Harnessing prognostics health management and product-service systems interaction to support operational decisions

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Purpose: Prognostics and Health Management (PHM) can support Product-Service Systems (PSS) contracts, especially in the case of high technology products where their condition and performance can be monitored. This paper investigates how PHM can support effective execution of some PSS contracts and sets out the future research agenda for the development of an online simulation modelling framework that will further harness the interaction between PHM and PSS.

Design/methodology/approach: The research methodology set off by collating facts and figures from the existing body of knowledge, from which a set of key findings is presented from both technical and business perspectives. Analysis of the key findings highlights the current state of PHM-PSS interaction, the capability of existing tools and techniques and a comprehensive analysis of PSS performances with and without PHM.

Findings: Increased demand for total asset performance from the customers has been the main driver for PSS providers to adopt PHM technology. In the case of high value assets, PHM is used to capture the condition of the assets and to feed this information back to the PSS operations management which, in turn, will be used to plan a maintenance regime, spare parts provision, as well as to mitigate the dynamic behaviour which commonly occurs in PSS. Simulation modelling, driven by asset health condition, shows a considerable potential as an effective tool to control the execution of the PSS contract. In addition to the benefits from the maintenance services, the PHM-PSS interaction can increase the controllability of the PSS contract execution and allow future modifications to PSS contracts.

Originality/value: The value of this paper lies in the comprehensive analysis of the interaction between PHM and PSS, especially focusing on the interaction during the PSS contract execution. This paper demonstrates the strengths and weaknesses of existing research in the research domain, and highlights the opportunities for future research.

Keywords: Product-Service Systems, Prognostics and Health Management, Online simulation, Dynamic behaviour.

1. INTRODUCTION

Product-Service System (PSS) has emerged as a new competitive strategy to open up new markets, whereby, companies shift their business model from selling 'products only' to selling 'an integrated of product and services' (Tan *et al*, 2009; Mont, 2002). Customers are, typically, no longer buying the assets, but are instead buying the availability or capability of those assets throughout a fixed contract period (lease or share) (Cook *et al*, 2006). In PSS, the Original Equipment Manufacturers (OEMs), typically, do not offer product ownership but an integrated solution combining the product and services provision. OEMs are, thus, responsible for routine maintenance in order to ensure timely repair and spare parts provision. In many cases, the use of Prognostic and Health Management (PHM) is desirable in order to keep the assets up and running reliably.

The benefits of PHM have been widely reported in the literature. These include reduction of downtime and mission failures (Collins *et al*, 2011) and improvement of system safety and maintainability (Sun *et al*, 2010). PHM has been recognised as an effective solution to monitor the conditions of the assets and then to execute the appropriate maintenance actions before the failure actually occurs, hence, avoiding catastrophic failures or unscheduled downtimes (Khalak and Tierno, 2006). PHM has the potential to address reliability problems, especially, due to the complexities in design and manufacturing as well as the environmental and operational use conditions and maintenance (Pecht and Jaair, 2010).

It is apparent that there is a relationship between PSS and PHM. PHM shows the potential to support more effective fulfilment of PSS contracts when the improvement of logistics aspect and maintenance services is subject to high asset availability or performance warranty. In particular, when the product ownership is shifted from the customers to the OEMs, PHM can be used to mitigate the risks, which in turn enables the OEMs to better understand the cost consequences related to failures as well as the benefits that can accrue from implementing such technology (Grubic *et al*, 2009).

One of the most successful and widely reported examples of PSS and PHM interaction is the Rolls-Royce's TotalCare®. Rolls-Royce claimed that TotalCare® is "a flexible approach to achieving an engine support service that has the correct fit and scope of services to meet the operator's specific needs". In this case, Rolls-Royce does not only supply the aero engine as an aircraft component, but also uses a particular Information and Management Asset by means of engine health monitoring to make an advance fault prediction in order to avoid expensive cost of operational disruption and unnecessary engine repairs (Rolls-Royce, 2010).

Another example is the method to perform PSS for machine tool proposed by Zhu *et al* (2011). In Industrial Product-Service System for CNC machine tool (mt-iPSS), the capability of the machine tool and its attachment are sold as an intangible service. The business core is to provide machining capability rather than product ownership. The service provider, usually, retains maintenance program ensuring machine utilisation over a given period of time (Azarenko *et al*, 2009). For the mt-iPSS architecture, a machining fault prediction module captures the machine's condition or health status and then feeds this information back to the operations management team. This information can be used by the team to optimise operational services with the ultimate objective to reduce the assets downtime and cost. Figure 1 graphically illustrates how PHM technology can be used to support PSS in the case of a machine tool manufacturer.

[Insert Figure 1 here]

Although there are many perceived benefits from the PHM-PSS interaction, the adoption of the PHM programme must take into account some issues related to the interaction. Some common concerns around this interaction are: what are the benefits expected from this interaction? How does PHM deal with dynamic behaviour that typically occurs in PSS contracts? How can PHM support short-term PSS operational decisions? Unfortunately, existing research in PHM mostly only perceives PHM from the technological point of view with limited consideration on the extension of how to cover the PSS business model (Grubic *et al*, 2009).

Apart from the literature about PSS and PHM technologies, independently, the literature on how to link PHM with PSS appears to be lacking. Most of them quote only the PHM benefits without necessarily investigating its response to dynamic behaviour that typically occurs in PSS operational decisions. One of the first studies of PHM benefits was carried out by Malley (2001). He added PHM component on a decision maker tool (ALSim) to efficiently manage the availability of the JSF aircraft. Other examples are MATHS and LIKEMATH (Greenough and Grubic, 2010). They investigated the use of Condition Based Maintenance (CBM) in 'servitization' contracts showing a considerable gain in terms of availability and assets utilisation with CBM technology usage. Without a proper investigation on how to explore this interaction to support operational decisions, the goals established on design phase cannot be achieved when the assets are affected by the dynamic behaviour. For this reason, PSS-PHM modelling tool is desirable to deal with these complexities.

Aiming to bridge the shortcomings in the body of literature related to PHM and PSS, the main purpose of this paper is to investigate how the PHM programme can support PSS in order to better understand the characteristics of this interaction. This paper is organised into four sections: Section 2 presents the research programme with the aim, scope, research questions and adopted search strategy. Section 3 presents the key findings from the research. Section 4 highlights the strengths, weakness and opportunities that will serve as a basis for future work. Section 5 concludes the paper.

2. RESEARCH PROGRAMME

2.1 Aim, scope and research questions

This paper reports some findings from an ongoing research project that aims to investigate how to further harness PSS and PHM interaction in order to better support the decision making process during the operational phase of the PSS contracts. The scope of this research is to clarify the concepts and to seek an innovative approach to provide such an effective PSS-PHM interaction by answering the following research questions:

1) What are the typical scenarios that lead a PSS provider to adopt the PHM programme?

2) How to manage the dynamic behaviour within a PSS business environment where the interaction between PSS and PHM commonly takes place?

3) What are the typical performance measures in PSS-PHM interaction?

4) How to achieve an effective PSS-PHM interaction?

1) What are the business benefits from PSS-PHM interaction?

2.2 Literature search strategy

Based on research questions, a systematic literature review has been carried out. One of the first steps in conducting the review was to select the databases hosting journals papers, conference proceedings, books, etc. Although many databases were considered, Google Scholar, SCIRUS, ScienceDirect, IEEE Explore and SCOPUS were finally chosen due to their entirety and ease of use. An appropriate set of keywords, such as Product-Service-System, Industrial Product Service System, Service Selling, Functional Sales, Integrated Product Service Offerings, 'Servitization', Prognostics and Health Management, Prognostics, Integrated Health Vehicle Management, Sensor Embedded Products and Cost and Benefits analysis, were used.

The first search encompassed a 5 years time frame between 2006 and 2011 with the hope to retrieve the most up-to-date publications, using the combination of the aforementioned keywords. Using this time frame and keywords combination, only 23 papers were retrieved, suggesting the need to employ different, broader search criteria. "Benefits and PHM" were then used as the next search keyword examples and the year of publication was also expanded to cover 2000 and 2011. From this, there were 136 papers found. A cursory reading in the abstracts reduced this group into 48 papers. A similar procedure was executed for other keywords combinations and their respective acronyms. Finally, 13 papers were considered prominent and were, subsequently, employed to guide the research. The excerpts from those papers are presented in Table 1.

[Insert Table 1 here]

3. GENERATION OF KEY FINDINGS

Based on the literature review and the initial investigation carried out to answer the research questions, key findings are generated. These key findings will be used to develop the future research agenda.

3.1 Typical scenarios for adopting PSS-PHM solution

Service has become a primary differentiator for companies that are moving towards the service-oriented businesses. Although prevalent, the provision of service has not necessarily been limited to traditional support practices, but more importantly to the delivery of an integrated solution (Tan *et al*, 2009). Service offering based on value-in-use often leads to better utilisation of asset performance and longer operation possibility enabling the customer to concentrate their core competences and tends to outsource secondary activities (Meier *et al*, 2010). The integrated service solution lies beyond to increase profits from manufactured products; it helps the producer to differentiate and to diversity their products to better respond to customer's demands (Sundin *et al*, 2009), creating a closer customer connection (Sundin, 2009).

Functional selling of availability and results (typically notice in Use-oriented and Result-oriented PSS contract) often requires optimization of the asset's usage in order to achieve business sustainability (Yang *et al*, 2009). In those cases, asset monitoring data can enable the improvement of performance parameters guiding to better scheduling of repair and maintenance activities ensuring optimal utilisation (Baines *et al*, 2009). Nonetheless, some cases of service-oriented offerings do not require asset monitoring data such as

InterfaceFLOR's carpet tiles business (InterfaceFLOR, 2011) and Parkersell case study (Parkersell, 2011). Asset monitoring data is particularly crucial when unplanned downtime on high value assets can lead to the total system failure that is obviously costly and hazardous to environment or even life-threatening (Tu *et al*, 2007).

Despite the advancement of technology, the means in which the assets may fail and the operation principles of critical components are too specific and may vary according to particular component characteristics (e.g. material, physical conditions, statistical correlations, etc). As a consequence, designing a generic framework to implement a PHM solution is challenging and, although prognostic techniques can provide the estimation of Remaining Useful Life (RUL), its implementation will always be application-specific (Roemer *et al*, 2005). Furthermore, a fully functional PHM programme is still considered an expensive solution to be employed to fit all asset health management applications. In this respect, the adoption of PHM solutions to support PSS businesses must be commercially viable for both the providers and customers of the PSS.

In this context, there appears a situation in which the avoidance cost will be less than the required investment, suggesting that it is unviable from the financial viewpoint. However, although the Return of Investment (ROI) can be very low, there are some cases where this cannot be directly quantified in financial terms, but it is still necessary in order to meet the requirements that could not otherwise be obtained, e.g. availability requirements (Feldman *et al*, 2009).

Finding 1. The scenarios that lead to the adoption of the PSS-PHM solution are, typically, driven by the stakeholders' needs, in particular, when the customers demand the total asset performance (e.g. high level of asset's availability, capability) and, likewise, when the ensuring performance will become a competitive advantage to the PSS providers in order to improve their business value and propositions.

3.2 Management of dynamic behaviour using PSS-PHM interface

Dynamic behaviour in PSS is related to the occurrences of any unpredicted events (e.g. perturbations, abnormal or extreme conditions where assets operate, etc.) that can affect the fulfilment of the agreed PSS delivery contract. Unlike the product-selling businesses, it is crucial for the PSS providers to understand the risk associated with the dynamic behaviour and then mitigate them. Dynamic behaviour, according to Phumbua and Tjahjono (2011) ranges from changes in the new customer requirements and asset failure to demand fluctuation and market shifting, as a result. For these reasons, short-term contract evaluation becomes challenging, due to limited visibility of the current assets reliability.

From the asset's reliability point of view, PSS contract usually leads the PSS providers to assume the risk of equipment failure and also to show strong commitments in providing higher capacity utilisation (Oliva and Kallenberg, 2003). However, during the contract execution, operational conditions and external events can affect the asset's lifetime due to systematic errors, i.e. an error that is usually caused by measurement error or unknown influences (Lisiecki and Kłysz, 2007). As the fault monitoring is the basic process of monitoring the failure that may occur when the system is running (Brenna, 2007), the outcomes of the PHM will provide information as a basis of the proactive actions in order to reduce the disturbance caused by the dynamic behaviour, making the management of PSS contracts more robust.

An effective PHM also helps increase asset's reliability and safety by using a concept so called the autonomic logistics (Banks *et al*, 2005). This concept considers a PHM system as an autonomic response or a subconscious reflex of human being's nerve systems to react timeously to an unforeseen potential problem. As a consequence, the service providers can precisely evaluate as to whether or not it is possible to meet a new customer demand. Even though the PSS providers cannot guarantee the same level of availability, at least, a possible availability reduction using the same assets can be negotiated with the customers. If this modification can be done without significantly affecting the customers, extending the usage of assets can become useful for both stakeholders.

Finding 2. The PSS and PHM interaction seems to provide a powerful management of dynamic behaviour, especially when dealing with unpredicted events during the execution of the contract. PHM technology can capture more reliable data from the assets and feed these back to the PSS operational plan where their impacts can be analysed in great detail.

3.3 Typical performance measures within PSS-PHM interaction

Service-oriented companies, usually, have different business objectives and performance indicators (Tan *et al*, 2009). Nonetheless, they commonly pursue efficiency and effectiveness to the endeavours of their service requirements. Likewise, service value and differentiation, through integration of product and service, is mostly achieved by assets performance or utilisation, rather than ownership (Baines *et al*, 2007), i.e., value-in-use, commonly used as a measure that can be translated into maximising the equipment utilisation with the reduction of lifecycle cost (Yang *et al*, 2009; Colen and Lambrecht, 2010).

Assets performance measures can be used to guide both stakeholders and decision makers during the whole PSS contract. They become a critical factor due to the customer's expectations of service (performance goal) and the supplier's implementation (how it is achieved) (Kim *et al*, 2009). In the design phase of PSS, there is a strong relation between asset performance indicator and business value. Furthermore, during the contract execution, asset performance measures guide the OEMs to support service activities.

Amongst the valuable performance measures, recognised by both OEMs and customers, is availability (Lindahl *et al*, 2005). Availability relates the ability of an asset (under combined aspect of its reliability, maintainability and maintenance support) to perform its required function at a started instant of time or over a started period of time (Rausand and Hoyland, 2004). Availability means a period of time in which assets are in operations (Fleischer and

Nesges, 2006). In particular, high asset utilisation may be especially desirable with a pay-for-use contract and a direct link can be made with revenue generation (Slack, 2005).

Currently, availability of asset during the contract execution (i.e. operational availability) is often predicted during the design phase of PSS using the asset's Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) information. This evaluation considers those parameters with constant value over time (Torell and Victor, 2004). However, the effects of dynamic behaviour during the contract execution may change the expected asset lifetime which, in turn, will affect the asset's reliability. Consequently, the scheduled (or predicted) operational availability does not necessarily match the actual one.

Although it has been recognised that a proactive maintenance programme to support better decision making requires a high initial investment, when well implemented and managed, it is the most effective method to manage risks and provides the best possible return on plant assets (Da Silva *et al*, 2008). With PHM, those effects can be captured and treated properly, and the actual assets reliability can be better estimated and used to update the existing operational availability.

Finding 3. Availability is one of the key performance indicators to support PSS contracts because it provides a valuable reference for service provider and customer to support the decision making process. Once a PSS contract is executed, PHM can be used to continuously update the actual operational availability and to provide a proactive way to guarantee the desired operational availability.

3.4 Achieving more effective PSS-PHM interaction

Effective system design is a challenging task because the system designers, usually, only have limited visibility of system performance, and this is also the case with the PSS-PHM interaction. Simulation modelling has traditionally been used to aid in the validation of the systems (or sub-systems) design in order to improve the overall system performance (Ingemansson *et al*, 2002). A simulation model can mimic what happens in reality and is capable of representing the outputs recorded from the real system (Banks *et al*, 2009). Simulation modelling can be intuitive and visually appealing to use to support decision making (Benedettini and Tjahjono, 2009), and it is, in this instance, simulation modelling is one of the worthwhile tools to support PSS design.

As pointed out by Phumbua and Tjahjono (2011), nonetheless, simulation modelling tools are usually employed only during the design phase of PSS. Furthermore, in traditional discrete-event simulation models, asset's lifetime uncertainty is only expressed with random variability. During the execution of the PSS, which is, typically, in the form of contractual agreement, various unpredicted events, such as machine overload due to extreme weather conditions, improper use, etc, can affect the expected assets lifetime. The impacts from these unpredictable events, unfortunately, cannot be properly modelled only with random variability and Mean Time Between Failure (MTBF) information alone. Any maintenance activities that do not consider modifications in the operational environment lead to many unexpected system and component failures (Markeset and Kumar, 2003).

As there is no direct couple between the simulation model and the actual systems, i.e. once the systems are designed, there is no further need to use the simulation model, the model usually runs from an initial or empty state. As the model reaches the steady state, experimentation can progress and various what-if scenarios can be done. Nonetheless, it is very common that this state does not, necessarily, correspond to the actual state which the actual system is currently at, and bringing the model to this state as the initial state of the model is challenging. One way to address those issues is by coupling the simulation model with the actual system in an online mode.

Online simulation, or real-time simulation as it is also known, uses some type of feedback mechanism to couple the model and the actual system. It adopts similar principles used in real-time control systems, where the simulation model is applied in the feedback loop. One distinct feature of the online simulation is that the parameters obtained from the actual system become a set of the current state of that system which, in turn, will be used to initialise the simulation model. This feature, consequently, enables the simulation model to be used not only during the design phase of PSS, but more importantly can be extended to the operational stage where the model can be used as a day-to-day operational tool.

The online simulation arises to enhance operational dynamic behaviour measurement data from the real-world system in order to allow more efficient, accurate and precise control (Song *et al*, 2008). The real-time control provided by online simulation can be used to identify, better understand, help anticipate problems and look for the means of increasing the reaction of the production systems (Mirdamadi *et al*, 2007). With online simulation, the simulation time can be compressed or relaxed allowing the identification of disturbances, anticipation of the risk and providing the right and accurate reaction for the control system. Figure 2 shows the usage of online simulation to provide PSS and PHM interaction.

[Insert Figure 2 here]

With the online simulation tool, once the PSS contract (with performance guarantee clauses) is established, the PSS provider should be able to accurately manage the asset's lifetime in order to avoid catastrophic failures. The provider can check the short-term, day-to-day operational plan and, if necessary, to quickly modify it in order to achieve the targets specified in the contract (see Figure 2). In this way, the system will provide a more proactive intervention mechanism hence allowing better decision making capabilities to support fulfilment of the business requirements.

Finding 4. Online simulation shows considerable potential as an effective tool to promote the proactive assessment and control during the whole-life of the PSS contract execution. To support this, the simulation module should be coupled with the assets so that the operational conditions of the assets act as a feedback mechanism that continuously drives the simulation engine. PHM technology will provide the fundamental data to update the online simulation module with the current assets health information making PSS operational decisions more reliable and credible.

3.5 Comprehensive re-evaluation of PSS business strategies

The delivery of an integrated product-service offering can be accomplished by the responsibilities and obligations during the whole contract period. The effectiveness requires inter-organisational integration that can be achieved through the coordination of manufacturing, maintenance, spare parts and logistic systems (Baines *et al*, 2007; Baines *et al*, 2009). The incorporation of supplementary activities allows PSS providers to maintain a closed and long-term rapport with the customers which at the same time locks-out competitors (Colen and Lambrecht, 2010).

The decision to sell an integrated-service solution should carefully be analysed and thought out during the design phase of the product-service offering. Once the solution with performance guarantee is sold, the PSS providers should, continuously, verify whether or not the targets (availability, reliability, lifecycle cost, etc.), within the current assets capability, are achieved. Without this, PSS providers are at risk of making poor decisions during the following asset's lifecycle phase leading to penalties and damaged customer relationship. Due to the fact that maintenance actions are related to the achievement of the required goals, maintenance optimisation actions become an important role in contributing to positive business performance (Waeyenbergh and Pintelon, 2004).

Nonetheless, the health monitoring data alone does not provide sufficient information to make a decision. Determining the best course of action usually requires other criteria such as availability, maintainability and lifecycle cost (Feldman *et al*, 2009). In other words, the asset's health monitoring capability is going beyond the protection of the assets from serious damage. It enables more robust decision making capability during the asset's usage (Iyer *et al*, 2005) and end-of-life phases (Ilgin and Gupta, 2011) even though it has been subject to perturbations. Indeed, when the incorporation of rapid reactions to unpredicted disturbance is often required, the OEMs who adopted an integrated PSS and PHM solution will add more value into their business model. It is, therefore, fundamental to guarantee the achievement of requirements established during the PSS design phase.

The PHM technology can increase the assets maintainability and safety, making the assets more reliable. This advantage allows OEMs to evaluate and to redefine service strategies, such as maintenance schedule, parts stocking policy and remanufacturing, whenever necessary. With the availability of PHM data, more reliable evaluation of the PSS business model can be made, allowing the existing design requirements to be re-evaluated and to be used for the subsequent PSS contracts. This re-evaluation provides a great opportunity for the manufacturers to improve their products (e.g. reduce the need for service throughout the user phase, discover latency design error more quickly and better knowledge of how a product is used) (Sundin and Bras, 2005). Furthermore, it can also provide a better understanding of the whole life cycle cost and the customer lifetime value (Sun *et al*, 2010). In short, with PHM technology, the risks associated with the evaluation of availability/capability contracts can be reduced (Jazouli and Sandborn, 2010).

Finding 5. The interaction between PSS and PHM allows re-evaluation of the PSS strategies. In addition to the benefits from maintenance services, the interaction allows the key performance measures to be continually updated. Thus, this interaction becomes fundamental to increase the controllability of the contract execution and to capture the essential modification in order to sustain the PSS businesses.

4. ANALYSIS OF KEY FINDINGS

This section presents the analysis of the key findings and highlights the current state of PSS-PHM interaction, the capability of existing techniques/tools and comprehensive evaluation of PSS, with and without PHM technology.

4.1 PHM as an effective technology to support PSS operational decisions

Even though the recent literature has recognised that the PHM programme can support certain PSS contracts, this interaction has not been fully investigated. The literature often considers the PHM programme only as a technological facet without explaining its value for business purposes. Moreover, PSS literature has focused on PHM applications only at the design phase with very little consideration on its potential benefits to support contract execution. Industrial cases, experimental results and numerical analysis are also desired to allow profit analysis from the reliable contract execution.

Commitment to adopting the PHM programme is mainly guided by the needs to access current asset's health status. With the health status embedded into the PHM data, unexpected changes into assets lifetime can be captured and back propagated for further analysis. Operational decisions, commonly, make during PSS contract execution can be reviewed and updated according to the current needs. Consequently, a reliable short-term modification of the operational plan can be implemented to achieve the specified business requirements. It is, particularly, desired for the performance-based contracts (PBC), where the customers pay for the number of hours in which the assets are available to use (Guajardo *et al*, 2011).

The current literature has regarded service value with asset performance or utilisation rather than product ownership. Value in use, qualitatively derived from the customer needs, are often incorporated in many models but indicators of service efficiency, such as overall product availability, operating times and functional reliability were not commonly found (Phumbua and Tjahjono, 2011). Regardless of this fact, availability has been reported as the strongest candidate for PSS performance evaluation. Furthermore, from the PSS perspective, high availability combined with high production rates may result in the direct revenue generation.

4.2 Capability of the current modelling tools and techniques

The second analysis maps the capability of current modelling tools and techniques. First of all, there appears to be a gap in modelling tools and techniques that can be used to integrate the aforementioned technologies throughout the execution of PSS contract. Existing modelling tools are, typically, used at an early stage of PSS business with long-term analysis over a wide range of contextual scenarios. Those simulation tools model PHM data with theoretical assumptions that, very often, cannot be verified in practices. By contrast, short-term decisions support, which is based on current state and recent history (Wynn *et al*, 2008), must incorporate current PHM data into the simulation model. Furthermore, tools that can be used to track the effects of dynamic behaviour (i.e., short-term contract extension, unexpected shop floor event, etc) and then be used to support short-term decision making during the PSS contract execution, are lacking.

Simulation models, typically, start from an empty state and time zero. They do not consider assets' lifetime variation due to unpredicted events. In those models, assets degradation is driven by historical data and probability distribution with MTBF information. Although it can be used at design phase of PSS, it cannot overcome some complexities during the contract execution (such as unexpected new customer requirements, short-contract extension, etc.). A simulation tool is particularly desired to deal with unforeseen behaviour and contextual changes throughout the contract execution. A maintenance service team can trigger asset health information to decide which part must be replaced and when the spare part should be purchased, for instance. Those benefits can also be extended for remanufacturing activities allowing more accurate estimation of the overall remanufacturing time. Without the appropriate simulation tool, which incorporates the latest assets health status upon service decision support, OEM’s may decline valuable commercial opportunities due to uncertainty around a business model.

For this reason, a computer-based simulation tool, in which assets model representation are updated periodically with the latest assets health status, is desirable. Updating the simulation model with current PHM data, asset representation becomes more credible, leading to more accurate simulation outcomes. As a consequence, short-term proactive decisions can be made to overcome the effects of unexpected assets lifetime variation leading to achieving the operational goals established during design phase of PSS.

4.3 Comparison between PSS with and without PHM technology

The third analysis carried out, compares the PSS businesses with and without the PHM technology. Firstly, not all PSS business analyses require the application of PHM.

Sometimes, the initial investment to implement it overcomes the expected stakeholder's business benefits. Moreover, some critical components do not have prognostic model or even health assessment data. In those cases, asset downtimes are modelled by probability distribution and MTBF information and the simulation outcomes obtained from the design phase of PSS are extended to PSS contract execution.

Nonetheless, manufacturing requirements and interactions are highly complex and cannot be predicted. Unexpected customer requirements or assets performance variation may arise during the contract execution. In those situations, PHM technology seems to provide essential information to assist the evaluation of new business requirements and also to avoid unscheduled downtime and contract penalties. Therefore, combining traditional PSS analysis method (i.e. modelling and simulation) with PHM technology can become a fundamental solution for more effective business analysis. Existing simulation tools must be customised to allow continuous updates of the simulation data from PHM.

4.4 STRENGTHS, WEAKNESSES AND OPPORTUNITIES ANALYSIS

Based on the findings from the previous sections, the strengths, weaknesses and opportunities within PSS-PHM interaction can be summarised in Table 2.

[Insert table 2 here]

From the strengths' viewpoint, conceptual definition of PSS requirements and PHM benefits are mature and widely reported in the literature. In fact, the interaction between PSS and PHM, for the design purposes, was found only in a few papers. Researchers also agree that there is insufficient research or qualitative analysis and industrial cases for this interaction.

From the weaknesses viewpoint, there is a lack of computer-based simulation technology to support PSS operational decisions. Furthermore, studies on proactive reactions caused by dynamic behaviour seem to be missing. Indeed, without appropriate computational tools to capture the current health assets data, the service provider cannot determine the best actions due to unexpected assets lifetime variation.

From the opportunities viewpoint, new methods, frameworks and techniques are required to support short-term decisions during the entire PSS contract execution. Development of computer-based simulation tools which incorporate PHM data into business analysis is also indispensable. This will allow unexpected assets lifetime due to effects of unforeseen circumstances to be further analysed, making it possible for the PSS provider to decide the most appropriate operational decisions to achieve the PSS design requirements. Once the new techniques and simulation tools are implemented, case studies and industrial cases are needed to validate the advantages provided by PSS and PHM interaction.

5. CONCLUDING REMARKS AND FUTURE WORK

The aims of this paper are 1) to capture the typical scenarios that lead the adoption of PSS-PHM solution, 2) to understand how to manage dynamic behaviour with this interaction, 3) to find out the performance metrics for PSS-PHM interaction, 4) to investigate how to incorporate rapid reactions to deal with the unexpected assets performance variation and the business opportunities promoted by this interaction. The main contribution of this paper is a comprehensive analysis of how PHM can support, more effectively, some PSS contract. Key findings drawn by this research allow fuller consideration of PSS-PHM interaction from both business and technical perspectives.

The strength, weakness and opportunity analysis suggest the following considerations. Firstly, PHM is an effective solution to support reliable fulfilment of some PSS contracts, in particular when high assets performance is mandatory. Nonetheless, the existing tools to analyse this interaction are typically usable only during the design phase of PSS, but not the execution phase. Consequently, the most valuable facet of PHM technology, i.e. the capability to capture unexpected assets lifetime variation, is missing. A computer-based simulation tool, based on the online simulation paradigm, can, potentially, be used to continuously update the simulation model with the asset data. Based on the research opportunities identified, this paper highlights the needs for future research agendas to harness PSS and PHM using online simulation methods. Moreover, a novel framework, describing PHM data propagation to support operational decisions, is also needed. The implementation of a framework-based simulation tool with practical case studies will allow the benefits accrued from the PSS-PHM interaction to be quantified numerically. The case studies should not be limited to updating day-to-day operational decisions, but also to compare the actual with the expected performance which has been obtained during the early business analysis.

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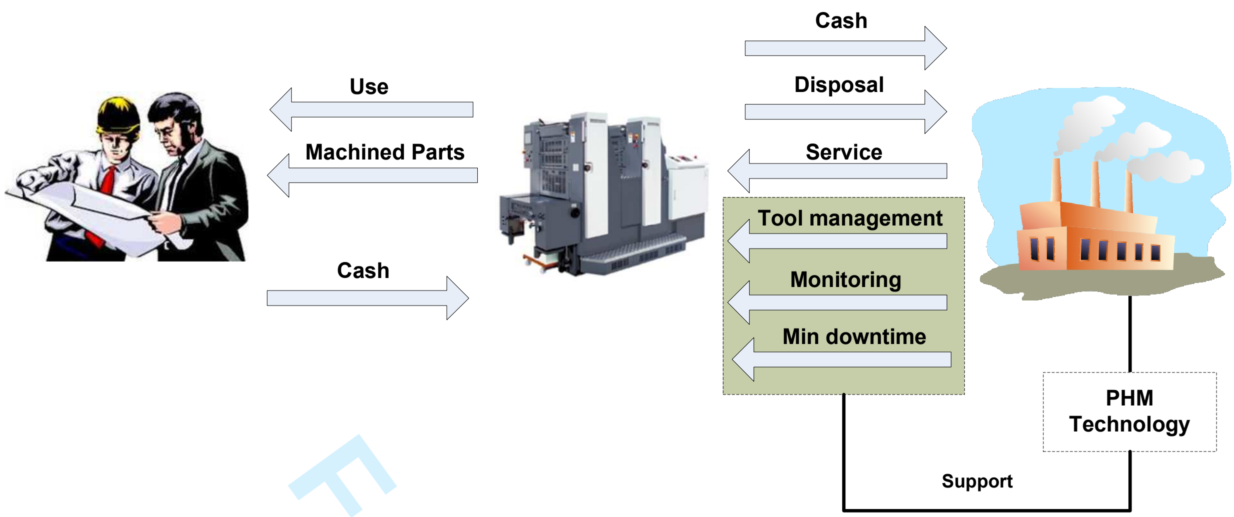

Figure 1: Using PHM technology to support PSS (adapted from Azarenko et al., 2009)

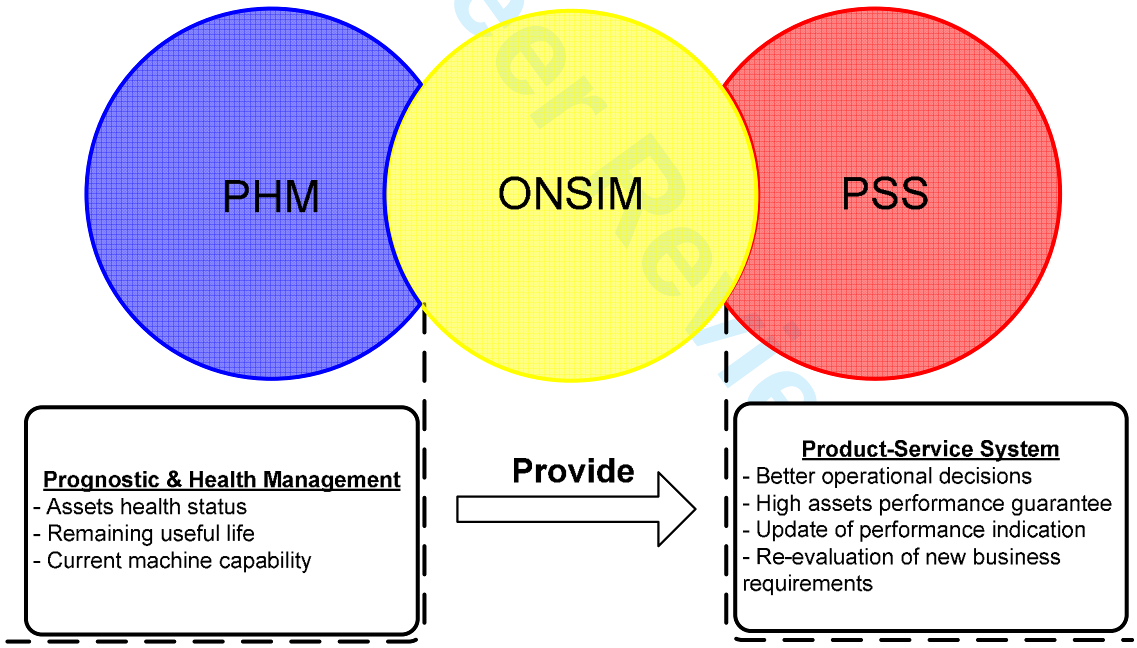

Figure 2: Using online simulation to provide PSS-PHM interaction

Table 1: Most relevant works and their characteristics

Reference	*Description*
Greenough and Grubic (2010)	*Development and validation of two software tools (MATHS and LIKEMATH) to explore the relationship between PHM technology and 'servitization' in the machine tool industry*
Ilgin and Gupta (2010)	*Qualitative evaluation of the impact of Sensor Embedded Products (SEPs) on the performance of an appliance disassembly line*
Ondemir and Gupta (2009)	*Economic justification of establishing advanced Disassembly-To-Order (DTO) system in which sensor-embedded end-of-life products are disassembled in order to fulfil sophisticated demands for both components and materials*
Grubic et al (2011)	*A survey conduced across UK manufacturing sectors to explore the extent, motivations, benefits and challengers of deploying diagnostic and prognostic technology as an element of competitive strategy*
Scanff et al (2007)	*Proposes a stochastic model to predict the life cycle cost impact associated with the application of PHM to helicopter avionics*
Willians (2006)	*Describes the benefits of Integrated Vehicle Health Management (IVHM) and also an analytical way to determine sensitivities in a system design and concept of operations*
Lee et al (2009)	*Detailed description of how maintenance can be transformed from pure*

	strategies into a service function
Feldman et al (2009)	*Proposes a methodology to obtain the ROI for PHM activities and also a study conducted using a stochastic discrete event simulation model to determine the potential ROI offered by electronics PHM*
Malley (2001)	*A methodology to model the PHM of Autonomic Logistics System Simulation (ALSim) to provide decision maker regarding the Joint Strike Fighter's (JSF) Autonomic Logistics System (ALS)*
Jazouli and Sandborn (2010)	*A new method to determine an unknown system attribute to fulfil a specific availability constrain. It was also demonstrated that the use of PHM technology under availability can provide value beyond failure avoidance and minimisation of cost*
Sun et al (2010)	*Detailed discussion of the benefits of prognostics in systems. They also discuss challenges that may be met in the application of prognostics from the viewpoint of both PHM system designers and users (such as selecting applicable prognostics methods, addressing inherent uncertainties, assessing prognostic accuracy, etc)*
Sandborn and Wilkinson (2007)	*Proposes a methodology for determining an optimal safety margin and prognostic distance for various PHM approaches in single and multiple socket systems where the LRUs in the various sockets that make up a system can incorporate different PHM approaches (or have no PHM structures at all)*
Khalak and Tierno	*Discuss the problem of determining performance metrics for pre-*

(2006)	*emptive condition-based maintenance, also referred to as PHM*

Table 2: Strengths, weaknesses and opportunities in PSS-PHM interaction

<table>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td>- Precise definition and understand of PHM benefits;
- Clear definition of PSS requirements;
- Existence of research on PSS-CBM interaction;
- Agreement that there is not enough investigation in this research area;</td><td>- Lacking computer-based simulation techniques to evaluate operational decisions during execution of PSS contracts;
- Missing evaluation of dynamic behaviour during the execution of PSS contract;
- Lacking research on PSS operational phase;
- Lacking research in exploring the technical details of PSS-PHM interaction;</td></tr>
<tr><th colspan="2">Opportunities</th></tr>
<tr><td colspan="2">- New technologies and approaches for short-term decision during PSS contract execution;
- Development of a computer-based simulation tool with the capability to capture PHM data;
- Numerical investigation to quantitatively assess how PHM can support more effective PSS operational decisions;
- Methods to update key performance indicators over contract execution;
- Business requirement evaluation under dynamic behaviours;
- Industrial case study implementation to validate this interaction;</td></tr>
</table>

Response to Reviewer's comments

Ref. No	JMTM-Jun-2011-0058
TITLE:	Harnessing Prognostics Health Management and Product-Service Systems interaction to support operational decisions

The authors would like to thank the Reviewers for the comments, constructive criticism, and suggested edits to improve the quality of the paper.

We found these comments very valid and have consequently addressed them in the revised manuscript. Individual comments from the Reviewers and the responses are presented below.

Reviewer #2

1. I find this paper very interesting and rather new of its kind. I agree that more research of this kind is needed. However, I find that the research search have been conducted in a somewhat narrow kind. This since the terms used in research have been changing during the years. Therefore I suggest you to check once again for other terms used for PSS such as: Service Selling, Functional Sales, Integrated Product Service Offerings and Industrial Product Service Systems as these also have been used as a similar term as PSS.

We took the advice on board. Search was repeated to include the suggested keywords above and these have been incorporated in page 5, section 2.2. With more keywords, we obviously found more papers to review. None of the new papers we reviewed are contradictory to what we found before. In fact, they are complementary.

2. On page 2 and 6 you are referring to a book by Sakao and Lindahl (2009). Now I wonder, since this book contains many chapters written by many authors on different subjects on PSS, is it possible to be more specific and refer to any chapter or do you really want to refer to the whole book and all chapters?

The reference has been amended. Instead of Sakao and Lindahl (2009), we cite Tan et al (2009), which is one of the papers inside Sakao and Lindahl (2009). This is also applicable to page 6.

3. On page 8, Row 14: "Amongst the valuable performance measures recognized by both OEMs and customers is availability." This finding was also found in Lindahl et al (2005).

For this reason, we cite Lindahl et al (2005) on page 9.

4. Can PHM technology include “Sensor-Embedded Products (SEPs)” which have been research by Professor Surenda M. Gupta from Northeastern University, USA?

Absolutely. PHM technology also needs to monitor the current assets health data as SEP does (see finding 4). However, in some cases, not only can PHM technology supply health assets data but it can also provide the remaining useful life of the monitored asset. This is particularly needed in order to update the current model component capable of providing an efficient way to make short-term decisions and to update the PSS business model.

5. It is nice that this paper investigates PSS research beyond the product life-cycle phases of design and production, taking in account e.g. service and maintenance. However, would it be possible to look even further in the product life-cycle to see how PHM technology and data can be used in the end-of-life decisions e.g. remanufacturing? See e.g. Sundin and Bras (2005). Please expand on this subject further since I think PHM has a good potential even in the latter phases of the product life-cycle along with SEPs.

We have amended the manuscript with some sentences. Please see page 13 paragraph 3. “In other words, the assets health monitoring capability is going beyond the protection of the assets from serious damage. It enables more robust decision making capability during the asset’s usage (Iyer et al, 2005) and end-of-life phases (Ilgin and Gupta, 2011)”.

Also, on page 16, we added some sentences on paragraph 1, which reads: “A simulation tool is particularly desired to deal with unforeseen behaviour and contextual changes throughout the contract execution. Maintenance service team can trigger asset health information to decide which part that must be replaced and when the spare part should be purchased, for instance. Those benefits can also be extended for remanufacturing activities allowing more accurate estimation of the overall remanufacturing time.”

Reviewer#1

1. PHM cannot be defined as an enabling technology to support PSS contracts, although it can be used this way (please change the purpose statement).
We agreed with the suggestion and we have modified the purpose.

2. The type of PSS that may be supported by PHM and how this might work?
We now clarify this, first on page 1 - Purpose. "Prognostics and Health Management (PHM) can support Product-Service Systems (PSS) contracts especially in the case of high technology products where their condition and performance can be monitored."

We also state on page 1 – Findings: "In the case of high value assets, PHM is used to capture the condition of the assets and to feed this back to the PSS operations management which in turn be used to plan maintenance regime, spare parts provision as well as to mitigate the dynamic behaviour commonly occurs in PSS"

We clarify on page 2 paragraph 3 that "…PHM shows the potential to support more effective fulfilment of PSS contracts when the improvement of logistics aspect and maintenance services is subject to high asset availability or performance warranty."

Finally, we added a paragraph on page 13 section 3.1. "Functional selling of availability and results (typically notice in Use-oriented and Result-oriented PSS contract) often requires optimization of the asset's usage in order to achieve business sustainability (Yang et al, 2009). In those cases, asset monitoring data can enable the improvement of performance parameters guiding to better scheduling of repair and maintenance activities ensuring optimal utilization (Baines et al, 2009). Nonetheless, some cases of service-oriented offerings do not require asset monitoring data such as InterfaceFLOR's carpet tiles business (InterfaceFLOR, 2011) and Parkersell case study (Parkersell, 2011). Asset monitoring data is particularly crucial when unplanned downtime on high value assets can lead to the total system failure that is obviously costly and hazardous to environment or even life-threatening (Tu et al, 2007)."

3. Why not use actual examples of real business models from the literature?
A new paragraph has been inserted on page 3 (second paragraph).

4. Finding 2 is too strong.
We have modified the sentences in finding 2.

5. There are examples in some of the literature of asset performance measures, but these will tend to vary with the specific nature of each contract. Those to which PHM is relevant will typically use availability measures such as aircraft-on-ground time, uptime etc.

We have modified the first paragraph of section 3.3 and finding 3.

Additional Questions from Reviewer #1:

6. Originality and contribution:
The paper claims to make a comprehensive analysis of the ways in which PHM technologies can support PSS contracts. However, the authors have not described typical contracts in terms of obligations on asset suppliers and expectations of users. How is it possible therefore to analyse the contribution of PSS?

We found in the relevant literature, a relationship between PSS and PHM and it has been reported to be valuable for high assets value. The contracts in terms of obligations on asset suppliers are especially hard to find in public domain and usually confidential, thus it is not possible to comment on this matter and is outside the scope of this paper. Nonetheless, we plan to further investigate this issue in our research. We explained in the paper at the first paragraph of section 4.1.

7. Relationship to Literature and Previous Work
The paper does demonstrate adequate understanding of relevant literature, but I would contest some of the claims such as the claim that in PSS, asset ownership typically remains with the manufacturer. This is emphatically not the case with Rolls-Royce, which is an often quoted example. Similarly I disagree with finding 3. Several authors have explicitly mentioned performance measures for PSS - usually environmental impact, but sometimes reliability related measures such as MTTR or availability.

The authors agree with the reviewer. We have made the suggested change. The sentence "claims such as the claim that in PSS, asset ownership typically remains with the manufacturer" was changed (see first paragraph from page 2). We also have modified the first paragraph from section 3.3 and the finding 3.

8. Methodology and Approach
No addition comments required.

9. Results and Conclusions

The authors agree that simulation is a powerful tool to model stochastic phenomenon, in particular, when the focus is on average or long-term behaviour over a wide range of scenarios. However, the online simulation technique which must be updated depending on the current assets health information is a powerful technique for short-term analysis to aid managers and maintenance service team in order to understand how reactions to unforeseen event will impact on contract execution.

10. Implications for research, practice and/or society

No additional comments required.

11. Quality of Communication

We are sorry for this and we have taken care of the grammatical and factual errors. The manuscript has now been proof read by a professional English speaker.