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RFID in product lifecycle management: a case in the automotive industry

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Abstract

The circumstances of globalisation and ever-stricter environmental legislation over the past decade have led enterprises to work together to transform products into extended products, and to manage these throughout their life cycle. Innovative Radio Frequency Identification (RFID) technology can be introduced as an enabler of Product Lifecycle Management (PLM) business, by enhancing the traceability of the product throughout its value chain via automatic identification, enabling the collection of product usage information during its Middle-of-Life (MOL) phase, and facilitating the integration of product life cycle information and knowledge across the value chain, thus closing the product's information loop from Beginning-of-Life (BOL), through MOL, to End-of-Life (EOL) and back again. This paper will introduce a framework for product life cycle information management with the support of RFID technology. A case study of how the framework supports the decision-making involved in the different life cycle phases of the automotive industry will be described using UML models.

Keywords: RFID; Product life cycle; Information loop

1. Introduction

Radio Frequency Identification (RFID) is a technology that uses radio waves to identify objects (Chow et al., 2006). Since the first RFID technology was developed by the Los Alamos Scientific Laboratories in

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1977 (Wu et al., 2006), RFID has seen increased usage from animal tracking and toll collection, to supply chain management in recent years.

Applications of RFID technology first came to general public attention when the world's retail giants (e.g. Wal-Mart, Tesco, Metro, Target and Albertson's) announced specific RFID mandates. The benefits of this RFID implementation were reported as reducing out-of-stock items and inventory holding, anti-theft, and the reduction of labour costs. According to research from the University of Arkansas, by using RFID technology, Wal-Mart reduced 16% of out-of-stocks and was 63% more effective in replenishing out-of-stocks than their peers (Chain Store Age, 2005).

Currently considerable numbers of companies are meeting retailers' mandates by the 'Slap and Ship' approach, whereby RFID tags are appended directly to the product, which involves a third party to ensure that shipments meet mandates (Baudin and Rao, 2005, Vijayaraman and Osyk, 2006). In the automotive industry, vehicle entry and security are the dominant uses made of RFID applications, which generated $3.7 billion in worldwide revenues in 2005 (RFIDUpdate, 2006). Beyond this, there are still only a few RFID applications centred on the fully automatic identification of objects to improve shop floor tracking and warehouse operations.

The periodical literature reports considerable RFID technology usage in the automotive industry. Toyota has implemented RFID systems to track engine/parts production and painting in French and South African facilities, and they have recently updated their RFID systems in the paint and production areas of its Burnaston plant in Britain from Allen-Bradley-brand active tags (adopted 10 years ago) to EMS systems (RFID Solution Online, 2007). In its cab plant in Umeå, Sweden, Volvo Trucks (VTU) had initiated an RFID system on the detail racks in its paint shop as early as 2000, with the system decentralising process information so the shop could have continuous production despite communication loss. Following this success, they implemented further RFID systems, first for the details and the cabs, and then in 2004, in the trim shop for exact tracking of the cabs and to decrease sequence faults (Fasth et al., 2005). Volkswagen

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has deployed IDENTEC SOLUTIONS' ILR technology—a commercial active RFID wireless technology—for tracking vehicles in Autostadt, where every vehicle is equipped with an active RFID tag that contains the vehicle ID number and pre-delivery tasks, which automatically detect the car when it enters the facility, with its status being written to the tag. These tags may be removed and reused when the car is delivered to the customer (IDENTEC SOLUTIONS, 2005).

Since 2003, BMW have implemented four RFID-based real-time location systems in four of their German plants. These implementations place active RFID tags on finished vehicles as they leave the production line to help BMW instantly locate cars before they are shipped to dealers. The same system is being rolled out worldwide, underscoring the value of the system to BMW (Collins, 2005). In Mexico, Ford uses passive RFID tags to track its production and assembly processes (Johnson, 2002). From 2005, Ford was rolling out an RFID technology based battery-charging system for electric forklifts throughout all its 42 North American plants; with this system, Ford can retrieve real-time information about the batteries and the charger itself, including the battery status, charger faults, battery temperature, frequency of charges and time etc. (Swedberg, 2005). Meanwhile, DaimlerChrysler has examined the use of RFID to improve the flow of parts from its own on-site storage to the workstations of its production line; they have determined that RFID is ready to be piloted at five of the seven plants in the Unterturkheim area of Germany (Collins, 2006).

Beyond simple automatic tracking in the automotive production process, as recounted by most of these examples, RFID technology can also influence the process of production itself, and even enable closer interaction between specific products and the process used to manufacture these. Li et al. (2004), for example, report that at some Ford plants they use RFID tags to carry all instructions needed to assemble each engine, in addition to the test data accumulated during manufacturing. In a similar application, Baudin and Rao (2005) report on an Omron plant developing a system called 'digital yatai' that uses barcodes on parts and RFID tags on tools and fixtures, to display assembly instructions and select parts

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and tools. Further, Kohn et al. (2005) has exploited the recent interest in RFIDs to develop an architecture for dynamic enterprise planning, scheduling and control, called the Enterprise Feedback Control System; this architecture is based upon information provided by RFID sensing systems to inform all levels of the framework.

These approaches, however, are normally limited to individual manufacturing organisations, and few extend to the after-sales phase of the product or to others in the product's value chain that may have an interest in shared information potentially available from technology such as RFIDs. In fact, owing to its ability to automatically identify the product, and because of the potential contained in its inner memory, RFID has the possibility to capture, store and exchange product information throughout its life cycle phases, thus closing the product's information loop and enabling a holistic product lifecycle management (PLM) strategy.

This paper draws on the experiences of the EU project PROMISE (Product Lifecycle Management and Information Tracking using Smart Embedded Systems) (IST F6: 507100), which is concerned with exploiting a new model of the product life cycle across beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) product phases, together with the support of product embedded information devices such as RFIDs, to document the flows of information and materials across the value chain of the product. The project is currently investigating the interaction of product embedded information devices such as RFIDs and backend PLM systems along the value chain and how information decision-support and material/product options may be most efficiently supported at each of the product life cycle's phases.

In the next section the concept and benefits of PLM will be further outlined. The state-of-the-art technology of RFID-based product information sharing infrastructures will be presented in section 3, including our approaches in the PROMISE project. This provides the impetus for section 4, which introduces the RFID-based PLM infrastructure. Section 5 gives a use case for implementing the infrastructure in the automotive industry, while section 6 completes the paper with conclusions.

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2. Product Lifecycle Management

2.1. Definition and Background

Product Lifecycle Management (PLM) has emerged, in the last decade or so, as the most popular approach towards the management of the product both inside the four walls of the company, and further afield, in the company's value chain. This emergence of PLM has occurred both upon the academic and commercial fronts: in the latter, vendor PLM offerings are now well-established and marketed, with product offerings including Teamcenter (by UGS), Agile, mySAP PLM (by SAP), Dassault PLM solutions (by Dassault Systèmes and IBM), and Oracle PLM[†]. Vendor applications are popular: Sudarsan et al. (2005) reports that manufacturing companies invested $2.3 billion in PLM systems in 2003; while both Ameri (2005) and El-Diraby (2006) report that PLM is one of the fastest growing markets for Information Technology (IT) within the enterprise, and the total revenues grew from slightly more that $2 billion in 2001 to more than $7.5 billion in 2006. In the academic research PLM analysis stretches from the marketing research of the 1950s to today's concentration upon the integration of material and information flows in the value chain environment.

Initially, the product life cycle concept centred around the need to produce a coherent framework that could account for the relative success or failure of an individual product introduced onto the market, when best to change strategies such as pricing (Dean, 1950) or product manufacture, and determining when a product should be discontinued (Kotler, 1965). From these early studies a biologically-inspired "life cycle" of the product emerged that was divided into four phases (birth, growth, maturity, and decline), together with the familiar bell-shaped curve describing a simple parabola upon an axis of sales volume versus time (Levitt, 1965). This theory was well-established by the 1960s with the first influential papers including

[†] Teamcenter: http://www.ugs.com/products/teamcenter/
Agile: http://www.agile.com/
mySAP PLM: http://www.sap.com/solutions/business-suite/plm/index.epx
Dassault PLM solutions: http://www.3ds.com/products-solutions/plm-solutions/
Oracle PLM: http://www.oracle.com/applications/plm/intro.html

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those by Forrester (1958), Patton (1959), Levitt (1965), Cox (1967), and Polli and Cook (1969). Sharp criticism of this marketing approach appeared in the 1970s, however, particularly over the construct's validity when applied empirically (Dhalla and Yuspeh, 1976), causing ambivalence towards the theory in the marketing environment in the long-term (Day, 1981).

From the late 1970s, however, the concept of a "life cycle" had begun to influence research beyond marketing. New formulations of the product life cycle concept were being developed to meet the needs of other research fields. These included: strategic management (Hayes and Wheelwrights' (1979) product-process matrix); organisational structuring (Bennett and Coopers' (1984) "business" life cycle); sustainability (Potts (1988) "service" life cycle, closely shadowing the operation of the product life cycle); and environmentalism (the emergence of product, as opposed to process, environmental legislation (Berkhout and Howes, 1997; Alting et al., 1997) leading to advanced Life Cycle Assessment techniques). In the inter-organisational literature, the emergence of Porter's (1985) value chain conception, and the associated research performed in the 1990s upon networked organisations (supply chains, extended enterprises, virtual enterprises), has allowed the product life cycle concept to be extended beyond the confines of the single enterprise to that of the multi-firm environment.

At another level, the recent popularisation of PLM vendor offerings has been realised by the appearance and wide dispersal of organisational applications and ICTs among co-operating value chain partners. With the advent of a range of relatively inexpensive Computer-Aided Design, Manufacturing and Engineering tools in 1980s, the opportunities for concurrent product design and development across the value chain became possible. New CAX tools enabled the geometric model of a product to be reused and modified by designers and engineers handily and quickly across the value chain. Further, the appearance of Product Data Management systems appeared to centralise product information, created by various information authoring tools, into single, authoritative databases capable of multi-firm interrogation. From these

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developments, a new sense of a shared possession of the product, owned and contributed to by many in the value chain, has had significant implications for the product life cycle theory.

In this way, the concept of PLM was to emerge from the combination of the academic research and the commercial exploitation of organisational applications. In fact, definitions proliferate, all based upon slightly differing definitions of what is meant by the term 'product life cycle', as the term has changed its emphasis with the passage of time. According to Ameri and Dutta (2006), PLM seeks to extend the reach of PDM, beyond its sole focus on design and manufacturing, into other business areas and to all the stakeholders throughout the product's whole life cycle. Sudarsan (2005) suggest that PLM is generally defined as 'a strategic business approach for the effective management and use of corporate intellectual capital'; while Thimm et al. (2006) define PLM as 'a strategic business approach that consistently manages all life cycle stages of a product, commencing with market requirements through to disposal and recycling'. Lee at al. (2006) argue that PLM is 'a concept within operations management which is concerned with the process of designing the product and production system as well as the realisation of production distribution and service'. These conceptions of PLM necessarily step beyond the confines of individual firms to the value chain environment in which the product is located, and in which it is to have its life cycle. By this process, product analysis is stretched beyond basic physical product considerations to include the management of the product's information and material flows among its value chain developers and users. This drives Product Data Management strategy towards PLM strategy, thus allowing one to manage the entire life cycle of a product from "cradle to grave", from its initial conception, through design, manufacturing and after-sales servicing, to its decommissioning stage.

The concept of the "extended" product represents this new product-offering in the value chain, and is becoming the focus of contemporary PLM. The extended product is represented as a three 'layer' model, consisting of:

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1. at the centre, a core product functionality including materials and technical functions of the tangible product;

2. a second tangible product layer surrounding the centre that includes the packaging of the core functions of the product; and

3. a third intangible product layer consisting of associated product services provided to assist the functioning of the product in its life cycle (Thoben et al., 2001; Hirsch et al., 2001).

In this vision the product is "extended" by the provision of support as it proceeds through its value chain "life"; based on product feedback, the product may be "extended" via service additions that are specially endowed by the digital business environment (Hirsch and Eschenbacher, 2000). This is achieved by the timely provision of services by Extended or Virtual Enterprise partners to the core, tangible product as necessary during its middle of life, thus enabling continued product differentiation that inhibits the decline of specific innovative "product attributes" of the product into mere "ordinary attributes", or by means of providing new innovations to replace those lost (Walley, 1998).

The contemporary vision utilised in PLM to reflect this is a product life cycle model that tightly couples both material and information flows at the product's design and manufacturing stages (called the beginning-of-life (BOL) phase for short). This is followed by a second stage where the product has emerged and is purchased by the customer and is used and repaired when necessary (called the middle-of-life (MOL) phase)—this phase decouples some of the information flow from the material flow and returns information to BOL as necessary. In a final phase the customer has completed their use of the product and this, in turn, is released for decommissioning (called the end-of-life (EOL) phase); here the final decoupling of the material and information flows first forged in BOL is made and material and components are returned to BOL and MOL, while information flows return useful maintenance information to MOL, and design and manufacturing information to BOL. This new product life cycle model is depicted generically in Figure 1, which follows the model generically outlined by Kiritsis et al.

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(2003). As can be seen from the figure, a variety of material return flows exist from EOL depending upon final component quality; these include: reuse components (to MOL); remanufactured components (retooled to original quality levels and reused in BOL); recycled materials (base materials—not components; back to BOL); and disposables from which some useful base materials may yet be retained (Thierry et al., 1995).

[Insert Figure 1 about here]

The chief characteristic of this product life cycle model is the fact that the product itself becomes a prototype for improvements to its own value chain, by the use it makes of its material and information flows. In particular the documenting of the information flows involved is innovative as technology constraints previously inhibited the implementation of this part of the model (the recent exploitation of RFID technology, however, aims to solve this). With this in place we find that the product life cycle model becomes a loop of continuous improvement, with flows from BOL to MOL and EOL and back again, allowing product designers in BOL to introduce ever-improved products to the value chain.

Unlike the BOL phase, where the information flow is quite complete and supported by intelligent systems such as CAD/CAM/CAPP, PDM, and Enterprise Resource Planning (ERP) systems, the information flow becomes less and less complete from the MOL phase to the final EOL phase. The basic function of PLM requires the management of product life cycle data, thus enabling:

1. centralising, controlling, and manipulating of the life cycle data related to the after-sales service (MOL stage), and product retirement process (EOL stage) as well as the previous design and manufacturing phases (BOL stage);

2. the sharing of this life cycle data to all relevant stakeholders by means of web-based or web-enabled technology; and

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3. the transformation of the life cycle data into a structured knowledge form that can be retrieved, represented and reused easily and efficiently by various organisations in the extended enterprise and throughout the whole product life cycle.

Such a PLM strategy holds the possibility of ensuring both an individual firm's competitiveness, and the success and health of the firm's immediate inter-organisational partners in the extended enterprise through PLM collaboration across the value chain. As El-Diraby (2006) and Ameri (2005) have suggested, PLM should focus on generation, dissemination, and utilisation of the product life cycle related knowledge, which may have diverse contents, formation and scope according to different fields of utilisation, and based upon the centralised life cycle data that has been collected.

2.2. PLM in automotive industry

PLM has been applied in the automotive industry in a number of capacities, as is exemplified by its currency on the web, where the adoption of vendor applications is particularly favoured. Academic research into automotive PLM, however, remains relatively static, and is based—for the most part—upon extensions of existing PDM methodologies (Amey, 1995), or applications of pre-developed LCA techniques. In the periodical literature, Nissan Diesel Motor has implemented an IBM PLM aplication for configuration management so as to speed up product development (Mitsuhashi, 2004). GM Daewoo, since 2003, has implemented a number of PLM solutions from vendor UGS: these include the provision of parametric and assembly design capabilities; and the structuring and managing of its product information within a vehicle assembly structure (UGS Solution, 2005). Toyota Motorsport GmbH have chosen two vendor PLM solutions to optimise car performance by speeding up the process of streamlining component delivery; and the enablement of efficient collaboration among all designers, production, and track teams (Dassault Systèmes, 2005). Examples of PLM, however, are relatively localised, and have yet to be extended into the value chain partnerships that these hold.

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Increased global competition and a permanent over-supply of the automotive market (May and Carter, 2001, Seidel et al., 2005) has made competition in the automotive market intense. Customer oriented service (e.g. customising, predictive maintenance, intelligent products etc.) has become an essential aspect of the contemporary automakers' product-offering, thus enabling product-differentiation in a crowded marketplace. Their activities no longer cease at the delivery of the vehicle to the customer; rather, to enable their extended product, product usage and maintenance information has to be tracked to enable customer-oriented service, so as to generate appropriate product life cycle knowledge to facilitate product servicing, and the conceptoin of the next-generation of products.

We can add to this the growth in 'green' politics and the emergence of greater social pressures on manufacturers to conform. Legislative and social expectations have insured that the producer must take a greater interest in the product than formerly, even when the product is not under its direct control. The automotive industry is a case in point: under policies adopted by the EU (EU Directive 2000/53), the recycling/recovery rates of all vehicles at their end-of-life must be 85% by weight in 2006, rising to 95% by 2015 (Ferguson and Browne, 2001; Reuter et al., 2005), with responsibility for this occurrence squarely delegated to the automotive producers themselves under the 'extended producer responsibility scheme' (Bellman and Khare, 2000). In response, automotive manufacturers are looking at a variety of ways to combat the problem, including the more obvious recycling techniques available to them, but also by encouraging closer links with downstream value chain partners in MOL service and maintenance, and EOL decommissioning. These attempts include a more innovative examination of existing PLM methods with the intention of forming cross-organisational, product-based collaborations that account for the integration of material flows and information flows.

In summary, the contemporary characteristics of the business environment that the product must face include:

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1. organisations that are more externally-oriented than heretofore, and more open to value chain collaboration;

2. higher social and legislative pressures placed on product producers and users; and

3. greater self-referential information and material feedback flows from later product life cycle phases to earlier life cycle phases.

2.3. RFID in PLM

PLM systems are generally computer-based information systems which assist the organisation's PLM strategy. According to the discussion above, the components in a full PLM system include:

1. an IT infrastructure;

2. an information management architecture to model, centralise, manipulate, and share product life cycle data and information;

3. a knowledge management system to generalise and disseminate product life cycle knowledge;

4. a set of business applications to support the utilisation of life cycle data and knowledge in various organisations and different life cycle stages respectively; and

5. a collaborative environment to integrate business units throughout the value chain network.

Most vendor PLM applications support BOL information management and engineering design collaboration; they also emphasise project and document management functionalities. Unfortunately, information and knowledge tracking related to MOL and EOL phases seems to be almost non-existent. However, a few companies have begun to tackle this problem of customer usage and product decommissioning and reusage; these include: Agile's product governance & compliance™, Omnify's

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Quality/Regulations[‡], and Teamcenter's enterprise knowledge and process management module. Agile, Teamcenter, and mySAP also provide maintenance or quality management modules in their PLM solutions, which approaches the MOL support and service phase of the product. These solutions, however, remain somewhat rudimentary and not sufficiently integrated as yet to provide full value chain PLM complicity. Owing to distributed locations, offline usage, various service providers, batch-specific product identification systems etc., the current PLM systems are unable to handle all PLM requirements.

Emerging RFID technology provides an opportunity to meet these information challenges for PLM strategy, as:

- via emerging RFID infrastructures, information and events derived in all organisations involved in the product life cycle can be shared throughout the whole value chain — despite the existence of individual designers, manufacturers, distributors, service providers, and recyclers;
- with the inner memory of the RFID tag, information can be held on the product itself before it reaches an available network, thus no important information will be discarded owing to transmission problems;
- via RFID sensors, the working conditions and parameters of the product can be recorded and the retrieval of usage information becomes much easier; and
- by means of automatic tracking of location information, the product can be updated in real-time, so that organisations can determine the current status of the product.

RFID systems can help complete the MOL and EOL product life cycle data absence that exists in most contemporary product life cycles. As noted above, thanks to the provision of numerous BOL applications, BOL information sent with the product into the MOL/EOL environment is quite complete. Problems begin to occur, however, when the provision of feedback required to formulate appropriate strategic responses for the product during its life cycle does not occur, or occurs only intermittently. It is in this case that RFID technology, being light-weight and relatively easy to append to products such as automotive

[‡] Omnify PLM: http://www.omnifysoft.com

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vehicles, can provide the backbone for the collection and storage of MOL and EOL data. This, coupled with appropriate PLM infrastructures that insure the return of the collected MOL and EOL data, illustrates the use of a value-chain wide RFID system being added to the contemporary PLM purview. There are a number of challenges to bringing-about this vision, however.

2.4. Challenges of applying RFID in PLM

Fleisch et al. (2005) report that, in an interview from November 2003 to January 2004, 80% of automotive companies said they have at least one operative application related to RFID. However the total number of RFID applications remains low, which indicates that RFID technologies are still in the exploratory stage and are not yet used as a company-wide standard solution. Should the technology be applied to the PLM realm, more challenges must be met. These challenges include issues of (1) infrastructure, (2) standards choice, and (3) policy choice. These are outlined below.

1. PLM strategy requires that RFID devices work properly along the whole product life cycle, which requires adequate performance from all RFID-related devices. Currently, there exists a disparate usage environment and well-known incompatibility issues with regard to read range, reliability and lifespan of RFID devices. Further, the accumulation of life cycle information would require an ever-larger memory capacity for the RFID tag; while the relatively open surroundings that exist in the usage phase of data collection may result in security fears for the RFID system. Also, the cost of RFID tags must remain low and drop even further if they are to accommodate large-scale RFID/product attachment schemes. Currently there are few RFID-sensors sufficiently mature in the marketplace to suit life cycle activities. Further complications are industry-specific: in the automotive industry, owing to interference caused by surrounding metallic components, the actual read and write rates, ranges and reliabilities of RFID tags and readers can be far below those experienced in a clean lab environment (Delahaye, 2006).

2. A PLM system connects various business partners and their existing information applications through the value chain, and a company may be involved simultaneously in several PLM systems (or other RFID

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applications) serving different value chains. Confusion is likely to arise if each RFID application defines its own tags, readers, data presentation, and software interfaces. Common RFID standards may prevent this problem of RFID equipment selection. Alternatively, standards could cover various levels in RFID-based PLM systems. At the physical level, several standards regarding the air interface have been published (e.g. ISO/IEC 18000, EPC Class 1 Gen 2); however, standards are still evolving and a unified, globally interoperable RFID standard is still missing (Wu et al., 2006). At the architectural level, EPCglobal and WWAI are developing standards regarding data and information manipulating and sharing. Both are based on unique code tags to locate product information; however, other potential life cycle information which might be stored on RFID tags (e.g. data from RFID-sensor) still lacks guides. At policy level, although EPCglobal is developing guidelines on public policy, there may be a long delay before the unveiling of a general security and privacy policy which meets PLM requirements. Further, standards for security and privacy still require large-scale research.

3. Once RFID devices are implemented throughout the product life cycle, security and privacy issues become more serious than when only applied in niche areas. Here *security* is responsible for the full denial of access to RFID data by unauthorised parties (including eavesdropping, tampering, forgery, denial of service etc.). Security issues have drawn the attention of lots of researchers since the birth of RFID technology. Supported by matured encryption standards (e.g. AES and RSA) and other approaches, security issues are considered to be more-or-less completed, although not every RFID tag in the market supports these approaches (Dressen, 2004). Privacy policies prevent RFID devices collecting information which the holders don't want other parties receive. This is fairly important in PLM strategy; in the contemporary business environment competition is between value chains, and it is common that one company is involved in several value chains which compete with each other. There are risks that one company's private information is unveiled to its competitors by the third party while involved in PLM activities. Similarly, product consumers may have fears over how collected data may be used or misused (e.g. vehicle owners may not want others to know where they have been). So it is important to specify

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policies related to the collection and usage of information, such as (1) what information can be retrieved; (2) who can access the retrieved information; and (3) where the information can be used. These must be agreed across the PLM value chain.

We will now turn our attention to those RFID technologies that are suitable for PLM purposes; these are discussed in the next section which outlines the chief approaches for RFID exploitation across the product's value chain.

3. RFID-based product lifecycle management infrastructures

In this section the most popular approaches that combine RFID and PLM are outlined briefly. Of those mentioned, the Auto-ID approach is by far the most popularly known at the moment, as it is probably the most developed; however, other issues are also covered, including the approach that we have utilised in the PROMISE project.

3.1. Auto-ID infrastructure

One promise made by RFID technology is the useful management and employment of an object's information once it has automatically identified its existence. The Auto-ID infrastructure provides this special service and operates with specialised interfaces for RFID systems. The production data generated in different organisations can be shared throughout the product value chain via this infrastructure. Usually organisations involved in a typical product life cycle are located in disparate geographical positions; therefore they tend to communication with each other via technologies that can overcome such locational difficulties, such as via the use of contemporary ICTs (such as the Internet). In order to transmit messages over such a network, the minimal requirement is that RFID tags must store some kind of reference to the backend system for establishing a connection. Currently there are three main methodologies for approaching the backend system in such a scenario:

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- via existing Domain Name Service (DNS), by embedding the internet address of the backend system in the tag itself, which can be expressed, for instance, by using an ID@URI (Uniform Resource Identifier) notation;
- via Object Name Service (ONS), supported by the EPC Network, which makes it possible to access the URI part through a universal unique identifier; or
- via peer-to-peer connection, approached by the World Wide Article Information (WWAI) protocol.

These three methodologies are discussed further in the following notes.

3.1.1. ID@URI

ID@URI is one of the methods used to locate product information in a remote system. Like an e-mail address, URI (Uniform Resource Identifier) indicates the internet address of the information service, while the ID part identifies the target product item at the URI. At the minimal level the ID@URI reference can be embedded as a barcode or use a passive RFID tag. Since the URI part uses existing standards, and there being many possible standards for the ID part, this approach does not need any new identifier standards. Most existing middleware solutions use this approach, i.e. an ID part serves as an index to a company's database at the URI address (Holmström and Främling, 2005).

3.1.2. EPCglobal Network

EPCglobal Network was developed from the Auto-ID Centre, a global research team managed through the Massachusetts Institute of Technology (MIT), who now direct EPCglobal[§]. The aim of the Electronic Product Code (EPC) is to provide a unique identifier for each object, which typically consists of three ranges of binary digits representing the manufacturer, product type, and item respectively. When a passive tag which refers to an EPC number reaches the range of a reader, the middleware (in this case Savant technology) can access the unique identity code of the target item. To reach the information associated with the EPC number, the middleware will connect to the Object Name Service (ONS), which provides the

[§] http://www.epcglobalinc.org/

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directory to convert an EPC into a number of internet addresses — currently based on the Domain Name Service (DNS) which provides IP address lookup for the internet — where further information about the given object may be found. Meanwhile, the EPC Information Service (EPCIS) provides a standard interface to allow partners to access and exchange their real-time data; while physical mark-up language (PML), a derivative of XML, is used in the EPC Network to standardise the communication vocabularies, i.e. interpret the data obtained via ONS and EPCIS (McFarlane, 2004).

3.1.3. WWAI network

The World Wide Article Information (WWAI)[**] protocol is based on the peer-to-peer (P2P) principle, which is most widely known for entertainment file sharing. WWAI tracks the information providers of objects in a distributed network and shares meaningful information about objects and their relationships between other objects. This means that one is able to find out the players involved with a specific object throughout the whole product life cycle. The WWAI network consists of WWAI compatible systems (WWAI nodes) connected together via the Internet. There is no centralised storage for any of the information in the WWAI network, and each of the nodes is responsible for their own data and systems. They may prevent or grant access to their information to other users as they wish.

The WWAI protocol — generic XML-based — defines messages that enable nodes to exchange any kind of information and link any kind of objects to each other by specifying a generic language for systems to communicate about objects and their relations between nodes in the de-centralised WWAI network. All communication in the WWAI network is related to a unique object code, which is globally unique regardless of the standards used for coding. In order to make sure of the uniqueness of the codes, each node has its own certificate for each code prefix. Certificates are delivered by a globally accepted certification authorities, who validate each player in the network and release the code prefixes to the network (Røstad and Myklebust, 2005).

[**] http://www.wwai.org/

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3.2. PROMISE infrastructure

Auto-ID infrastructures promise universal information sharing for product life cycle management. The ID@URL approach is based on the matured DNS service, which simplifies the initiation of the network. Currently few standards can be found to regulate this approach, which limits its implementation in an open environment. EPCglobal employs a powerful team to develop standards and infrastructures, but the network relays using EPC code and a dedicated ONS service. RFID can contain much more information than the sole identity code, but EPCglobal's infrastructure inhibits the direct manipulating of the information. Although WWAI promises a flexible item coding-acceptance and system-independence, according to their website, the specification of WWAI protocol is under development and is still unpublished.

These three approaches all focus on locating and sharing information by identifying an item. However, automatically collecting product information by the product itself (especially in the MOL stage) is also critical for PLM implementations. The PROMISE project devotes itself to developing a new IT infrastructure and ubiquitous PLM software using product embedded information devices (PEIDs), including RFIDs, and wireless communication in order to collect and generate this information.

In the PROMISE architecture (see Figure 2), the implementation of the PEID can be RFID-based (including various forms of RFID tag, from passive/active tags, or RFID sensors). The PEID systems are attached to the product to collect and record all the relevant information in the product life cycle, including design, production, usage, maintenance, and retirement data. When conditions permit, the information collected by the PEID system will be sent to the Product Data and Knowledge Management (PDKM) system, which provides centralised data and whole product life cycle information; while Decision Support Systems (DSSs) are integrated into the PDKM system to analyse individual parts of the collected information and to transfer the collected information into specific knowledge in the form of decisions. In Figure 2 the operational hardware for the PROMISE system include (1) PEIDs (including RFIDs) at MOL

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and EOL phases; (2) PROMISE and other middleware (including RFID readers) at BOL, MOL and EOL; and (3) various PDKM functionalities including Data Analytics and Management, DSSs, plus Metadata and System Management to manipulate the collected data. This three-step system passes data to users using the control interface whereby RFID data may be updated via the middleware, or the business process may be materially altered by the appearance of new control data from the PDKM. The PROMISE system, as the inter-connection of the BOL, MOL and EOL phases implies, crosses the value chain and utilises a centralised PDKM to control data.

[Insert Figure 2 about here]

4. RFID-based PLM infrastructure

As we argued in section 2, the emerging RFID technology provides an opportunity to meet the information challenge for the PLM strategy; i.e. to close the product information loop that normally breaks down after the delivery of the product to the customer. The proposed infrastructure of the RFID-based PLM system is illustrated in Figure 3, which is depicted in a UML (Unified Modelling Language) use case diagram. Use case diagrams partition the behaviour of a system, subsystem, or class into transactions meaningful to actors — an idealisation of an external person, process, or thing interacting with the system, subsystem, or class (Rumbaugh et al., 1999). The use case diagram contains 4 major elements: (1) the described *system* itself; (2) the *actors* which interact with the system; (3) *use cases* which are coherent elements of externally visible functionalities provided by the system unit, and expressed by a sequence of messages exchanged by the system unit, and one or more actors of the system (Rumbaugh et al., 1999); and (4) the *relationships* between these elements.

In Figure 3 we can see that there are two main positions for the RFID-based PLM system: that is, interactions deriving from the RFID, in this case usually the RFID tag or sensor; and the interactions deriving from the backend PLM system. In its actual progression through the product life cycle, the RFID

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tag on the product and its related PLM system develop an iterative relationship, whereby each in turn interrogates the other to provide updates to the product life cycle information collected. For example, the arrival of a product with an RFID tag at any particular life cycle phase (say MOL, for example), immediately requires the PLM system to be informed of this fact, and consequently to be updated with the data that the RFID tag contains. On the other hand, the PLM system can update the RFID tag by writing new instructions or information to its inner memory as required, so as to make the progression of the product, with RFID tag attached, through its life cycle more transparent to downstream value chain partners (such as in EOL).

In Figure 3 we can see how life cycle information is collectively and iteratively shared and managed between both RFID and the PLM system, with the former having particular responsibilities for data collection throughout the product MOL and EOL phases, while the latter has particular responsibilities for the transformation of the collected data into meaningful information and, eventually, decision-making knowledge as described above in Figure 2. Both support business applications: the RFID tag by its constant collection of relevant data from the product; and the PLM system by its advanced decision-making and information aggregation capabilities.

[Insert Figure 3 about here]

In the infrastructure, all the relative life cycle information and knowledge will finally be stored and managed in the PLM system using the Auto-ID methodology, while the scheme for storing information on the RFID tags can have a variety of classifications. To diminish the cost of the attached RFID tags, the storage of the serial number of the components (e.g. EPC number) is enough to target the product's information in the PLM system in most situations, except for the capture of MOL information. On the other hand, to improve its ability to deal with unexpected situations and to aid the performance of life cycle activities, some critical information can also be recorded on the RFID tags, e.g. the disassembly guide, the service history, or the product's status. In the next section, we will introduce a case of the

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implementation of the RFID-based PLM strategy in the automotive industry, focusing on its business process and information scheme across BOL, MOL and EOL life cycle phases.

5. Case study

This case study was implemented in an automotive PLM value chain located in southern Europe; the identities of those involved being protected for confidentiality reasons. The following paragraphs outline the first results obtained from this case which is currently on-going in its investigations in the PROMISE project. The case is dominated by an initial BOL focus that is concerned with increasing the return of MOL and EOL life cycle data for individual automobiles in the customer's hands in MOL, and for the increased integration of the second-hand and dismantling markets by using RFID technologies in the EOL phase. The BOL automobile producer in this case expects the benefits of exploiting PLM enriched with RFID technology to include:

- a closer integration, in terms of both information and material flows, with MOL practitioners, including service and maintenance personnel, especially with regard to their maintenance activities; i.e. both as to the volume and frequency of their services;
- an enriched information feedback loop from MOL on certain environmental parameters selected in BOL;
- a closer integration, in terms of both information and material flows, with EOL practitioners, including dismantlers and second-hand exchange markets, especially with regard to the volume of sales of certain components, and the cost of decommissioning end-of-life vehicles;
- metrics on the volumes of components and materials being reused, remanufactured, recycled and disposed at EOL;
- an enriched information feedback loop from EOL on certain environmental parameters to aid designers in BOL.

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As has been outlined above, the contemporary emphasis on self-sustainable products, together with both social and legislative pressures are obliging the BOL producer in this case to act on their value chain by implementing techniques and technologies that enhance closer co-operation with their downstream value chain colleagues. In particular they mention the pressures of upholding the legislative requirements of the EU in relation to end-of-life vehicles under the extended producer responsibility scheme.

Considering all the activities involved in the whole life cycle of an automotive vehicle is too detailed for this article, so here we focus on some of the critical activities for PLM in the particular case under investigation (see Figure 4). The operators involved in the model include:

- designer — responsible for creating drawings and models for the conception of the new vehicle, or component of the new vehicle;
- manufacturer — responsible for turning the design into a production process, manufacturing the components and assembling the car;
- distributor — responsible for the distribution of the car to the customer;
- customer — user of the car in MOL;
- service engineer — after-sales service provider responsible for maintaining and servicing the sold car;
- dismantler — responsible for collecting the end-of-life vehicles, dismantling them into components and selling them to the second-hand market.

The critical systems involved in the RFID-based PLM business process (refer Figure 4) are:

- RFID tags—attached on the vehicle and the essential components for identifying the vehicle and the individual vehicle parts; may store critical life cycle information (e.g. maintenance history, dismantling instructions etc.) if required.
- RFID sensors—sensors with RFID transponder for measuring the predefined parameters of the vehicle's working environment, e.g. temperature, humidity, number of clutch usage, number of engine

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start-ups etc. The sensors are embedded in the critical components in the car, e.g. engine and air compressor.

- Vehicle's onboard computer (ECU)—filtering and storing the measured data from the RFID sensors;
- PLM system—backend computer-based information system for co-ordinating, centralising, and sharing the life cycle information, transforming the information into knowledge, and supporting business applications using this knowledge.

Besides these, RFID readers and middleware are also involved in the system to read/write the data to/from the RFID tags and sensors, and promise a seamless collaboration for the backend system with the RFID tags.

[Insert Figure 4 about here]

Figure 4 maps the whole automotive life cycle across BOL, MOL and EOL phases in a use case diagram. Both designers and manufacturers are intimately involved in BOL where the car is created and ultimately distributed; at this stage the RFID system of the car is primed for operation throughout the product life cycle, with initial instructions and data-collecting metrics written to its inner memory via the PLM system. Once the car is distributed to MOL, the car is actively used by the customer and maintained by service personnel; here the individual RFID sensors interact with the vehicle's onboard computer, while, in maintenance, the vehicle's whole RFID system becomes connected with the PLM system for data collection and transmission to BOL, and the provision of instructions for service and updates to metrics. When the vehicle is finally released for decommissioning, the dismantler in EOL accesses the onboard computer for vehicle-level metrics of usage, and individual RFIDs on components to determine more detailed usage patterns. Based upon these operations the car is dismantled and the components are sold, some to be reused in MOL, some to be remanufactured in BOL, some to be recycled, and some to be disposed. Information flows in EOL between the RFID system and the PLM system complete the transactions of the product life cycle.

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Figure 5 depicts the typical sequence of events involved when a practitioner at any life cycle phase wishes to interrogate the vehicle's RFID system and interact with the backend PLM system. When the automotive vehicle is interrogated the onboard computer is queried, this being in contact with the various RFID tags on the vehicle. The middleware (reader) reads the information stored in the RFID tags and onboard computer, and directs the retrieved information to the PLM system. The PLM system filters and analyses the new data, and compares and develops this with existing (stored) life cycle information and knowledge in the system; the output of this analysis is used by dedicated Decision Support Systems to generate the appropriate decision support. Newly generated information and knowledge during the process is transmitted back to the PLM system, and also written onto the RFID tags and onboard computer via the middleware, if necessary.

[Insert Figure 5 about here]

The BOL producer of this case has decided to select a portfolio of potential solutions, to be tested, tuned and applied to different vehicles. The portfolio consists of: both passive HF (High-frequency) tags and active ZigBee (based upon a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4 standard for wireless personal area networks) tags (equipped with a set of sensors) that are utilised across a wide range of vehicle components. The location of the tags is on those components which have a good potential for resell/reuse/recycling; i.e. all those components that have a middle-to-high resale price; in principle this covers the vehicle's mechanical, electric, and electronic systems. These can be located all over the car, but for the purpose of empirical testing we have chosen to focus upon the alternator, starting engine, and cooling system.

Following tests on these components, different technical applications may be provided, depending on the type and dimension of the product (e.g. truck, automotive vehicle, etc.), and the components to be monitored (their lifespan, and the potential for remanufacture, reuse or recycling).

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In the following parts we introduce each of the life cycle phases BOL, MOL and EOL individually, and analyse the data requirements that are transferred to and fro using the generic PLM infrastructure explained above, as the product proceeds through its life cycle.

5.1. Beginning-of-life: preparing the RFID infrastructure

The BOL phase in a car's life cycle is the period from the conception of a new car model, to the transfer of the conception to the design and subsequent production of the car, until the delivery of the car to the customer. As the product design stage determines 70% of the product cost (Lee et al., 2006), and this figure may rise to 85%, according to research by Asiedu and Gu (1998), the BOL phase is critical in PLM strategy. In the automotive industry it is usually the manufacturers' responsibility to organise the life cycle management strategy, owing to the larger quotient of resources they retain compared to other stakeholders, and because of their duty for maintaining high recycling levels as stipulated by the EU's extended producer responsibility scheme. The environment in which the product is to have its life cycle is largely determined in the manufacturing stage for each product. Figure 6 illustrates the key activities involved in the BOL phase, including the design, production, and distribution of the car.

[Insert Figure 6 about here]

In the design stage, the designer examines the existing products' information and knowledge from the PLM system. The previous design models can be reused; the production, maintenance and recycling knowledge derived from the existing products' life cycle activities can be extracted to support the design decision, which enables DFX strategies (e.g. design for manufacture, design for assembly, design for disassembly, design for environment etc.); the PLM system can further co-ordinate the concurrent engineering process in the design activities. Simultaneously, the designer will create a new design model and knowledge and store them in the PLM system.

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RFID tags and sensors are attached to the car during the production process. The essential information of the car and its components — at least its serial numbers — is initiated on the attached tags, corresponding to the information held on the backend PLM system, which, in turn, corresponds to the management of the detailed design, manufacture, and assembly information. Ideally, information can be tracked to all parts of the value chain — material suppliers, distributors, dismantlers etc. — for the new manufactured components, and comparisons between the original product's information can be made against the remanufactured components.

The location and status of the car can be updated in the PLM system via the RFID-based tracking and tracing system during distribution activities; while the warehouse management system can monitor the stock status and provide real-time stock information to the PLM system, facilitating production planning.

The activities mentioned above are critical processes for the holistic PLM strategy. Besides, the RFID tags attached on the vehicle components and the vehicle itself, also facilitate the local business respectively; for example, by the automatic identification, process reminder, product tracking, and warehouse management facilities reported by Angeles (2005), Baudin and Rao (2005), Brewer et al. (1999), Vijayaraman and Osyk (2006), Zhekun et al. (2004), and Huang et al. (2007). The primary product life cycle information and knowledge involved in the activities is summarised in Table 1, which corresponds to the key activities depicted in Figure 6.

[Insert Table 1 about here]

In Table 1, the RFID system or the PLM system can be updated or used throughout the value chain. The design phase relies principally on previously-developed knowledge maintained in the PLM system. In BOL the RFID tag has no primary influence in the design phase, as it is used only after the production of individual components. Hence both design and the early phases of production utilise existing databases of the PLM system to set the BOL phase into operation. After manufacturing, new RFIDs, or existing RFIDs, are used or updated with mandatory or optional elements. The serial number of the elements is updated on the RFIDs for automatic identification and tracking, while the corresponding information and knowledge

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is centralised to the backend PLM system for further utilisation. In distribution the RFID serial number is utilised to assess current stock levels and location.

In conclusion, organisations operating in the products' BOL stage can reap benefits from the RFID-based product lifecycle management in the following areas:

- reduced time to market — opportunities to reuse previous design models and knowledge, and the enablement of concurrent engineering with manufacturing, service, and retiring will reduce the product's launch time to market;
- lower total development cost — development cost will go down along with the reduction of the length of the design period, reuse of previous work, and the reduction of potential reworking probabilities via collaboration throughout the product life cycle;
- lower manufacturing cost — using design for manufacture (DFM) strategies, supported by knowledge generated from the manufacturing phase in the early design stage, will subsequently decrease the manufacturing cost;
- reduce out-of-stock or over-stock situations — by real-time updating and transparent sharing of retail information the bull-whip effect across the value chain can be minimised; and
- more customer-oriented — co-operating tightly with sales, marketing and service departments can make the design more attractive to potential customers.

5.2. Middle-of-life: predictive maintenance

The MOL phase of a product expands the value-added processes after the delivery of the product to the customer; indeed, this phase of the life cycle is experiencing rapid growth as its importance becomes increasingly recognised. After-sales market sizes in the auto, computer, and telecommunication industries in 1994 were 90, 16.4 and 15.8 billion dollars respectively (Cohen and Whang, 1997). Further, it is reported that up to 30% of the funds quota of the German mechanical engineering industry results from after-sales service (Westkämper et al., 2001); while Cohen (1997) has argued that in some industries —

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including construction equipment, elevators, main frame computers, and automobiles — the profit margin for the provision of service parts and after-sales services far exceeds the margin on the sale of the product itself. Figure 7 illustrates the key activities involved in the MOL phase of a car in a use case diagram.

[Insert Figure 7 about here]

As the user drivers the car, the embedded RFID sensors will measure the relevant environmental parameters related to the components (e.g. temperature of the engine, humidity in the compressor of the air conditioner) and the actual component usage (e.g. times of braking, driving wheel angle, pressure on brake pedal); via radio frequency transponder technology all the measured data is sent to the onboard computer to be filtered, analysed and stored.

When the car is sent to an authorised garage — triggered by a predefined maintenance schedule or an unexpected action (such as a breakdown), the attached RFID tags are read so that targeted maintenance knowledge may be deduced from the design and production information in the PLM system. Also, the sensor-measured data is retrieved from the onboard computer to allow for the analysis of the car's usage status and the current status of the car and its components with the help of a maintenance-dedicated DSS, which will give a set of instructions for service procedures and plan the next maintenance schedule. At the end of the maintenance process, the service engineer will update the car's information in the PLM system, including its current status, usage information, maintenance history and knowledge.

The relative data collection and transference activities for MOL are displayed in Table 2. In the actual use phase — that is, while the customer actually drives the car — it is only the RFID sensors that are continually operating as they collect environmental information. In maintenance, at an automotive service station, the usage data collected by RFID sensors is read from the onboard computer, and the current condition of the vehicle is evaluated by comparing the usage data and life cycle information and knowledge in the PLM system. The service process and further maintenance schedule will be given by the

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DSS after the evaluation. The product life cycle information and knowledge centralised in the PLM system is updated during the process, and some critical information can also be written onto the RFID tags, to improve the ability of dealing with unexpected situations and facilitate future life cycle activities.

[Insert Table 2 about here]

In brief, the PLM strategy can bring organisations serving in the product's MOL stage the following benefits:

- improved service quality — by comparing the current usage data of the target vehicle with the cumulative usage and maintenance knowledge stored in the PLM knowledge base, service engineers have an opportunity to make a refined predictive maintenance plan for the product;
- reduced repair time — with more product usage information and maintenance knowledge available, the diagnosis should be made more convenient; the design for the service strategy and the transparent product's design information will bring more convenience to the repair process; and
- improved service profitability — a higher service quality, with simultaneously a shorter service time, would subsequently improve service profitability.

5.3. End-of-life: dismantling decision supports

An end-of-life vehicle is a vehicle to be processed by dismantling, depollution, reuse or remanufacturing of parts; shredding, recycling to material, energy recovery, or disposal to landfill. Legislation related to EOL product management has proliferated over the past decade both in the EU and in the US. Governments require manufacturers in many industries, including automotive and electronic industries, to take the responsibility of their products' EOL processing under schemes such as the extended producer responsibly scheme (Bellman and Khare, 2000).

The dismantler's role (see Figure 8) in end-of-life vehicle processing is critical for returning vehicle components and information from EOL to BOL; the dismantler effectively decides the end-of-life

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vehicle's recycling/recovery path and converts the end-of-life vehicle into components for reuse, remanufacturing or recycling — as recovery can be at the product, part or material levels (Goggin and Browne, 2000). When the dismantler receives an end-of-life vehicle, they have to face a set of decisions: for example, which parts should be removed from the vehicle; how to recover (reuse or remanufacture) the removed parts; which customers should the parts be sold to; and where to store the parts (Ferguson and Browne, 2001).

[Insert Figure 8 about here]

By exploring the usage data and information — measured by RFID sensors — stored in the onboard computer and the cumulatively enriched life cycle knowledge from its BOL phase and MOL phase managed in the PLM system, the dismantler can remove decision-making at EOL from the region of rule-of-thumb experience or guess-work, and turn to the use of an EOL-dedicated DSS developed to manipulate the numeric data from the RFID-based PLM system. This DSS is too large to be explained here, but more details may be found in Cao et al. (2006). The current quality of the components can be examined and the expected residual life for each component can be predicted using the DSS, by comparison with the relevant product life cycle information and knowledge available in the PLM; this is summarised in Table 3.

[Insert Table 3 about here]

In Table 3 recovery decision-making is a process for generating the list of components to be removed from the vehicle, and for deciding on their further regeneration (i.e. by reuse or remanufacture). With the support of usage data stored in the onboard computer, and with communication with the product life cycle information and knowledge that is managed in the PLM system, the EOL DSS can help to find the best, or at least good enough, recovery method for individual components. The dismantler proceeds to disassemble the components from the vehicle according to a remove-list developed from these parameters, leaving

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components that are to be recycled to be shredded as base material with the rest of the vehicle's body. Simultaneously, the newly generated life cycle information and knowledge is transmitted to the PLM system, and thus closes the product information loop.

With knowledge reuse and business collaboration enabled by PLM, the EOL process can meet social and legislative requirements more efficiently by being, for example:

- more environmentally friendly — by means of design for environment, the retiring of the product will impact the environment as little as possible;
- reducing process time — the design for disassembly strategy will facilitate the disassembly process, and the life cycle data and knowledge can help to pre-digest the decision process;
- increase business profits — the life cycle information of the target product and the accumulated knowledge will support the EOL practitioner to find the best, or at least good enough, retirement method and downstream customer for their recovered vehicle parts; thus retaining maximum profits for the recovery business.

6. Conclusions

Ever-stricter environmental legislation over the past decade has led to the search for greater efficiencies everywhere, including the product and its life cycle. PLM today holds the promise of seamless integration of product information throughout all the stages of a product's life cycle, especially given the recent technological advances that have seen RFID technology being introduced to many different products. RFID technology has been seen as a chief enabler of advanced PLM, not least because (1) it enhances the traceability of the product throughout the value chain; (2) it enables the collection of product usage information; and (3) it facilitates the integration of product life cycle information and knowledge across the value chain, and thus closes the product's information loop from BOL, through MOL, to EOL and back again. This paper depicts a contemporary product life cycle model that accounts for the regenerative and inter-connected nature of today's extended product — that is, a product that consists of a traditional

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core while maintaining a range of additional services and added features in after-life. This modern conception of the product has come about owing to the growth in concerns over recycling and the development of more sustainable goods; the preference of organisations today towards inter-organisational infrastructures which imply more sharing of product-related information; and the development of capabilities such as RFID technology that can support such a conception of the product.

Previous studies in the automotive industry concerning RFID usage have been minimal, and have for the most part utilised the experience of only one organisation—they have not considered the value chain in which the product resides. This paper draws on the experiences of the EU project PROMISE to examine how a new model of the product life cycle operates across the automotive value chain, together with the support of product embedded information devices such as RFIDs, allowing for the documentation of the flows of information and materials across an automotive case study. This case study was implemented in an automotive PLM value chain located in southern Europe, where the case is dominated by an initial BOL focus that is concerned with increasing the return of MOL and EOL life cycle data for individual automobiles in the customer's hands in MOL, and for the increased integration of the second-hand and dismantling markets by using RFID technologies in the EOL phase.

In principle the case displays the interactive relationship between the individual RFID tag located on the vehicle and the backend PLM system. As the product proceeds through its life cycle, it will, at many points, require the assistance of the information and knowledge residing within the PLM system. To this end, therefore, the product's RFID system is regularly accessed (i.e. read) and the data obtained is used by the PLM system to issue updates to be written to the RFID tags, and provides instructions for the operator's convenience. Thus, the use of RFID technology in the product life cycle not only ensures greater feedback of data, which was previously inaccessible, from the product, but, via the PLM system, it also allows for the provision of more detailed instructions and advice (for example, maintenance instructions, dismantling instructions) at each phase of the life cycle. RFID technology brings two main

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benefits to PLM: (1) more precise feed-forward information, provided at the right location, to the right person, at the right time; and (2) a greater volume, and higher quality, of product feedback data.

For the advantages of RFID technology in the automotive PLM value chain to be fully available, however, a number of issues related to the RFID technology must be resolved in the long term; these have been identified in a previous section as issues of RFID infrastructure, RFID standardisation, and RFID policy. Each of these threaten the value chain element of PLM, as without sufficient consensus among value chain partners on these issues, the whole RFID part of the PLM conception will suffer from problems of incompatibility—reducing the usefulness of the RFID tags, and the amount of MOL/EOL data returned. As with many projects working with RFID technology, future work demands that close attention is paid to new solutions to these issues as they become available in the research, and their incorporation into the existing PLM-RFID infrastructure should be considered.

Advanced PLM techniques, coupled to RFID technology, promise a solution to the ever-increasing range of ethical and legislative issues that face the modern manufacturer, while they further complement the modern propensity to join inter-organisational formations on the part of many firms. Ultimately, RFID technology allows the product to be truly *extended*, in that the product may provide data although it is no longer owned by the original BOL producer and may, in fact, be at its EOL. In short, through RFID technology, the product has the opportunity to participate in its own evolution, through the provision of contemporary MOL and EOL product data. This data may be used as input into the next BOL phase, and thus the product is improved on a continuous basis as long as RFID technology is implemented and actively used throughout the product life cycle. Key research remains, of course, to refine this model further: issues such as the policies required for privacy across the value chain, remain to be developed, and will be done so as soon as advances in research make this possible.

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References

ABIresearch, 2005 RFID End-User Survey Results. ABIresearch, 2006. Available online at http://www.abiresearch.com/whitepaperDL.jsp?id=22 (last accessed 05/02/2007)

Alting, L., Hauschild, M., Wenzel, H., Stahel, W.R., Roy, S., Smith, G.D.W., Environmental assessment in product development (and discussion). *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 1997, 355 (1728), 1373-1388.

Ameri, F. and Dutta, D., Product lifecycle management: closing the knowledge loops. *Computer-Aided Design & Applications*, 2005, 2 (5), 577-590.

Amey, R.G., Automotive component innovation: development and diffusion of engine management technologies. *Technovation*, 1995, 15 (4), 211-223.

Angeles, R., RFID technologies: supply-chain applications and implementation issues. *Information Systems Management*, 2005, 22 (1), 51-65.

Asiedu, Y. and Gu, P., Product life cycle cost analysis: state of the art review. *International Journal of Production Research*, 1998, 36 (4), 883-908.

Baudin, M. and Rao, A., RFID applications in manufacturing. SME Automation & Assembly Summit, Saint Louis. Available online at: http://www.mmt-inst.com/contents.htm#Articles (last accessed 14/08/2006).

Bellman, K. and Khare, A., Economic issues in recycling end-of-life vehicles. *Technovation*, 2000, 20 (12), 677-690.

Bennett, R.C., and Cooper, R.G., The product life cycle trap. *Business Horizons*, 1984, September-October, 7-16.

Berkhout, F., and Howes, R. The adoption of life-cycle approaches by industry: Patterns and Impacts. *Resource, Conservation and Recycling*, 1997, 20 (2), 71-94.

Brewer, A., Sloan, N. and Landers, T. L., Intelligent tracking in manufacturing. *Journal of Intelligent Manufacturing*, 1999, 10 (3 - 4), 245-250.

Browne, J., Sackett, P. J. and Wortmann, J. C., Future manufacturing systems — Towards the extended enterprise. *Computers in Industry*, 1995, 25 (3), 235-254.

Cao, H., Folan, P., Lu, Z., Mascolo, J., Francone, N. and Browne, J., Design of an End-of-Life Decision Support System using Product Embedded Information Device Technology. In *Proceedings of the 12nd International Conference on Concurrent Enterprising*, 2006.

Chain Store Age, Research Confirms Wal-Mart's RFID Benefit. *Chain Store Age*, 2005, 81 (12), 80.

Chow, H. K. H., Choy, K. L., Lee, W. B. and Lau, K. C., Design of an RFID case-based resource management system for warehouse operations. *Expert Systems with Applications*, 2006, 30 (4), 561-576.

For Peer Review Only

Collins, J., BMW rolls out RFID worldwide. RFID Journal, 20/09/2005. Available online at http://www.rfidjournal.com/article/articleview/1877/1/1/ (last accessed 12/02/2007)

Collins, J., DaimlerChrysler putting RFID tags in Kanban cards. RFID Journal, 07/06/2006. Available online at http://www.rfidjournal.com/article/articleview/2405/ (last accessed 13/02/2007)

Cox, W.E., Procut life cycles as marketing models. *Journal of Business*, 40 (4), 375-384.

Dassault Systèmes, Doubling design productivity with V5 PLM. Dassault Systèmes Story Description, 09/11/2005. Available online at http://www.3ds.com/fileadmin/your_strategy/customer_stories/TMG/Toyota_Motorsport_8_page_DDR_brochure_DSonly.pdf (last accessed 21/03/2007)

Day, G.S. The product life cycle: analysis and application issues. *Journal of Marketing*, 1981, 45(4), 60-67.

Dean, J., Pricing policies for new products. *Harvard Business Review*, 1950, November, 45-53.

Delahaye, F., Tracking Parts in a Car Engine. Submission for the degree of Master of Philosophy. Institute for Manufacturing Department of Engineering, University of Cambridge, 2006.

Dressen, D., Considerations for RFID technology selection. Atmel, 2004. Available online at: http://www.atmel.com/dyn/products/other_docs.asp?family_id=671 (last accessed 07/02/2007)

Dhalla, N.K., and Yuspeh, S., Forget the product life cycle concept! *Harvard Business Review*, 1976, January-February, 102-112.

El-Diraby, T.E., Web-services environment for collaborative management of product life-cycle costs. *Journal of Construction Engineering & Management*, 2006, 132 (3), 300-313.

Fasth, Å., Johansson, A., Karlsson, L., Application of RFID in the production industry. Master Thesis in Information Systems in Logistics, IT University of Göteborg, 2005.

Ferguson, N. and Browne, J., Issues in end-of-life product recovery and reverse logistics. *Production Planning and Control*, 2001, 12 (5), 534-547.

Fleisch, E., Ringbeck, J., Stroh, S., Plenge, C., and Strassner, M., From operations to strategy: the potential of RFID for the automotive industry. In *Auto-ID Labs White Paper Series (Edition 1)*, Auto-ID Labs, 2005. Available online at: http://www.autoidlabs.org/single-view/dir/article/6/203/page.html (last accessed 05/02/2007)

Forrester, J.W., Industrial dynamics. *Harvard Business Review*, 1958, July-August, 9-14.

Goggin, K. and Browne, J., The resource recovery level decision for end-of-life products. *Production Planning and Control*, 2000, 11 (7), 628-640.

Hayes, R.H., and Wheelwright, S.C., Link manufacturing process and product life cycles. *Harvard Business Review*, 1979, January-February, 133-140.

Hirsch, B.E., Eschenbächer, J., Extended products in dynamic enterprises: the IST project cluster EXPIDE. In E-Business—Key Issues Applications Technologies IOS Press, Amsterdam, 2000, 622-628

Hirsch, B.E., Schumacher, J., Eschenbächer, J., Jansson, K., Ollus, M., Karvonen, I. Extended products: observatory of current research and development trends. In *Proceedings of E-work and E-commerce conference*, vol. 1, Venice, Italy, 2001.

Holmström, J. and Främling, K., Design patterns for loosely coupled track, trace, configuration, and check operations in multi-company environments. In *Proceedings of EUROMA 2005 conference*, 2005.

Huang, G.Q., Zhang, Y.F. and Jiang, P.Y., RFID-based wireless manufacturing for walking-worker assembly islands with fixed-position layouts. *Robotics and Computer-Integrated Manufacturing*, 2007, 23 (4), 469-477.

IDENTEC SOLUTIONS, VW Autostadt. IDENTEC SOLUTONS Case Study, 2005. Available online at http://www.identecsolutions.com/automotivemanufacturing.html (last accessed 12/02/2007)

Jagdev, H.S., Brennan, A. and Browne, J., *Strategic Decision Making in Modern Manufacturing*, Kluwer Academic Publishers, Netherlands, 2004.

For Peer Review Only

Jagdev, H.S. and Browne, J., The extended enterprise-a context for manufacturing. *Production Planning & Control*, 1998, 9 (3), 216-229.

Jagdev, H. S. and Thoben, K.-D., Anatomy of enterprise collaborations. *Production Planning and Control*, 2001, 12 (5 SPEC), 437-451.

Johnson, D., RFID tags improve tracking, quality on Ford line in Mexico. *Control Engineering*, 2002, 49 (11), 16.

Kiritsis, D., Bufardi, A. and Xirouchakis, P., Research issues on product lifecycle management and information tracking using smart embedded systems. *Advanced Engineering Informatics*, 2003, 17 (3-4), 189-202.

Kohn, W., Brayman, V. and Littleton, J., Repair-control of enterprise systems using RFID sensory data. *IIE Transactions*, 2005, 37 (4), 281-290.

Kotler, P., Phasing out weak products. *Harvard Business Review*, 1965, March-April, 107-108.

Lee, C. K. M., Ho, G. T. S., Lau, H. C. W. and Yu, K. M., A dynamic information schema for supporting product lifecycle management. *Expert Systems with Applications*, 2006, In Press, Corrected Proof.

Levitt, T., Exploit the product life cycle. Harvard Business Review, 1965, November-December, 81-94.

Li, Z., Gadh, R. and Prabhu, B. S., Applications of RFID technology and smart parts in manufacturing. In *Proceedings of DETC'04: ASME 2004 Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2004.

Martinez, M. T., Fouletier, P., Park, K. H. and Favrel, J., Virtual enterprise — organisation, evolution and control. *International Journal of Production Economics*, 2001, 74 (1-3), 225-238.

May, A., and Carter, C., A case study of virtual team working in the European automotive industry. *Interantional Journal of Industrial Ergonomics*, 2001, 27 (3), 171-186.

McFarlane, D., Networked RFID in industrial control: current and future. Keynote presentation in *Proceedings Of Basys 2004*, Vienna, 2004. Available online at: http://www.ifm.eng.cam.ac.uk/automation/publications/#2004 (last accessed 15/09/2006).

Mitsuhashi, O., PLM speeds product development @ Nissan Diesel. *Automotive Design & Production*, 2004, 116 (8), 31-31

Patton, A. Stretch your products' earning years. *Management Review*, 1959, 38 (June), 67-79.

Polli, R., and Cook, V., Validity of the product life cycle. *Journal of Business*, 1969, 42 (4), 385-400.

Porter, M. *Competitive Advantage*. The Free Press, New York, 1985.

Potts, G.W., Exploit your product's service life cycle. *Harvard Business Review*, 1988, September-October, 32-36.

Reuter, M. A., Van Schaik, A., Ignatenko, O. and De Haan, G. J., Fundamental limits for the recycling of end-of-life vehicles. *Minerals Engineering*, 2005, In Press, Corrected Proof.

RFID Solution Online, Toyota upgrades with EMS RFID application. RFID Solution Online, 01/25/2007. Available online at http://www.rfidsolutionsonline.com/content/news/article.asp?docid=54a7a730-37d8-447b-8160-fb5fd328455a (last accessed 19/02/2007)

RFIDUpdate, RFID drives into auto manufacturing. RFIDUpdate, 21/03/2006. Available online at http://www.rfidupdate.com/articles/index.php?id=1078 (last accessed 19/02/2007)

Røstad, C. C. and Myklebust, O., DR3.2 PROMISE Demonstrators & State-of-the-art. PROMISE Delivery, 2005.

Rumbaugh, J., Jacobson, I. and Booch, G., *The Unified Modeling Language Reference Manual*, Addison Wesley Longman, Inc., Massachusetts, 1999.

Seidel, M., Loch, C.H., and Chahil, S., Oqu Vadis, automotive industry? A vision of possible industry transformations. *European Management Journal*, 2005, 23 (4), 439-449.

For Peer Review Only

Sudarsan, R., Fenves, S. J., Sriram, R. D. and Wang, F., A product information modeling framework for product lifecycle management. *Computer-Aided Design*, 2005, 37 (13), 1399-1411.

Swedberg, C., Ford deploys RFID-enabled chargers. RFID Journal, 19/01/2005. Available online at http://www.rfidjournal.com/article/articleview/1348/1/1/ (last accessed 12/02/2007)

Swink, M., Building collaborative innovation capability. *Research Technology Management*, 2006, 49 (2), 37-47.

Thierry, M., Salomon, M., Van Nunen, J. and Van Wassenhove, L., Strategic issues in product recovery management. *California Management Review*, 1995, 37 (2), 114.

Thimm, G., Lee, S. G. and Ma, Y.-S., Towards unified modelling of product life-cycles. *Computers in Industry*, 2006, In Press, Corrected Proof.

UGS Solution, Korean automaker adapts business strategy to "buyers' market". UGS Solutions, 2005. Available online at http://www.ugs.com/about_us/success/gm_daewoo.shtml (last accessed 21/03/2007)

Vijayaraman, B. S. and Osyk, B. A., An empirical study of RFID implementation in the warehousing industry. *International Journal of Logistics Management*, 2006, 17 (1), 6-20.

Westkämper, E., Niemann, J. and Dauensteiner, A., Economic and ecological aspects in product life cycle evaluation. *Proceedings of the Institution of Mechanical Engineers Part B*, 2001, 215 (5), 673-681.

Wu, N. C., Nystrom, M. A., Lin, T. R. and Yu, H. C., Challenges to global RFID adoption. *Technovation*, 2006, In Press, Corrected Proof.

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Figure 1: The product life cycle (adapt from Kiritsis et al., 2003)
Figure 2: PROMISE architecture
Figure 3: Infrastructure of RFID-based PLM system
Figure 4: Automotive life cycle
Figure 5: RFID-based PLM strategy
Figure 6: BOL phase in RFID-based PLM for an automotive case
Figure 7: MOL phase in RFID-based PLM for automotive case
Figure 8: EOL phase in RFID-based PLM for automotive case

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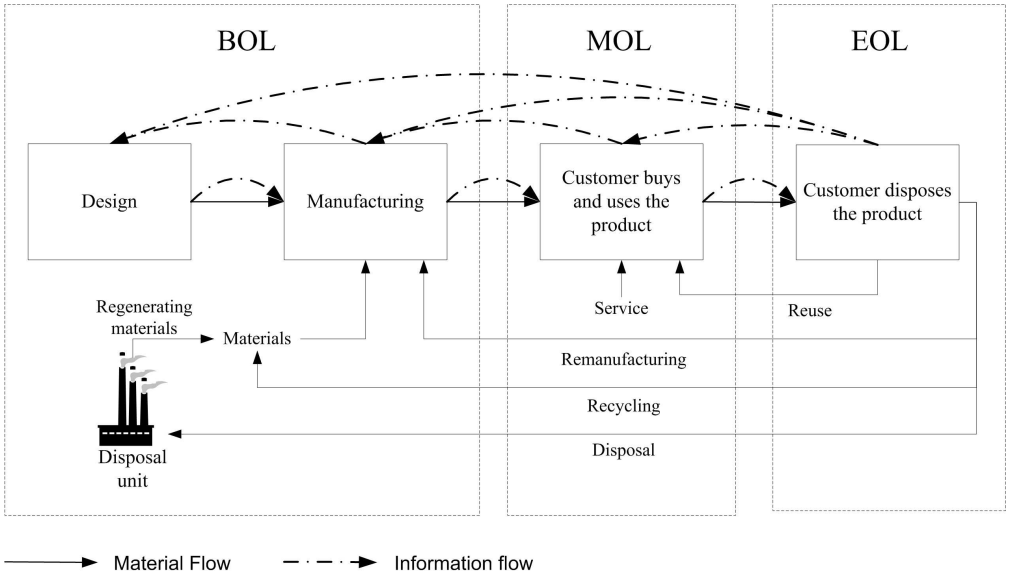

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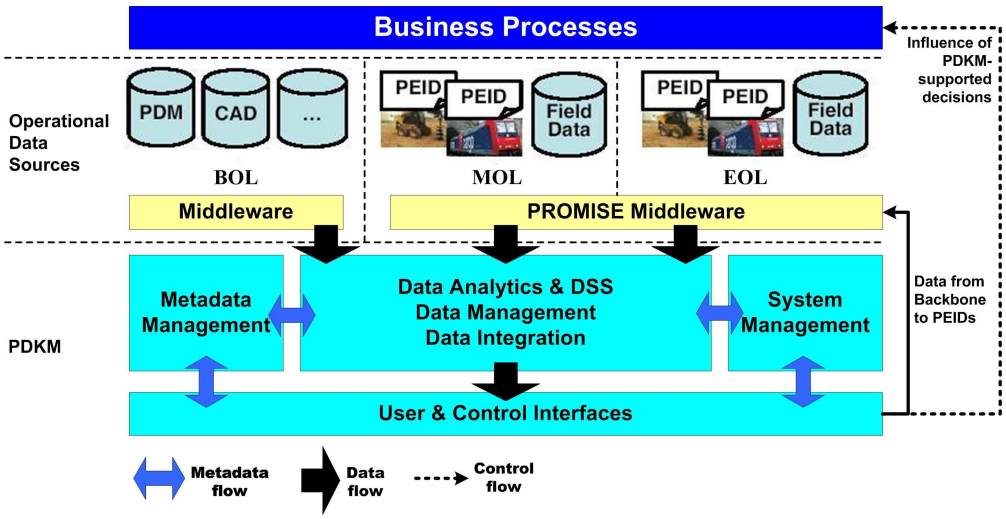

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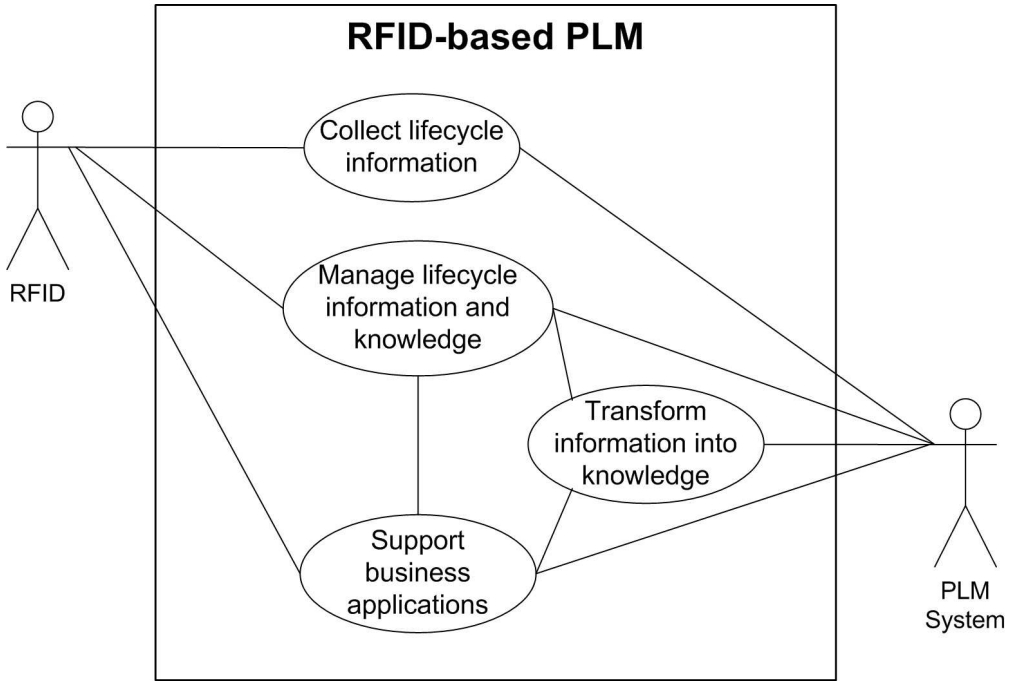

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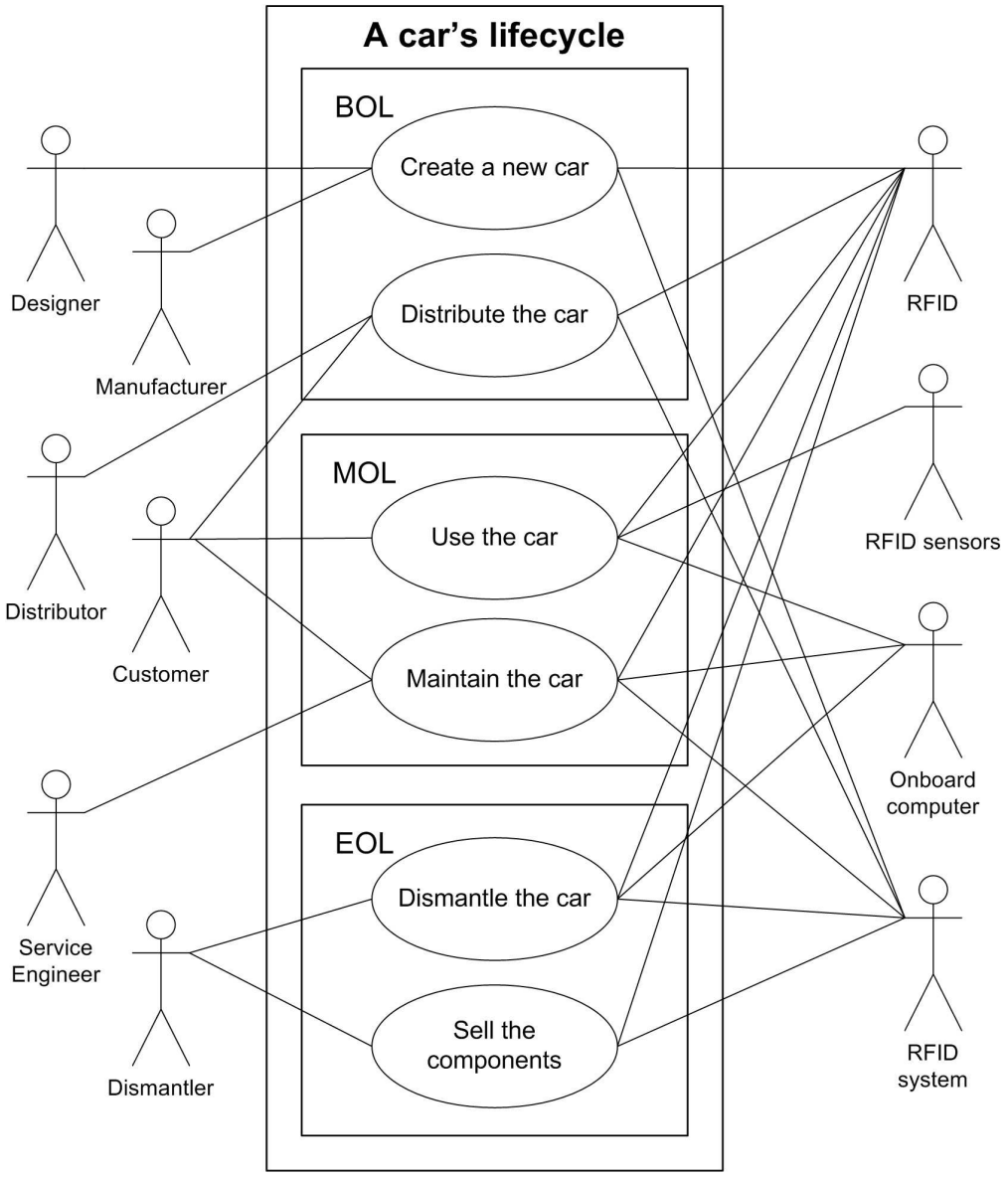

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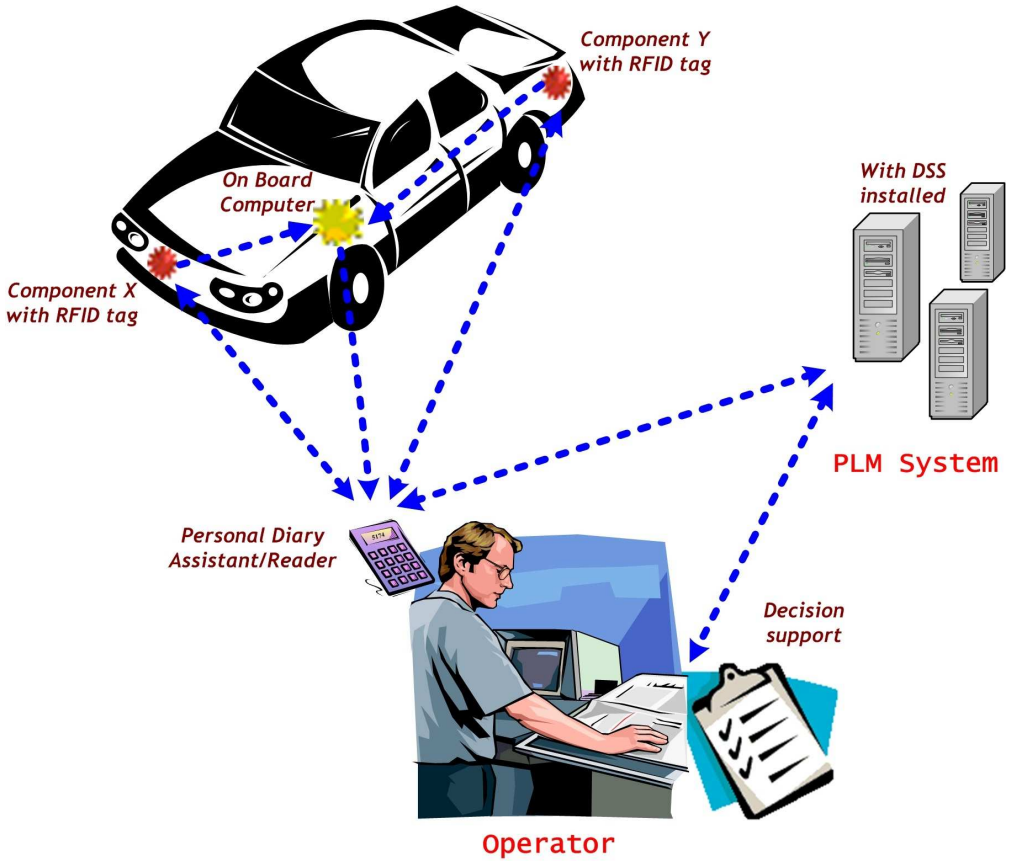

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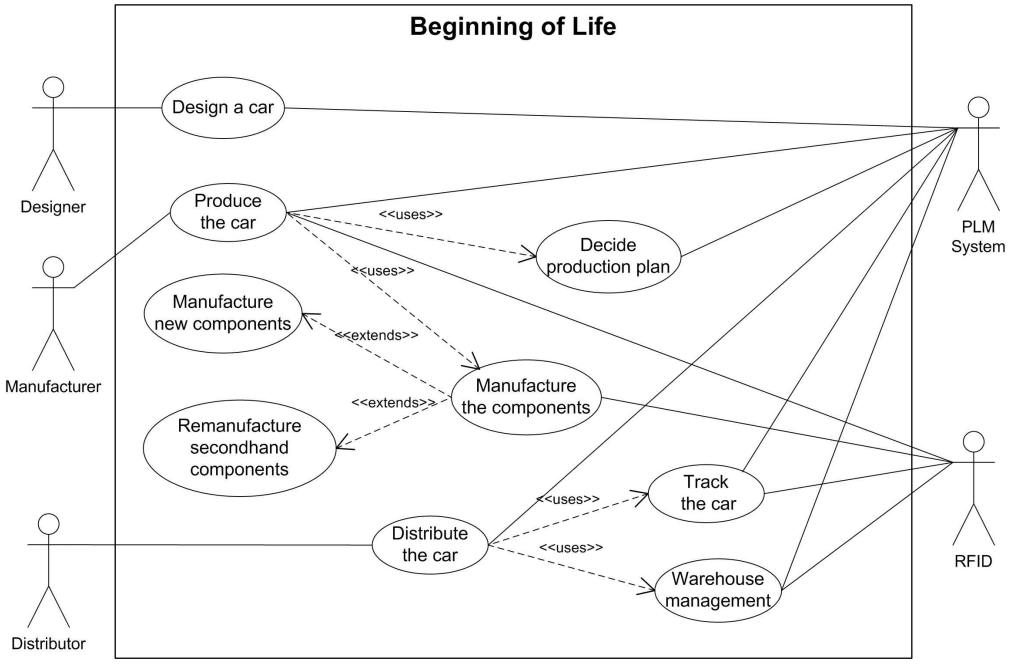

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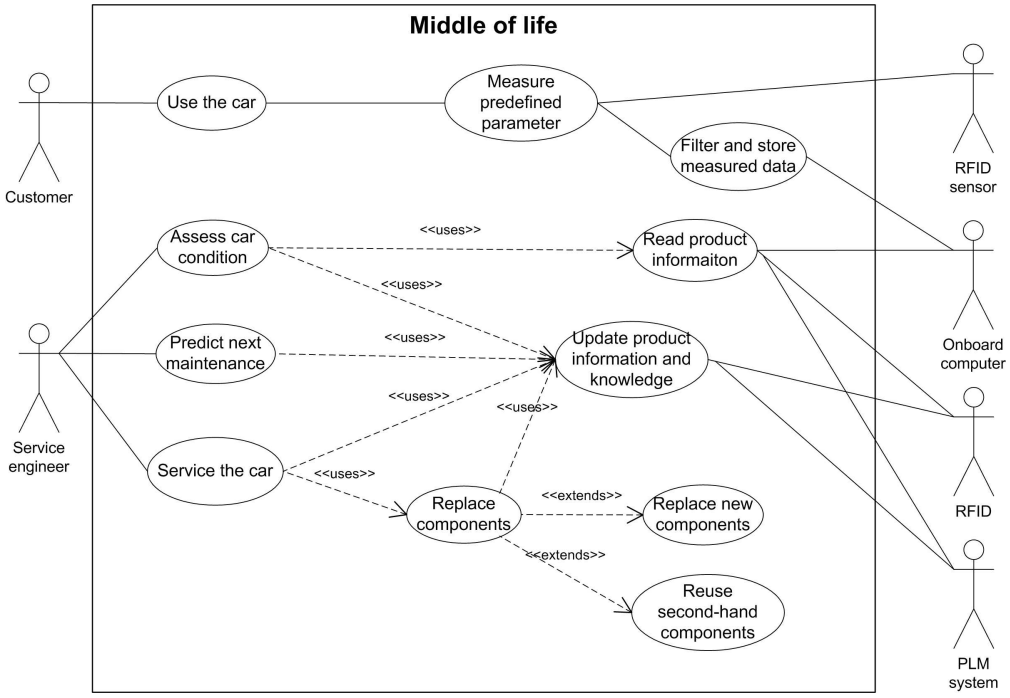

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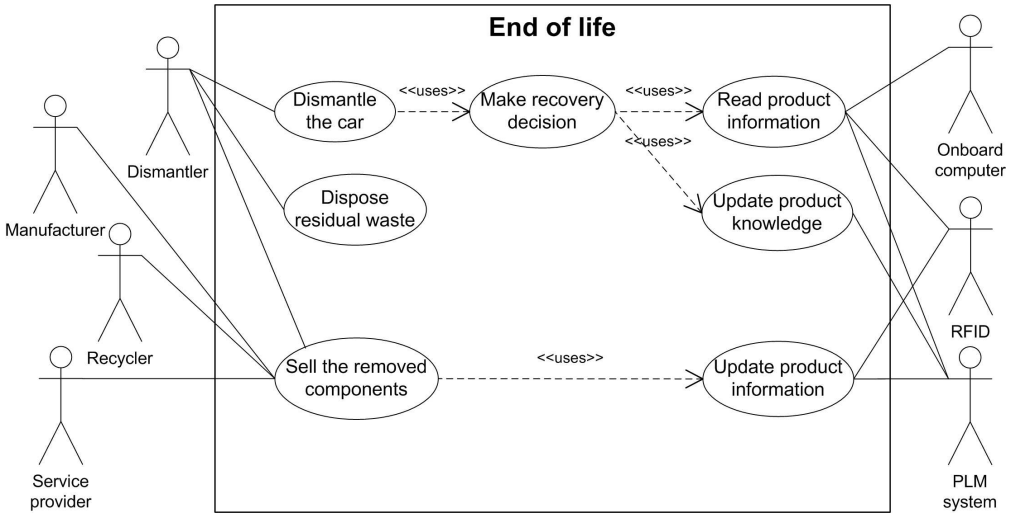

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