The Interaction of PSS and PHM

- a mutual benefit case

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ABSTRACT

In the PHM literature a majority of the research deals with solving technically related issues and there is a lack of material addressing the business benefits of such technology. Although PHM has the potential of creating a true paradigm shift, little consideration has been given to PHM being used for revenue generation other than the frequently cited case of maintenance cost reduction and certainly not as a new and powerful business model enabler. The thesis offered here is that a Product-Service System (PSS), which offers a bundle of products and services where emphasis shifts from selling a product to selling the use of a product, is the true business reason for adopting PHM. This paper presents an approach and the tools developed to support a cost/benefit analysis of deploying PHM technologies on a machine tool, where PHM is being used to support a PSS business model. The paper also introduces a model which could frame future research direction, exploring the further benefits PHM technology could bring to a business and the changes necessary to realise those benefits.*

1 INTRODUCTION

The current research direction in Prognostics and Health Management (PHM) can be ascribed to at least three developments: (1) increasing asset complexity (Söderholm 2004), (2) advances in technologies such as wireless, sensors, and telecommunications (Price *et al.*, 2003), and (3) advances in prognostics, which is seen as the next frontier after the successful applications of diagnostics (Hess and Fila 2002). The research is predominately technology oriented and lacks a wider assessment of the application context, e.g. specific cost/benefit business models. This paper aims to put PHM technology within a broader business context by relating it to the Product-Service System (PSS) business model.

PSS can be defined as an integrated combination of products and services where the emphasis is put on the 'sale of use' rather than the 'sale of product' (Baines *et al.*, 2007). Central to this new business model is a shift from selling a product, and its related spare parts as required, to selling a solution that supports a customer's needs in the form of a service delivering a fully maintained and useable product. Due to prolonged product life-cycles, companies are increasingly faced with a growing installed base and stagnating new product demand. They have realized that building competitive advantage solely on cost and/or product differentiations has become unsustainable and are making the move to service-driven strategies to protect market share or boost revenue. By offering a bundle of products and services companies can expect benefits in three areas (Gebauer *et al.*, 2006): strategic, marketing and financial. In respect to strategic benefit, and mainly due to their intangible nature, integrated product and service solutions are more difficult to imitate than products and can bring needed competitive advantage to a company. At the same time, knowing a customer's needs allows a supplier to build closer and longer relationships and thus achieve marketing benefits which in turn should result in long-term steady cash flows.

At Cranfield, PHM technology is seen as a key enabler of an effective PSS. Inherent to a PSS business model is a shift of risk to the supplier, where availability is sold instead of the system itself. In these cases, PHM can be used to mitigate this risk which in turn calls for building a deeper understanding of related costs and benefits. This paper will present an approach and the tools developed to evaluate the costs and benefits incurred when deploying PHM to support the PSS on a machine tool as well as future efforts to understand the role of this technology in value creation.

Section 2 introduces an overview of existing PHM cost/benefit approaches and identifies potential gaps. Section 3 then presents the approach and tools developed to explore the cost/benefit analysis of deploying PHM for a machine tool company adopting a PSS. This illustration raises a need to further explore the role of PHM technology in creating value for both supplier and user and thus, before the conclusion, Section 4 presents a model which frames possible future research efforts in this area.

2 PHM COST/BENEFIT - REVIEW AND GAPS

There are several papers in the literature which propose cost/benefit analyses of PHM enabled systems. The papers provide a variety of approaches and include those by: Byer *et al.* (2001), Kacprzynski *et al.* (2002), Banks *et al.* (2005), Wilmering and Ramesh (2005), Hoyle *et al.* (2007) and MacConnell (2007); these are briefly reviewed below.

2.1 Review of existing approaches

Byer *et al.* (2001) introduced a methodology for performing a cost/benefit analysis on the Autonomic Logistics System (ALS) for the Joint Strike Fighter (JSF) aircraft which is enabled by PHM. ALS is a system in which automation is applied for locating and ordering parts to support the operation of the JSF. The approach consists of 11 steps in which a baseline system without PHM is compared to a PHM enabled one. Apart from introducing some of the problems encountered with cost/benefit evaluations, no real example was presented to support the proposed approach. Kacprzynski *et al.* (2002) introduced an approach for development, simulation and cost/benefit optimisation of a PHM enabled system. The approach is founded on FMECA methodology and aims to address some of the shortcomings for use in a cost/benefit analysis, e.g. sensor placement, precursors and credit for health monitoring. For each failure mode a cost function which summarises direct and indirect costs can be modelled. This can then be used to optimise the overall PHM design in a manner which minimises risk and costs.

In order to provide a simple cost/benefit analysis which engineers can use when designing, developing and implementing PHM enabled systems, Banks *et al.* (2005) introduced a four step approach. The first step deals with selecting a system and performing a degrader analysis. This should result in identifying top degraders which in turn provides input for selecting an appropriate PHM technology whose development and implementation cost is calculated in the second step. The last two steps estimate the benefits of the technology implementation and calculate the return on investment respectively. Wilmering and Ramesh (2005) presented an OCCAM (Ownership Cost Calculator for Aerospace health Management) approach which supports a so called Integrated Vehicle Health Management (IVHM) candidate analysis process. It has been developed to assist engineers in evaluating the life cycle cost impacts of various IVHM designs and is based on a mathematical failure process model which in turn triggers maintenance and logistics events which generate costs. Versions for commercial airplanes, military and space, have been developed recognizing differences in their maintenance, logistics and support models.

Hoyle *et al.* (2007) proposed a cost/benefit analysis approach which supports Integrated Systems Health Management (ISHM) for aerospace systems and demonstrated it by using a simplified satellite reaction wheel problem. The key to their approach is the use of a formulated objective function which quantifies cost/benefit factors involved when deploying ISHM on various subsystems. They also proposed an optimisation framework which maximises profit from the system. Finally, MacConnell (2007) introduced a study which included experts from the Air Force, industry and academia that aimed to define and assess the benefits of the ideal ISHM system. Although qualitative in nature and developed from the perspective of an ideal system, the study provided a lot of new insights into the way this technology should be perceived and its related benefits. This was helpful when identifying the gaps in existing cost/benefit approaches.

2.2 Gaps

The above review of existing cost/benefit approaches revealed five gaps, as briefly summarised below.

2.2.1 Approaches developed by engineers for engineers

All of the approaches introduced and reviewed here have been developed by engineers for engineers and therefore suffer from lack of business input. The latter brings with it a view of the customer, and the cultural and process drivers that are so important to the success of a PSS venture.

2.2.2 Aerospace dominance

There is a need to broaden the interest in PHM cost/benefit approaches as the majority of approaches have been developed to support PHM development and implementation in the aerospace sector.

2.2.3 Approaches do not address overall system capability

Existing approaches do not address the entire cost/benefit spectrum of the overall system capability. Namely, assessment of diagnostic and/or prognostic technologies is usually very application specific where technologies are applied to solve failure diagnosis and prediction problems and do not address the degradation of overall system performance. This in turn demands a deeper understanding and assessment of costs and benefits which result from having a fully integrated PHM system.

2.2.4 Limited view about the benefits of PHM

Existing approaches reflect the prevailing view of PHM technology being a necessary supportability cost where the technology is aimed at saving a lot of money tomorrow. Thus, the benefits reported are in terms of maintenance cost savings (e.g. time saving, availability improvement, cost of spares, etc.) and no approach considers PHM as an enabler for revenue generation. Further to this, no holistic knowledge about the benefits of PHM really exists. This knowledge should provide an answer to a question such as: how will the users and suppliers of PHM enabled systems benefit from this technology? This may be because companies operating PSS models do not openly publish their findings and so the literature may reveal a biased point of view. It might also be because a focussed direction for PHM does not exist.

2.2.5 Lack of direction for PHM

Through his study MacConnell (2007) concluded that ISHM (PHM) should be considered as a game changing technology which has the potential to create a paradigm shift. Unfortunately, what current PHM research is missing (apart from the JSF with ALS) is a business led direction which is directly linked to the understanding of the benefits of PHM technology. Simply, without having an in-depth knowledge about costs and benefits it is hard to develop a clearly focussed technical direction. PSS has the potential to provide this direction for PHM.

Some of the gaps presented here have been addressed in the approach and tools which are introduced in the next section. Others, such as a need to build a deeper knowledge about the benefits of PHM technology, form a research opportunity and are examined in the fourth section.

3 COST/BENEFIT APPROACH OF DEVELOPING A PHM SYSTEM TO SUPPORT A PSS

This section introduces a simulation developed to examine the cost/benefit trade-offs of deploying PHM technologies on a machine tool (e.g. lathe, grinding machine, etc) which is being offered according to a PSS business model. The approach has been developed by using a number of sources. The first were the papers that explore the experiences of machine tool manufacturers attempting to make the transition to service provision. This provided a framework which was then used to inform interviews with UK producers of specialised machines, second source, to see how they maintain service levels and to investigate the operational environments in which their products perform. The third and final source was two software tools developed by The Boeing Company and given to Cranfield University as part of development of the Cranfield IVHM Centre. These tools are called SHOAM (System Health Operations Analysis Model) and PICAM (Probabilistic IVHM Cost-benefit Analysis Model).

SHOAM (Williams, 2006) is a discrete event simulation built around the civil aerospace market and developed using ARENA software. For the work presented here the same basic structure was adopted but the detail changed, complemented by the information above, to model a machine tool life cycle; the resulting simulator being MATHS (MAchine Tool Health Simulation). PICAM picks up the events in SHOAM and performs the cost/benefit analysis based on product sale and maintenance support. This has been considerably adapted for the machine tool case, with features that reflect the full PSS business model, the result being LIKEMATH (LIfe-cycle risK Evaluation of MAchine Tool Health).

The approach developed comprises two stages, each being supported by these purpose built decision tools. The first stage assesses the operational benefits of using different PHM solutions across a range of machine tool platforms (MATHS). The next step determines the costs and benefits of deploying the PHM solution and its impact on a business (LIKEMATH), which also supports risk modelling plug-in software.

3.1 MAchine Tool Health Simulation (MATHS)

An overview of the elements of MATHS is shown in Figure 1.

Machine Tool Manufacturer: At the start of the simulation the machine tools are designed and created with a percentage given PHM systems; the learning capabilities of those systems and the engineer resources available (whether or not an engineer will be on-site) are also introduced. The reliability of each machine tool is also specified here together with machine tool design characteristics. A machine tool is modelled as consisting of nine subsystems each having separate reliability, maintainability and prognostic characteristics. The subsystems are: spindle, CNC controller, power supply, lubricant pump, oil filters, motor bearings, X motion, Y motion and rotary Table.

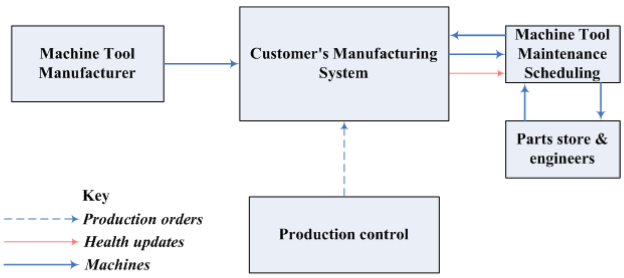

Figure 1: Elements of MATHS

Production Control: This element generates and introduces production orders into the customer's manufacturing system. It is used to generate the manufacturing scenario in which the machine tool and service arrangement can be simulated. MATHS allows the user to explore scenarios in which machine tool capabilities are sold as part of a service contract for the duration of 5, 10 or 15 years.

Customer's Manufacturing System: This element models a manufacturing scenario in which the machine tools are aged according to the operational usage specified in Production Control. Machine tools are introduced and assigned to orders that age them. Where used, PHM systems send repeated health updates to maintenance which are used to schedule maintenance resources and the machine tool will also be checked for remaining useful life. From interview feedback the three subsystems on the machine whose decrease in performance affect the machine tool most are: X motion, Y motion and rotary table.

Machine Tool Maintenance Scheduling: In this element machine tools are repaired and reintroduced back into the manufacturing system. Preventive maintenance can also be scheduled here. The parts store and engineers are modelled as part of Maintenance Scheduling. In this store, parts are held in stock and ordered according to a schedule or at the request of a PHM system.

3.2 Assessing the operational benefits of PHM with MATHS – an example

The example chosen looks at machine tools being introduced into a customer's factory at the rate of one a year for ten years; for simplicity only one machine tool type is considered. Each tool has a serviceable life of 15 years and the simulations are run over a 25 year scenario, from the introduction of the first machine tool to the retirement of the last. Production control ensures that the overall utilisation of the machine tools is roughly constant (at industry standard levels), so that the factory output varies with the number of machine tools employed.

The example compares the use of machine tools without PHM support (Baseline Design) to those with (PHM design). For this example the PHM design deploys PHM on six of the subsystems: the spindle, lubricant pump, motor bearings, X motion, Y motion and rotary table. Due to space limitations, Table 1 shows the major inputs (for the PHM Design case) but only a fraction of the input data that is used in this example.

Table 1: MATHS inputs

Cell size=10 units
Percentage of machines with PHM=100%
Learning capability of PHM system=0
Percentage of machines with engineer on site=0%
Engineer response time=24hrs (0hrs)
Delivery and/or machine installation time=0hrs
Spindle: MTTR=Lognormal (16hrs, 1.6 hrs); MTBF=exp(5000 hrs)
CNC controller: MTTR=Lognormal (4 hrs, 0.4 hrs); MTBF=Uniform(4500 hrs,5500 hrs)
Power supply: MTTR=Lognormal (2 hrs, 0.2 hrs); MTBF= Uniform(4500 hrs,5500 hrs)
Lubricant pump: MTTR=Lognormal (2 hrs, 0.4 hrs); MTBF= Lognormal (3000 hrs, 20 hrs)
Oil filters: MTTR=Lognormal (1 hrs, 0.1 hrs); MTBF= Lognormal (2000 hrs, 30 hrs)
Motor bearings: MTTR=Lognormal (16 hrs, 1.6 hrs); MTBF=exp(4000 hrs)
X motion: MTTR=Lognormal (4 hrs, 0.4 hrs); MTBF=exp(3000 hrs)
Y motion: MTTR=Lognormal (4 hrs, 0.4 hrs); MTBF=exp(3000 hrs)
Rotary Table: MTTR=Lognormal (4 hrs, 0.4 hrs); MTBF= Uniform(2800 hrs,3500 hrs)
Prognostics interval: 50 hrs (for all subsystems)

The simulation was run for a 15 year long service contract in which the capability of 10 machine tools is sold instead the machines themselves. Statistics are gathered at six monthly intervals for both baseline and PHM design. These record several performance metrics (availability, utilisation, breakdowns, jobs complete, good quality output, poor quality output, and waiting times of jobs for three different priority modes).

The results for these performance metrics averaged for the service contract duration for both baseline and PHM design are shown in Table 2. These results clearly show that the PHM design outperforms the baseline design in all respects. With almost 13% increase in availability, the results show that PHM can help markedly and thus simultaneously provides the contracted service level to the customer and reduced risk to the supplier. From the standpoint of operational performance it appears that investment in developing a PHM design is justified. The second tool, LIKEMATH, aims to determine if such an investment would be justified from the overall business standpoint. Would both the customer and the machine tool supplier derive long-term financial benefit from the PHM enabled machine tool design?

Table 2: Simulation results

Baseline design	PHM design
Availability=81.4%	Availability=93.84%
Utilisation=73.83%	Utilisation=74.67%
Breakdowns=181	Breakdowns=54
Jobs complete=6025	Jobs complete=6150
Good quality output=5573	Good quality output=5864
Poor quality output=453	Poor quality output=286
Waiting time for priority 1 jobs=1.31	Waiting time for priority 1 jobs=1.02
Waiting time for priority 2 jobs=5.9	Waiting time for priority 2 jobs=3.54
Waiting time for priority 3 jobs=137.74	Waiting time for priority 3 jobs=21.34

3.3 LIfe-cycle risK Evaluation of MAchine Tool Health (LIKEMATH) analysis tool

The LIKEMATH model derives costs, profits and benefits of developing, producing, operating, and reconditioning a PHM enabled machine tool, for both the customer and a machine tool supplier. It has been designed to show a split of costs, profits and benefits between these parties that may be incurred in any stage of the machine tool life-cycle, i.e. development and production, operation and support, remanufacturing. It comprises several spreadsheets arranged in a workbook and is designed to be used by following the order of the sheets. This starts with the 'input parameters' spreadsheet which provides the majority of the information required for calculating subsequent spreadsheets. Due to space limitations, the input parameters spreadsheet is provided in the Appendix (Table A1).

Other spreadsheets are: Development & Production Costs, Machine tool delivery schedule, Operation & Support Costs, Benefits, Remanufacturing, Machine tool supplier cost & profit, Customer cost, profit & saving, Cash Flow and Summary of costs & benefits. Figure 2 outlines the relationships between different spreadsheets of the LIKEMATH model. Each of the remaining spreadsheets is briefly introduced below.

Development & Production Costs spreadsheet: This spreadsheet derives the cost and net present value (NPV) of developing and producing a particular PHM solution, spreading those (non capital) costs for each year throughout the entire development and production years. Development of the PHM solution occurs in 1 year and production over the next 10 years. The cost elements covered are: Concept Refinement, Technology Development, System Development and Demonstration, and Production and Deployment. Besides costs, the user defines the number of machine tools produced each year as well as any profits, maybe from technology spin out, which can be expected from any stage in the development and production processes.

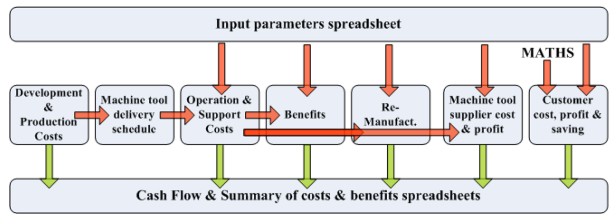

Figure 2: Spreadsheets of the LIKEMATH

Machine tool delivery schedule spreadsheet: This spreadsheet shows how many machine tools are being delivered each year.

Operation & Support Costs spreadsheet: Building on the machine tool delivery schedule, this spreadsheet calculates total cost and NPV of operating and supporting the machine tools for the entire duration of the agreed service contract. Data required for the calculation should have already been set in the input parameters spreadsheet and the only input required here is the split of total operation and support costs between the machine tool supplier and the customer (contract dependent). These costs are further broken down into: Maintenance, Personnel, Transportation, Maintenance Support, Penalties and Indirect Support.

Benefits spreadsheet: By comparing PHM and baseline designs for the entire duration of the agreed service contract, this spreadsheet derives the saving and NPV which result from deploying a PHM solution. A PHM solution is expected to benefit directly by reducing removals costs, unscheduled maintenance action costs and cost of the spares. These benefits can then be split between customer and machine tool supplier.

Remanufacturing spreadsheet: This spreadsheet derives any cost, profit and the related NPV incurred, when remanufacturing and selling machine tools upon the end of the service contract.

Machine tool supplier cost & profit spreadsheet: This spreadsheet derives cost, profit and the related NPV for the machine tool supplier for the entire duration of the agreed service contract. As a critical success factor for organisations adopting a PSS business model is the creation of a separate organisation to handle the service offering, suggested by Oliva and Kallenberg (2003), the cost of such, funded by venture capital or a loan, is accounted for here. Profit for the machine tool supplier comes from an annual leasing fee and any interest on the deposit the customer may be asked to put down before the machine tool can be delivered.

Customer cost, profit & saving spreadsheet: This spreadsheet derives cost, profit, savings and the related NPV the customer may experience for the duration of the service contract. The costs for the customer mirror the profit sources for the machine tool supplier. Profit for the customer should come from increased availability and improved quality, both of which can be affected by deploying a PHM solution on a machine tool.

Cash Flow spreadsheet: This spreadsheet summarizes all the costs, profits and savings for both the customer and the machine tool supplier, and translates them into annual and cumulative investments and returns, and spreads those for each year throughout the machine tool life cycle.

Summary of costs & benefits spreadsheet: The final spreadsheet provides a single point overview into potential success or failure of particular business case. It pulls all the financial data calculated in the above spreadsheets and calculates Return on Investment (ROI) and Internal Rate of Return (IRR) financial metrics for both customer and supplier.

3.4 Determining costs and benefits with LIKEMATH – an example

Continuing from Section 3.2 this example takes the simulation results previously produced by the MATHS model (Table 2) and the input data (Table A1) required by the LIKEMATH model. Due to space limitations, the overall financial data from Summary of costs & benefits spreadsheet is presented in the Appendix (Table A2).

Based on financial outputs presented above, Return on Investment (ROI) and Internal Rate of Return (IRR) financial metrics were calculated and presented in Table 3.

Table 3: Financial metrics – an example

Metric	Total	Customer	Supplier
Net Present Value - NPV	£2,506,095	£1,564,832	£941,263
Return on Investment - ROI	78.2%	40.8%	174.9%
Internal Rate of Return - IRR		NA	41.21%

It seems from Table 3 that both customer and supplier can expect positive returns on their investment. In case of the supplier this figure looks really positive. Finally, Figure 3 shows cash flows for customer and supplier. This figure clearly shows that after an initial period where cash flows are largely negative mainly due to initial investment, they pick up later and gradually increase right to the end of service contract when they start to decrease.

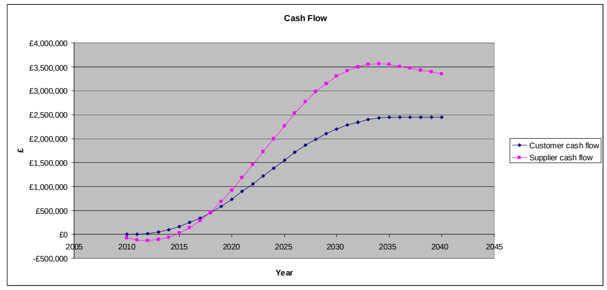

Figure 3: Cash flow – an example

4 EXPLORING THE BENEFITS OF PHM TECHNOLOGY

In an attempt to validate the approach and tools developed, machine tool vendors who were likely to benefit from a PSS business model were identified and interviewed. Unfortunately, it was not possible to collect empirical data on machine reliability or operational performance for three reasons. First, this data seldom exists in a form required by the tools proposed here. Second, even if this data is available, suppliers of high value machines would not release the data claiming that it was confidential. Third, some suppliers simply were not interested in developing services beyond the traditional after-sales services such as training, warranty support and spare part sales. It was, however, possible to present both simulation tools to a manufacturer of high value machine tools and to collect their opinion. The reason for their interest in PSS is awareness of the value to their customers of reducing the cost of ownership of their products. The managing director of this company is confident that the machine tool industry is moving towards the PSS business model, at least for high-value machines, but what his company lacks is a comprehensive analytical approach which would assess the risk of this type of business.

The company feedback was very positive and they expressed an interest in supporting the continuation of research to improve both tools. This exposure also helped us to realise some of the drawbacks of the approach which limit the appropriation of true costs and benefits. For instance, the company commented about the practice by which accountants in manufacturing organisations currently calculate costs and revenues which could be a large barrier to overcome when transforming the organisation to PSS.

This highlights some of the organisational changes that require an investment to fully realise all the benefits of PSS. Therefore, in order to build a realistic cost/benefit analysis more research is required to explore the role of PHM technology to add value both to suppliers and users of machine tools. Coupled with the lack of holistic knowledge about the benefits of PHM beyond maintenance cost savings introduced in section 2.2.4, we set out to further explore the value of this technology.

Here this issue is approached from the perspective of the information systems research field, which is research about the business value of information technology (IT). This field provides plenty of research which could provide a foundation in building a research framework that explains the benefits of PHM technology and the changes necessary to realise them. We introduce here a framework which is adopted from Chircu and Kauffman (2000) which in turn is based on work by Davern and Kauffman (2000). This framework conveys our approach in building a deeper understanding about cost and benefits of PHM technology adoption. The framework is shown in Figure 4.

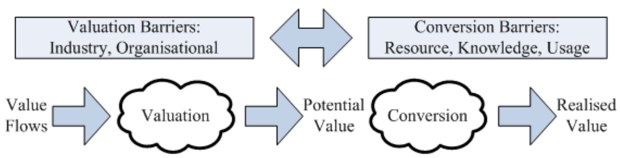

Figure 4: Framework for exploring the benefits/value of PHM technology (Adopted from Chircu and Kauffman 2000)

The framework starts with identifying the value flows from an IT. In the case of PHM technology a starting point would be to build an understanding of the possibilities of the technology which in turn could come from identification of main types, applications and functionalities. To support this step, Davern and Kauffman (2000) have also introduced the locus of value concept which represents a level of analysis at which IT value can be recognized. Here they emphasise the importance of process-level and market-level value flows which promise to deliver a blend of operational effectiveness and strategic positioning values. In the case of application of PHM to PSS, this would require for example identifying the relevant business processes and extent to which these are impacted by PHM.

Once all value flows are identified, these are assessed during the valuation process to determine the potential value of IT. In the case of PHM, the potential value would be that obtained from PHM technology if the implementation process is 100 percent successful. This represents the most important piece of information since it gives us an idea about the potential of adopting a particular IT. Because of so called conversion contingencies (Davern and Kauffman 2000) which are factors that intervene in the process of conversion (for example existing accounting procedures in the case of the machine tool manufacturer example), the potential value is discounted and the result is a realised value.

When building an understanding of the benefits from an IT, important pieces of information come from identifying and overcoming the valuation and conversion barriers (Figure 4). Valuation barriers are factors which limit the potential value of IT and according to Chircu and Kauffman (2000) there are two types of valuation barriers: industry and organisational. In the case of PHM, industry barrier could be the lack of industry specific standards. Organisational barriers represent characteristics that are unique to the company, such as: culture, norms, expertise, customer and supplier relationships, etc. Different characteristics may lead to different potential value assessments.

Conversion barriers have an impact on the amount of potential value which can be translated into realised value. There are three groups of conversion barriers Chircu and Kauffman (2000): resource, knowledge and usage barriers. In order to realise most from IT systems, investment in additional resources is often required. This could be business process redesign or investment in complementary technology. Adoption of a new IT system and redesign of business processes may in turn be limited by the existing knowledge of employees. Therefore, investment in training to overcome this barrier may be necessary. Finally, even if all the barriers mentioned so far are overcome, the success of the overall project depends on how the IT is adopted by its intended users. The users of PHM are maintainers and system operators and one of the problems might be to convince them into validity of the outputs of those systems.

Overcoming the barriers introduced before comes with a price tag; therefore it is important to include those costs into the overall cost/benefit assessment. The framework introduced here could be used to explore the benefits of PHM technology in greater detail and thus address the gap highlighted in section 2. The knowledge about these benefits and their related barriers should enable formulation of a better vision for PHM technology.

5 CONCLUSION

The majority of research into PHM is concerned with technological issues and can be characterised as technology push. Apart from some cases (Joint Strike Fighter) there has been a lack of vision for PHM. This was demonstrated by reviewing a variety of approaches for cost/benefit analysis of PHM enabled systems. Apart from reporting the benefits, in terms of maintenance cost savings, no approach considers PHM as an enabler for revenue generation. We argue that the lack of vision explains our limited understanding of the benefits that can be accrued from PHM technology. This paper set out to propose such a vision by relating PHM with Product-Service Systems (PSSs). These systems offer a bundle of products and services where emphasis shifts from selling a product to selling the use of a product. Intrinsic to this business model is a shift of risks from a user to a supplier. We see PHM as a mean to mitigate this risk and a key enabler of an effective PSS. In this paper we reported on research aimed to develop an approach and tools which a machine tool manufacturer could use to evaluate costs and benefits of PHM in the context of a PSS business model. Although the research received positive feedback from a manufacturer of high-value machine tools, a need has been identified to do more research into building an understanding about the benefits of PHM. Knowledge gained through such research would help us to develop more realistic cost/benefit analyses and it could help in framing better strategies which build on this technology. Therefore, at the end, we proposed a model which is borrowed from information systems research field that frames our future intentions in exploring the benefits of PHM.

APPENDIX

Table A1: Input parameters spreadsheet of LIKEMATH

Variable		
Baseline Design Input Data	**Input**	**Note**
Operating hrs/Machine Tool/Year	1,000	Real operating hours - same for both designs (assumption)
Available working hrs/Machine Tool/Year	1,200	Same for both designs (assumption)
Mean Time To Replace Subsystem (hrs)	10	Same for both designs (assumption)
Mean Time To Repair (hrs)	2	Same for both designs (assumption)
Mean Time To Subsystem Removal (hrs)	2,000	Different than for PHM Design
Mean Time Between Unscheduled Maintenance Action (hrs)	20	Different than for PHM Design
Unscheduled Maintenance Labor £/Maintenance Manhour	£20	Same for both designs (assumption)
Scheduled Maintenance Labor £/Maintenance Manhour	£15	Same for both designs (assumption)
Total Scheduled Maintenance Manhour/Machine Tool/Year	50	Same for both designs (assumption)
Average cost per spare	£5,000	Same for both designs (assumption)
PHM Design Input Data	**Input**	**Note**
Annual Leasing fee	£40,000	Per Machine Tool
Deposit	£0	Per Machine Tool
Duration of service contract (Years)	15	Allowed values are 5, 10 or 15 years
Remanufacture & sell after service contract	No	Yes or No
% of Machine Tools with PHM	100%	
% of Machine Tools with Engineer On Site	0%	
Annual Engineer On Site Cost	£40,000	Per engineer
Agreed availability	92%	
Distance to customer (miles)	200	
Fuel consumption (miles/galon)	50	
Fuel £/Galon	£4	
Annual Indirect Support Cost	£40,000	
Penalty (£/hr)	£500	Due to providing less than agreed availability

Table A2: Summary of costs & benefits spreadsheet - an example

	Customer Costs	**Customer NPV**	**Supplier Costs**	**Supplier NPV**
Development	£0	£0	£110,000	£90,088
Production	£0	£0	£0	£0
Operation & Support	£0	£0	£2,116,068	£522,423
Remanufacturing	£0	£0	£0	£0
Venture capital cost			£100,000	£20,398
Leasing fee + Deposit	£6,000,000	£3,839,495		
Total Cost	£6,000,000	£3,839,495	£2,326,068	£632,909
	Customer Benefits	**Customer NPV**	**Supplier Benefits**	**Supplier NPV**
Development & Production	£0	£0	£36,000	£29,483
Unscheduled Maintenance Actions	£0	£0	£190,880	£46,350
Removals	£0	£0	£6,400	£1,595
Spares	£0	£0	£160,000	£39,863
Profit + Savings from increased/improved availability/quality	£8,445,372	£5,404,327		
Leasing fee + Deposit			£6,000,000	£1,456,880
Sell of remanufactured machine tool	£0	£0	£0	£0
Total Benefits	£8,445,372	£5,404,327	£6,393,280	£1,574,172
Return	£2,445,372	£1,564,832	£4,067,212	£941,263

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REFERENCES

(Baines *et al.*, 2007) T. Baines, H. Lightfoot, S. Evans., A.D. Neely, R. Greenough, J. Peppard., R. Roy, E. Shehab, A. Braganza, A. Tiwari, J. Alcock, J. Angus, M. Bastl, A. Cousens, P. Irving, M. Johnson, J. Kingston, H. Lockett, V. Martinez, P. Micheli, D. Tranfield, I. Walton and H. Wilson. (2007), State-of-the-Art in Product Service Systems. P I Mech Eng B-J Eng, Vol. 221, No. 10, pp. 1543-1552.

(Banks *et al.*, 2005) J. Banks, K. Reichard, E. Crow and K. Nickell. (2005), How engineers can conduct cost-benefit analysis for PHM systems, in Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, 5-12 March, pp. 3958-3967.

(Byer *et al.*, 2001) B. Byer, A. Hess and L. Fila. (2001), Writing a convincing cost benefit analysis to substantiate autonomic logistics, in Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, 10-17 March, pp. 3095-3103.

(Chircu and Kauffman, 2000) A.M. Chircu and R..J. Kauffman. (2000), Limits to value in electronic commerce-related IT investments, Journal of Management Information Systems, Vol. 17, No. 2, pp. 59-80.

(Davern and Kauffman, 2000) M.J. Davern and R..J. Kauffman. (2000), Discovering potential and realizing value from information technology investments, Journal of Management Information Systems, Vol. 16, No. 4, pp. 121-143.

(Gebauer *et al.*, 2006) H. Gebauer, T. Friedli and E. Fleisch. (2006), Success factors for achieving high service revenues in manufacturing companies, Benchmarking: An International Journal, Vol. 13, No. 3, pp. 374-386.

(Hess and Fila, 2002) A. Hess and L. Fila. (2002), Prognostics, from the need to reality – from the fleet users and PHM system designer/developers perspectives, in Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, 9-16 March, vol.6, pp. 2791-2797.

(Hoyle *et al.*, 2007) C. Hoyle, A. Mehr, I. Turner and W. Chen. (2007), On quantifying cost-benefit of ISHM in aerospace systems, in Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, 3-10 March, pp. 1-7.

(Kacprzynski *et al.*, 2002) G.J. Kacprzynski, M.J. Roemer and A.J. Hess. (2002), Health management system design: development, simulation and cost/benefit optimization, in Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, pp. 3065-3072.

(MacConnell, 2007) J.H. MacConnell. (2007), ISHM & Design: A review of the benefits of the ideal ISHM system, in Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, 3-10 March, pp. 1-18.

(Oliva and Kallenberg, 2003) R. Oliva and R. Kallenberg. (2003), Managing the transition from products to services, International Journal of Service Industry Management, Vol. 14, No. 2, pp. 160-172.

(Price *et al.*, 2003) D.C. Price, D.A. Scott, G.C. Edwards, A. Batten, A.J. Farmer, M. Hedley, M.E. Johnson, C.J. Lewis, G.T. Poulton, M. Prokopenko, P. Valencia and P. Wang. (2003), An integrated health monitoring system for an ageless aerospace vehicle, in Structural Health Monitoring: From Diagnostics & Prognostics to Structural Health Management, Ed. Fu-Kuo Chang, DEStec Publications, Lancaster, Pennsylvania, USA, pp. 310-318.

(Söderholm, 2004) P. Söderholm. (2004), Continuous improvement of complex technical systems: A theoretical quality management framework supported by requirements management and health management, Total Quality Management & Business Excellence, Vol. 15, No. 4, pp. 511-525.

(Williams, 2006) Z. Williams. (2006), Benefits of IVHM: An analytical approach, in Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, 4-11 March.

(Wilmering and Ramesh, 2005) T.J. Wilmering and A.V. Ramesh. (2005), Assessing the impact of health management approaches on system total cost of ownership, in Proceedings of IEEE Aerospace Conference, Big Sky, Montana, USA, 5-12 March, pp. 3910-3920.

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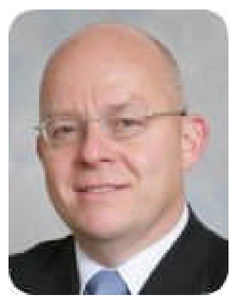

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