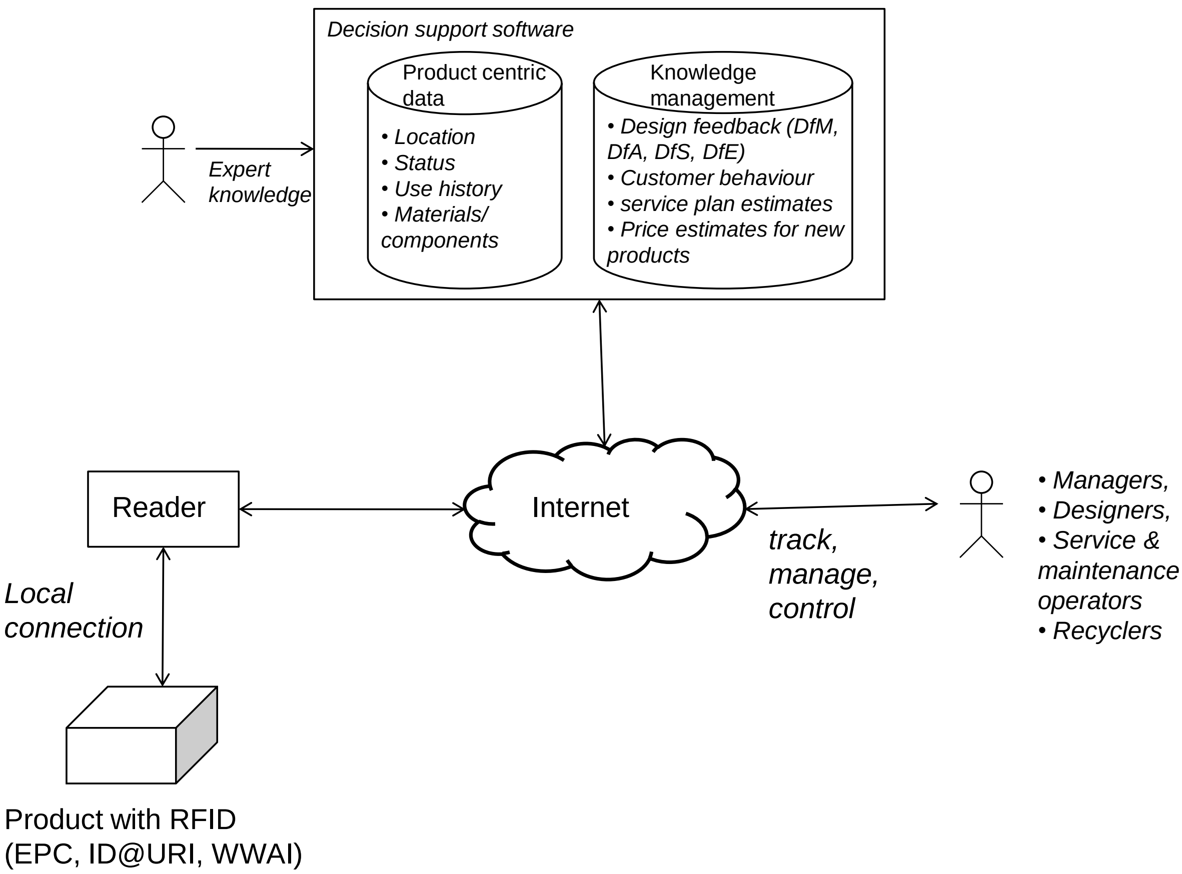

Figure 5: Life cycle management system.

Within this system each product is uniquely identified with an RFID or Barcode, which is interrogated by a reader. Relevant information is linked via an Electronic Product Code (EPC), ID@URI or World Wide Article Information (WWAI) to a specific product. Electronic product code (EPC) is a global standard, which assigns unique numbers to manufacturers and product groups. A unique serial number is stored in the RFID chip and a networked database system links data to this number [18]. ID@URI stores a unique web link to a location in the RFID chip, where relevant data can be accessed. The World Wide Article Information (WWAI) scheme uses a peer-to-peer based look-up service to relevant data. A comparison of these identification techniques are presented by Främling et al. [19] .

Key elements of decision support software systems are databases that combine product specific information, expert knowledge and aggregated product information in the form of a knowledge management database. A configuration relevant for PSS integration composed of a local connection to the product, an internet connection to the knowledge system, data and information flows and the decision support software is described in [10]. This integrated product life cycle system should enable managers, designers, service maintenance operators and recyclers to "*track, manage, control any time and at any place a product*" [10] and overcome the information gap between the BoL, MoL and EoL.

A similar approach has been presented by Yang [3] where the concept of an intelligent product is used to develop a method for realizing a product service system. The product is equipped with an intelligent data unit (IDU) which acquires the life cycle data [20]. The communication architecture of the knowledge management system is referred to as the communication support infrastructure, while the knowledge support system is termed the Service Enabler. Yang [3] suggests using such a system for remote diagnostics, remote monitoring and use pattern analysis.

These centralised systems [3] assume that all data relevant to the specific product is transferred and updated in the remote central decision support software databases. Although the OEM holds the ownership throughout the life cycle of the product, information is generated in different stages, by different stake holders e.g. in the supplier network, at the user, at the repair facilities. This implies that the partners that create (and use) product data, require interconnected IT systems between partners and OEM. An information backbone is described in [21] that can be established across company borders to update ERP systems. Alternatively the adaption of advantages of e-hubs as a mean of interchanging information between companies is analysed in [22].

In the automotive industry, information inter-connectivity has led to the establishment of the Automotive Network Exchange (ANX) business-to-business virtual private network [23], which is accessible only to certified members [24]. This network allows the direct exchange of information between certified suppliers and OEMs.

3. The risk for OEMs in the electronic domain

Original equipment manufacturers in the electronics manufacturing domain in Europe, in particular in the UK, generally manufacture low volume and high value products since the high volume, low variety products have migrated to manufacturers in the low wage economies. As illustrated in Figure 6, high quality requirements such as reliability, safety, serviceability, recyclability need to be fulfilled. Operations, documents and components for aerospace and defence customers must be treated as confidential. Mounting pressure to increase reuse value as demanded by customers and governments (e.g. the WEEE directive) is also impacting on life cycle support and profitability.

These constraints and requirements lead to logistical, quality, confidentiality, recycling and customer considerations that need to be addressed in the product service system for an electronic product. Product return plans need to be established to account for maintenance and overhaul, repair or disposal at the end of life. It is necessary to know the customer / product location and the status of the product to make decisions on time and content of the product service or maintenance. High quality production and demands for reduced down times require fast root-cause analysis in the event of failure. As such, information flow needs to be integrated across the enterprises spanning the supply chain. Product manufacturing history and visibility of the product within the supply chain is essential to fulfil these demands. At the end of life the reuse value also needs to be optimised (e.g. by determining the value of components and amount of useful life remaining in the product) and regulations (e.g. WEEE, RoHS) require compliance.

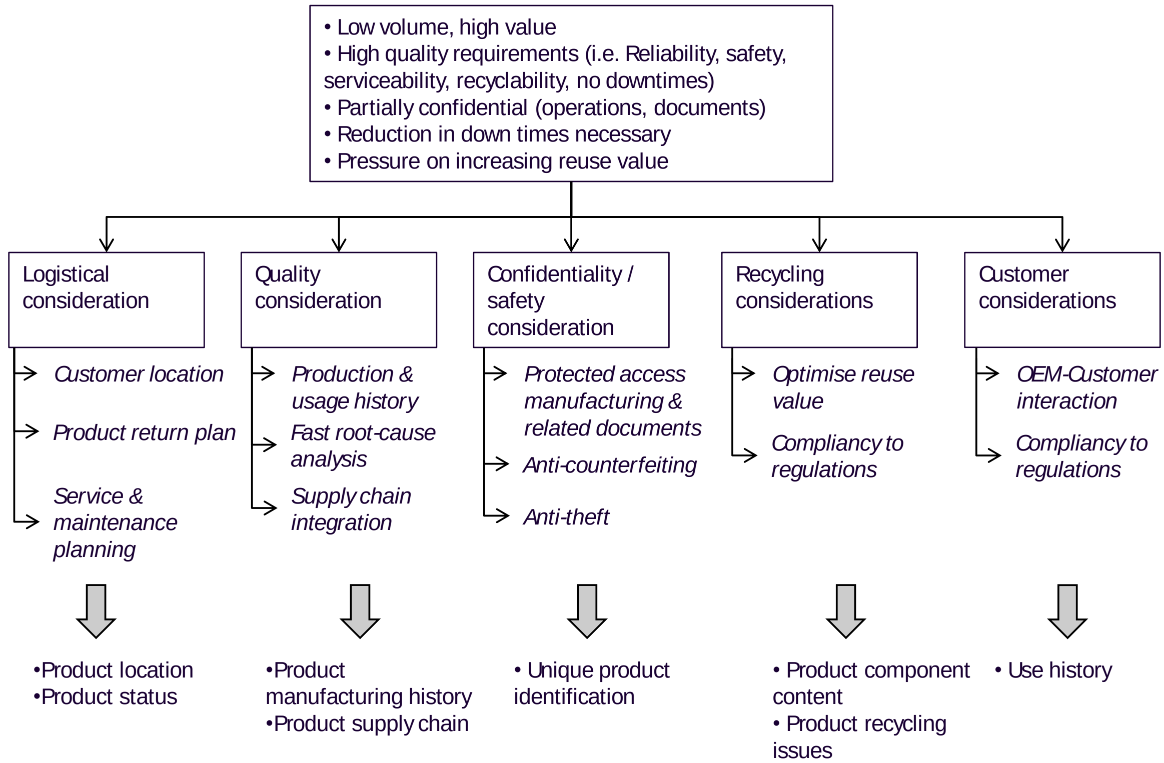

Figure 6: Influences on a product service system in the electronic product domain.

The issues described above lead to a requirement for product centric information including location, status, manufacturing history, supply chain, components, recycling and use history, which is needed for a product service system. Uncertainty and risk arises since this information is not always available for all stakeholders at all locations and times. An overview of these parameters and the risk that develops due to the uncertainty of availability is shown in Table 1. Along with an assessment of the influence this uncertainty has on the PSS proposition is also derived.

The risk of long reaction times to customer requests occurs if the location in production is not known. Interviews with manufacturing experts in the electronic manufacturing domain have revealed that the exact location of work in progress (WIP) is often uncertain. Customer requests requiring engineering changes or halts in production to address the root causes of field failures can represent severe problems for low volume production or new product introduction (NPI) processes. The influence of delayed reaction to customer requests on the PSS system can be seen in a longer time to service delivery and a longer MTTR.

Manufacturing processes or products usage outside specification is a risk, which can result from uncertain information flow in the supply chain. Often specifications or manufacturing results from one supply chain partner have to be passed onto the subsequent supply chain partner. The usage of experience instead of defined specifications due to lack of information could result in shorter MTBF.

	Uncertain parameter	Developed risk	Influence on PSS system
Logistics	• Location in production	• Long reaction time to customer requests	• Longer time to service delivery & longer MTTR
	• Information flow in the supply chain	• Missing information forces use of default parameters/ mistreatment of product	• Shorter MTBF
Quality	• Aggregation of manufacturing data (e.g. birth history)	• Time loss in root cause analysis if not available	• Longer MTTR
	• Status of product	• If not available no optimal service plan	• Higher cost to repair/ Longer MTTR
Confidentiality/ Authenticity	• Authenticity of ID/ components	• Usage of non original components or products	• Lower MTTR
Recycling	• Material / component content	• Loss of reuse value	• lower revenue or cost at EOL treatment
Network	• Availability of network communication	• No access to product data and decision support software	•

Table 1: Uncertain product data and consequential risk

Time loss in root-cause analysis is a risk that can be related to the uncertainty of availability of aggregated manufacturing data (e.g. birth history) and support for the capture of operational data and working environment monitoring. The time required to locate that could highlight the causes of errors during production or from field returns could lead to higher costs to repair and longer MTTR.

Confidentiality and the need to authenticate original products and components are essential to a PSS. Usage of non original components and products could lead to lower MTTR but also to unresolved liability issues and warranty responsibilities.

Reduced revenue or disposal costs at the end of life of an electronic product is a potential risk if decisions around recycle, reuse or remanufacture cannot be made due to lack of qualitative data. A qualified decision has to be made on the optimal route at the end of life. Loss of reuse value and increased environmental impact resulting from inappropriate EoL decisions could result in lower total revenue for the OEM in the PSS business proposition.

Finally, if distributed networked data systems are used to integrate the product centric data, there exists the risk that relevant information would be not available if network connectivity was lost of unavailable. If there was no capability for autonomous storage of information this would have a severe impact on the associated OEM risk in supporting the PSS.

4. Embedding of RFID system

To increase product visibility throughout the life cycle and to decrease the risk associated with data unavailability, an RFID tag could be embedded with the product at the PCB manufacturer during the initial stages of the electronics manufacturing supply chain (see Figure 7). In this case each board can be traced and information acquired and stored from the beginning of the life cycle of the product.

The RFID memory has to be structured, such that relevant information can be added at subsequent life cycle phases. Experts within the electronic manufacturing domain have requested the storage of a unique ID, manufacturing times, production process steps and test results, special instruction and the order number in the limited RFID memory. In addition, provision is required for URL link a central data bases to update stored and additional data at the OEM. This integrated knowledge system would include typical failures, signatures and usage along with monitoring capability part of pre-emptive service plans obviously requiring class 3 RFID devices capable of supporting sensors (e.g. temperature, acceleration, orientation).

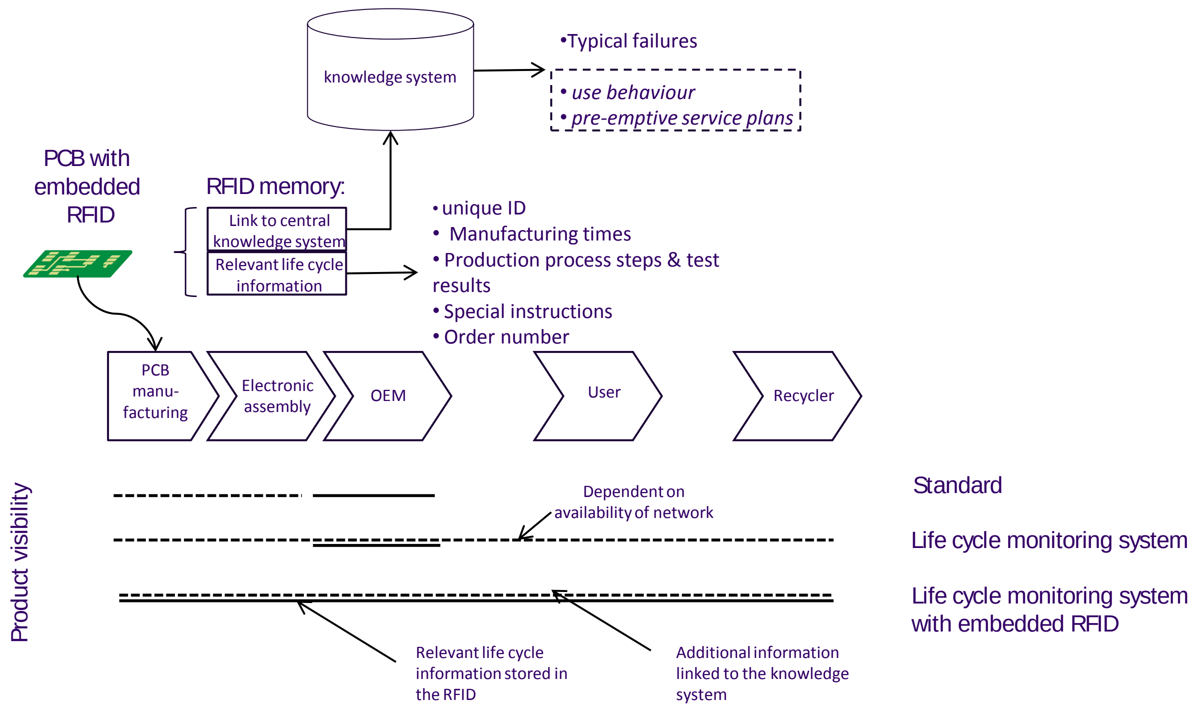

Figure 7: Increase of life cycle product visibility by embedding an RFID tag into the structure of a PCB.

By embedding the RFID into the PCB it is physically embedded in the product and stored information travels with the product through the supply chain and throughout the product lifecycle to the user and the recycler.

Original equipment manufacturers standard manufacturing systems (e.g. manufacturing execution systems (MES), Product life cycle management (PLM) and production planning systems (PPS)) typically support product visibility only within the company boundaries. Visibility throughout the supply chain (dashed lines in Figure 7) is possible only if integrated IT systems are adopted.

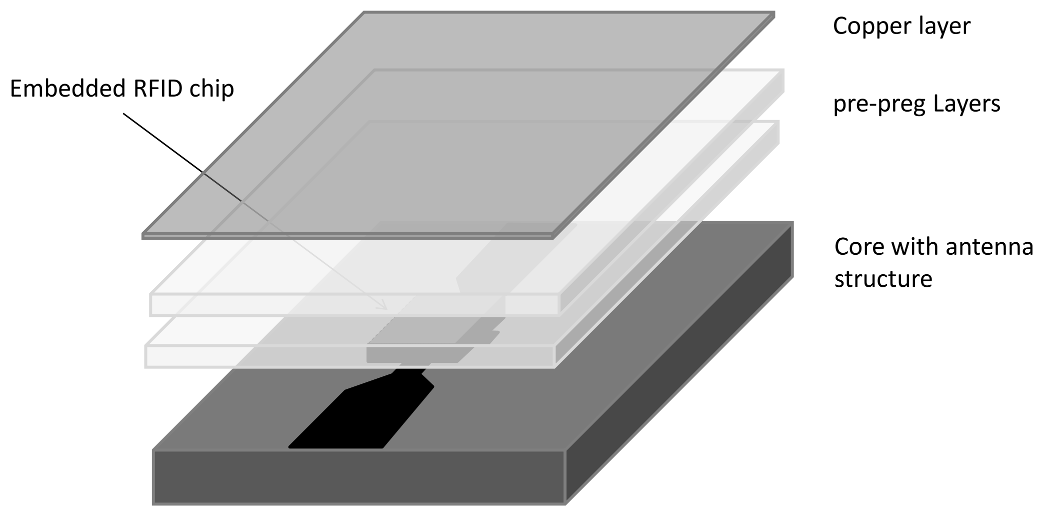

Figure 8: Structure of embedding an RFID tag in between the structure of a printed circuit board.

New life cycle monitoring system approaches, as discussed above, have been proposed to overcome the information boundary between the supply chain and the end user and recycler. However, an IT system or network access needs to be available to allow full product visibility. The uncertainty of network availability introduces a risk of losing visibility during the product life cycle. In contrast, the proposed system with an embedded RFID tag offers ready visibility of relevant product data across the whole life cycle of the product. Only additional operational data is reliant on network connectivity, whilst relevant data is directly accessible from the product itself.

The process of embedding RFID tags into the structure of the PCB is detailed in [29]. In summary, the RFID tag is placed onto an inner surface of a multi-layer board on which the antenna structure has been etched. The multi-layer structure forms a rigid stack of dielectric and conductive layers. After the PCB bonding process the embedded RFID tag is completely encapsulated. A cross-section of the embedded tag is shown in Figure 9.

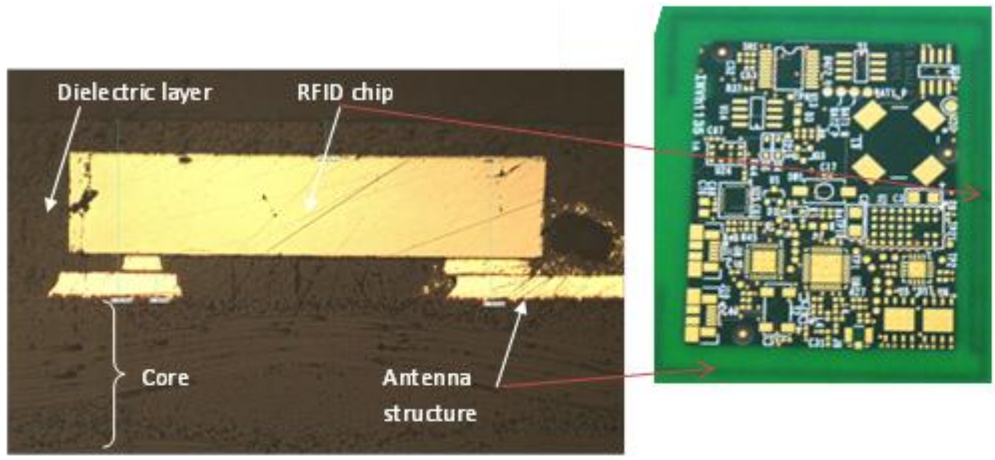

Figure 9: Cross-section of an embedded component in the structure of a printed circuit board.

5. Use cases

Use cases have been analysed in the electronics manufacturing domain with an embedded RFID tag (Higgs-3 supplied by Alien Technologies), in which life cycle data was stored into it, as shown in Figure 7.

The use cases involve

1) Logistical considerations

2) Quality considerations and

3) Recycling considerations

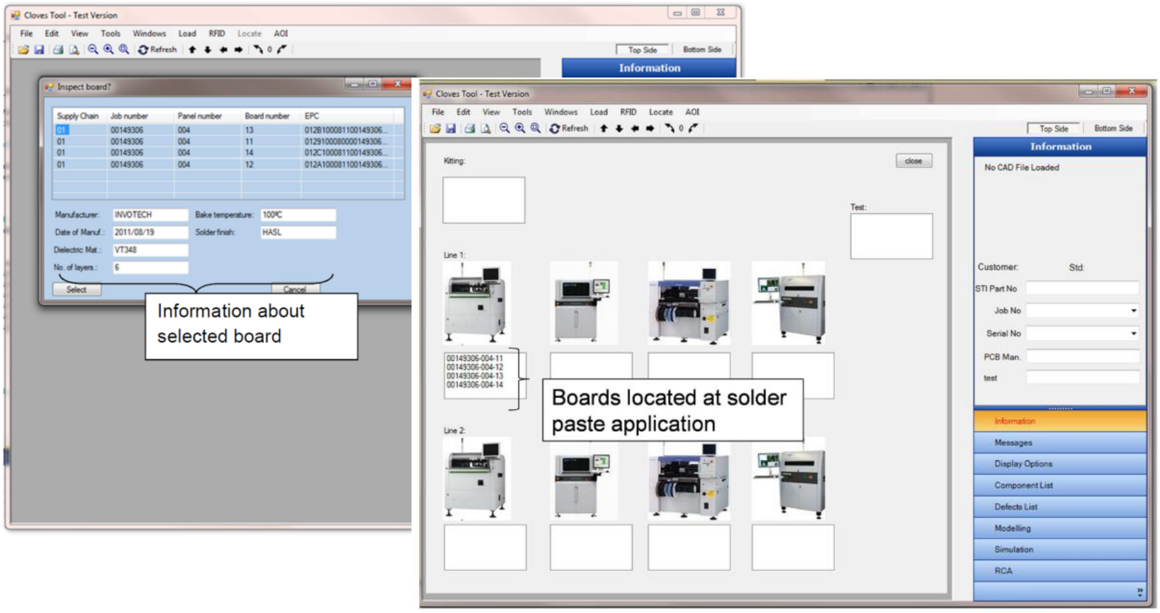

Figure 10: Visualisation software for life cycle monitoring applications.

A front end graphical user interface (GUI) has been developed, using the Visual .NET platform to enable the contents of the embedded tag's memory to be visualised along the additional / knowledge linked to the tagged PCB via an embedded URL. A typical window proforma is show in Figure 10.

The system offers the functionality to register the PCB (e.g. unique identification and any special requirements such as baking requirements), store PCB test results and display manufacturing process data in the PCB "memory". Additionally GUI tabs enable the location of the PCB to be determined via triangulation of signal strengths observed at in-plant antenna locations and the PCB registry to be queried.

5.1 Logistical considerations

Information flow and product flow are considered as important logistical considerations of a PSS. Typical business activities within goods inwards of an electronic manufacturer (i.e. the interface in the supply chain between PCB manufacturing and electronic assembly) are illustrated in Figure 11. After the PCB has entered the facility at goods inwards it is passed to the PCB Storage and Moisture control activities. Initial treatment of the PCB (i.e. baking temperature, baking time, temperature ramp rates) has to be decided at this stage. Optimal parameter selection is based on expert knowledge and depends on the technologies used in the PCB (e.g. number of layers, usage of micro vias, specifics of the organic materials).

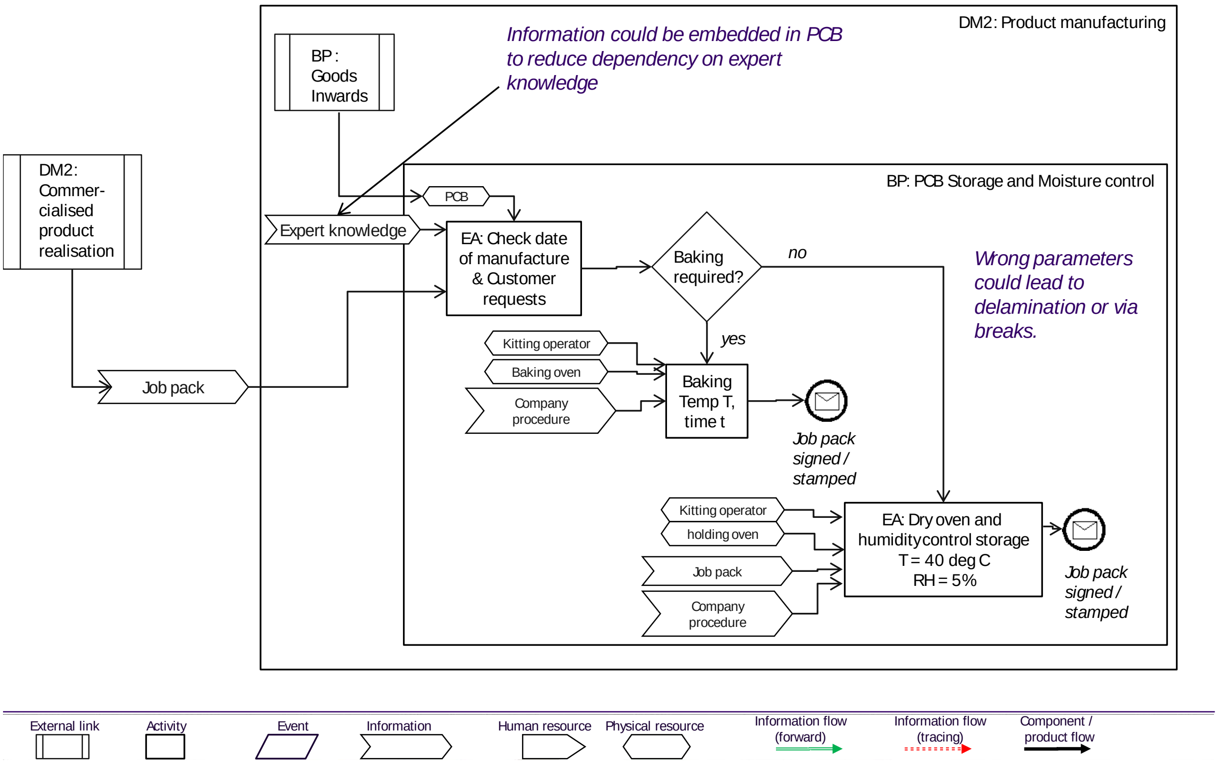

Figure 11: Logistical considerations in the electronic product domain.

As this decision is based on human experience and knowledge it is prone to variability which could lead to failures such as delamination or breaks in track interconnections (e.g. micro vias) baking temperature is too high. An embedded RFID tag, which stored the temperature specifications in the product, could reduce this risk of error as the relevant information can be read automatically from the tag's memory.

5.2 Quality considerations

High quality products are essential to survive in a global market. This is especially important when supplying a product service system in which the OEM retains ownership of the product. Although manufacturing processes are continuously improved, statistical variations and changes (e.g. due to input material variability, wear, operator variability, new technologies) in these processes will be such that the probability of in-process failures can never be reduced to zero. As failures cannot be excluded completely it is essential that root-cause analysis and repair have to take place within a minimum amount of time to minimise the effect on reduced uptime of the product.

A typical corrective action business process and its impact on time and cash flow in a product service system is shown in Figure 12. The time to repair can be divided into three phases:

1. Reaction time from occurrence of the failure to when it is reported to the relevant manufacturer in the supply chain;

2. Time for root cause analysis;
3. Time for repair.

The *reaction time* is influenced by how quickly information can be passed from the user to the OEM and then to the responsible manufacturer/service provider. Currently this information flow is not standardised and often involves manual searches using the ERP or PLM software systems at the OEM. With the manufacturer names and order numbers directly embedded in the product it is possible to assign the information directly to the responsible supplier via a simple examination of the product 'on board' memory.

A major part of root-cause analysis is gathering of relevant manufacturing information about the product under investigation. The typical business activities include: 1) assign and hand over problem description to actionee (EA1.1); 2) finding the job pack and review the job pack (note, the job pack contains the order number of the product, bill of materials and special instructions, EA1.2, see Figure 12); 3) finding the route card (note, the route card is a list of the performed process steps and test results, which are signed off by the operators, a route card is mandatory in safety critical applications, EA1.3); 4) find additional product documentation (e.g. EA1.4); and finally, 5) undertake root-cause analysis (EA1.5). Currently however, the majority of information is stored on paper and has to be located before any corrective action is taken.

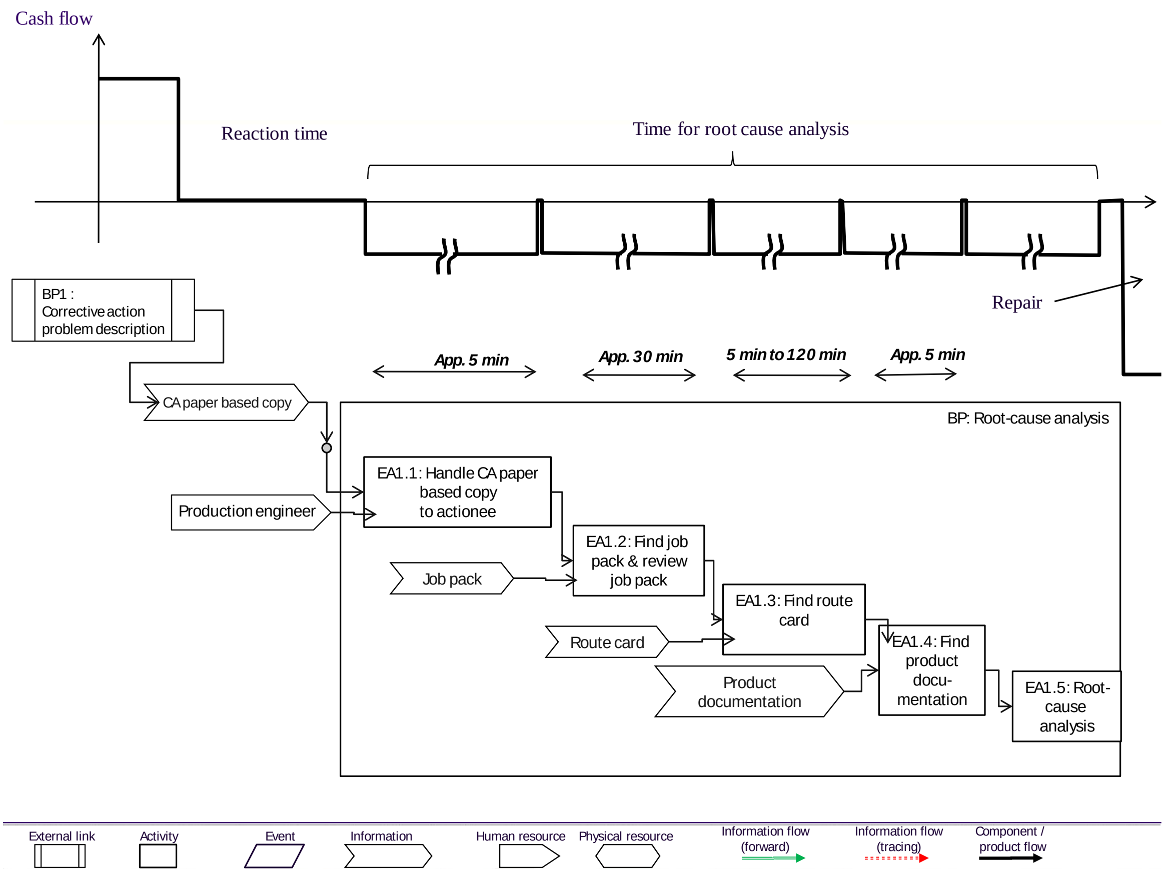

Figure 12: Cash-flow implications during a typical root cause analysis process.

The typical times for these activities, which involve finding relevant product data, are in the range between 45 and 160 minutes (see Figure 12). It has been demonstrated in preliminary tests that with life cycle information embedded in the product, it is possible to directly access these data via a simple read of the tag, which reduces this time to the interrogation time of the embedded RFID.

Additionally, since the information is embedded into the product, the information is accessible at the customer site, which could allow direct intervention and without shipping the product back to the relevant supplier.

5.4 Recycling considerations

End of life responsibilities in a PSS could result in either a cost for recycling or revenue if materials are reused, components reused, product remanufactured or redeployed [1]. An examples EoL decision based process utilising embedded RFID tags has been described by the authors in [26], using a laptop with embedded lifecycle and usage information to test the feasibility of the system. Information was readable from the RFID tag even though the electronics were situated within the casing of the laptop. The decision making at goods inwards, repair and refurbishment could be optimised due to the availability of data.

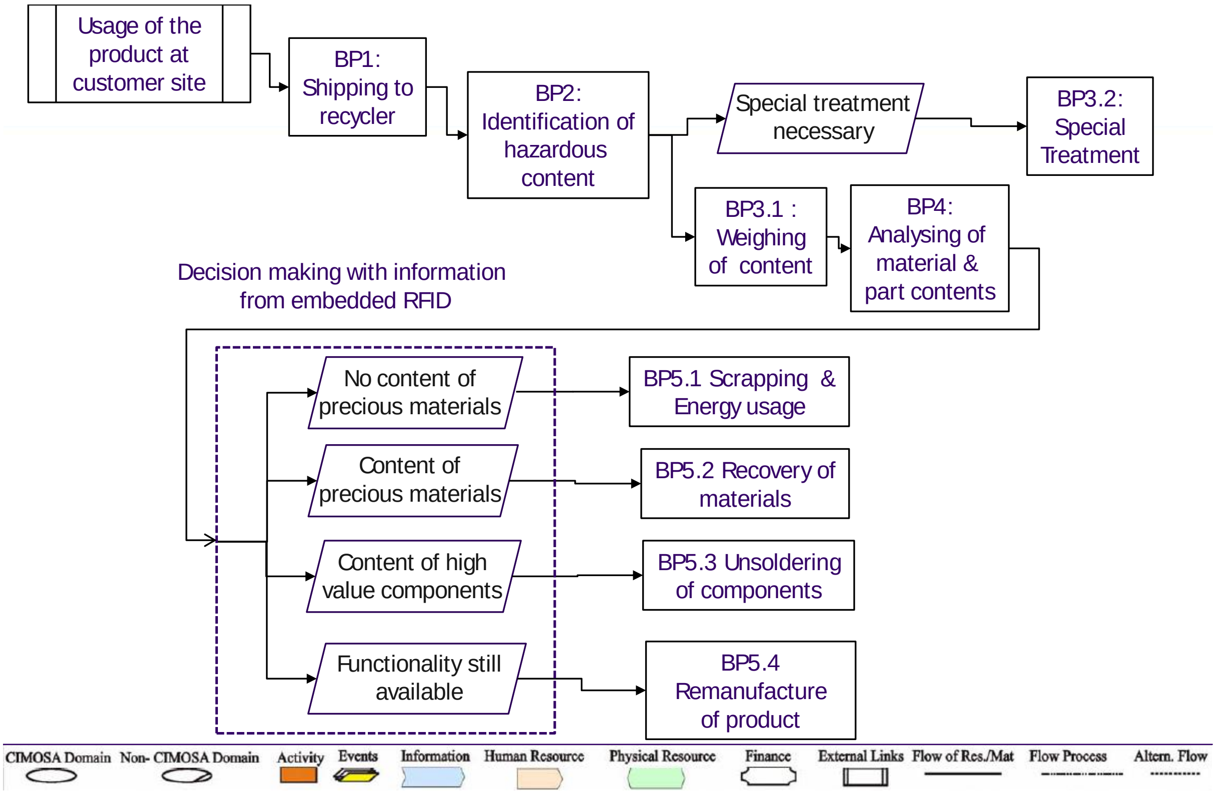

Figure 13: Typical decision making process at the end-of-life of an electronic product.

A schematic of such a decision process has been illustrated in Figure 12 above, where the resultant EoL process determined for a specific product has been based upon a sequence of business processes, the product use data, and the inherent functionality/material content of the product.

6 Conclusion and further developments

It has been demonstrated in this paper that embedding of an RFID tag within the structure of the PCB could reduce and limit risks of a product service system within the electronics manufacturing domain by embedding life cycle relevant information such as:

- unique ID;
- manufacturing times;
- production process steps and test results;
- special instruction;
- order number;

In addition, both the risks and uncertainties associated with a PSS have been discussed, and the current data and knowledge gap has been identified. The full lifecycle of the product has been considered, and various key data requirements have been identified. These include: logistical information, quality control and assurance, EoL determination and processing, and product security.

	Developed risk	Limitation of risk
Logistics	• Missing information forces use of default parameters/ mistreatment of product	• Automatic reading of instructions (i.e. baking temperature) prevents human error or missing information in paper based system
Quality	• Time loss in root cause analysis if not available	• MTTR reduced by 45 min up to 160 min
Confidentiality/ Authenticity	• Usage of non original components or products	• Identification and data physically embedded into the product. The chip cannot be changed or altered without damaging the product. Data is password protected and not accessible to unauthorised people.
Recycling	• Loss of reuse value	• Marking of relevant or high value components prevents from loss of reuse value.
Network	• No access to product data and decision support software	• Relevant data is embedded into the product and travels with the product. Inaccessibility is reduced to RFID to reader communication. Failures in RFID to reader communication have been shown to be very low.

Table 2: Limitation of risks by embedding information into a PCB

The paper has addressed how each of these different requirements may be supported by the adoption of secure product intelligence, in the form of embedded RFID tags, and this claim has been supported via the description of a product case study. How a developed risk is reduced by the availability of information directly stored within the product is summaries in Table 2.

A second generation tag has been developed that consists of a high memory RFID chip, external interface to sensors and a microcontroller. This embedded wireless device will enable operational usage behaviour to be monitored including as:

- Usage time and use frequency;
- Use environment (e.g. temperature and humidity);
- Mechanical shocks (e.g. acceleration and turn rates).

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Curriculum Vitae

Axel Bindel is a Research Associate at Loughborough University. His research focuses on embedded wireless components, distributed systems and lifecycle monitoring systems. He graduated with a Dipl.-Ing. in Electrical Engineering and Information Technology in 2006 from University of Stuttgart. From 2006 to 2009 he worked for Fraunhofer TEG where he led the research group *Integration of Electronic Systems,* which focused on contract research and consultancy in the field of integrated electronics mainly for the automotive, automation and machine building industry. In 2009 he joined Loughborough University for an industry led collaborative research project in whole life cycle monitoring system with RFID.

Dr Emma Rosamond is lecturer in Sustainable Design and Manufacturing at Loughborough University. Emma graduated as PhD at Loughborough University, focused on prototype design and design methodologies. On completion of her PhD in 2006, Emma joined Pera Innovation, as a project manager in the Recycling Practice - managing UK and European research collaborating projects. She was appointed as the position of Team Leader of the Environmental Practice, and was involved in coordinating research projects, both research and industrial proposals, project contracts and industrial collaborations. In 2009 Emma returned to Loughborough University as a senior research associate in the area of sustainable manufacturing, and in January 2010, Emma was appointed as a lecturer.

Paul Conway is Professor of Manufacturing Processes at Loughborough University, where he heads the Interconnection research Group that has been serving the electronics manufacturing sector since 1989 in contract research, consultancy and training. He is also Academic Director of the UK's Innovative *electronics* Manufacturing Research Centre, established in 2004 by the Engineering and Physical Sciences Research Council. His research interest in process simulation for product and process design and optimisation, materials processing, lead free technologies and optoelectronic packaging.

Dr Andrew West CEng FIMechE is Professor of Intelligent Systems, leader of the Distributed Systems Research Group and founder member of the Manufacturing Systems Integration Research Institute at Loughborough University. His main research focus has been on the lifecycle engineering (e.g. requirements, specification, design, analysis, implementation, maintenance and reuse) of intelligent, distributed, component-based control and monitoring systems. Interests and activities have focussed on a number of areas but are centred on research into the development of the control, monitoring and evaluation of the next generation of manufacturing systems based upon distributed control (i.e. software and hardware) components.