The Future of Maintenance for Industrial Product-Service Systems

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Abstract. This paper aims to present a landscape of interests that are emerging for the future of maintenance in Industrial Product-Service Systems. Across manufacturing industries there is growing interest to integrate products and services, where maintenance has a key role in delivering performance driven solutions (e.g. availability). It is observed that industry is aiming to gain competitive advantage, and the customer is increasingly intending to transfer the risks and uncertainties as reflected in contracts. The shift towards services is also putting more pressure on industry to accurately predict service requirements in terms of resulting cost and performance that enables the service provision. In light of these drivers, technologies and organisational themes are emerging to reduce uncertainty and cost for the in-service phase as explained and discussed in the paper.

Keywords: Maintenance, Through-life Engineering Services, Industrial Product-Service System, Uncertainty, Availability, Cost.

1 Introduction

Manufacturers are increasingly recognizing that the in-service phase of the life cycle offers increased revenues and profitability [1]. This has promoted the need to understand the processes, resources and technologies that are required to sustain and enhance the equipment health and performance over the life cycle. This paper focuses on the Industrial Product-Service Systems (IPS^2) context and aims to present an overview of the trends in product maintenance research to support the integrated product and service offering. Maintenance serves as the major engineering service in the IPS^2 delivery model. Maintenance involves a combination of technical, administrative and managerial actions during the life cycle of an item with the aim of retaining it in, or restoring it to, a state in which it can perform the required function [2]. Also, Maintenance, repair, and operations (MRO) or maintenance, repair, and overhaul involves resolving any sort of mechanical, plumbing or electrical device issues in the case of becoming out of order or broken. Whilst the customer is typically acknowledging the large cost burden experienced from maintenance, innovative forms of contracting are increasingly emerging that puts further pressure on the solution provider to extend the product life cycle through services and so reduce the overall cost [3,4]. The

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motivation of this paper is to guide both academia and industry to understand the role of maintenance in IPS^2 type contracts and to explain how the cost and performance targets can be achieved. Section 2 presents an overview of maintenance and associated targets. Section 3 presents the emerging themes for the future of maintenance. Finally, Section 4 covers concluding remarks.

2 Understanding the Role of Maintenance

2.1 Research Background in Maintenance and MRO

Research interest in maintenance and MRO within the engineering domain (including aerospace, defence and engineering) has been growing dramatically since 2005, as demonstrated in Figure 1. The search was conducted in Scopus with the keywords: maintenance or MRO and aerospace or defence or automotive. It is also recognized that the USA has produced over 600 articles, whilst the two other highest article producing countries have been China and the UK with over 200 articles from each.

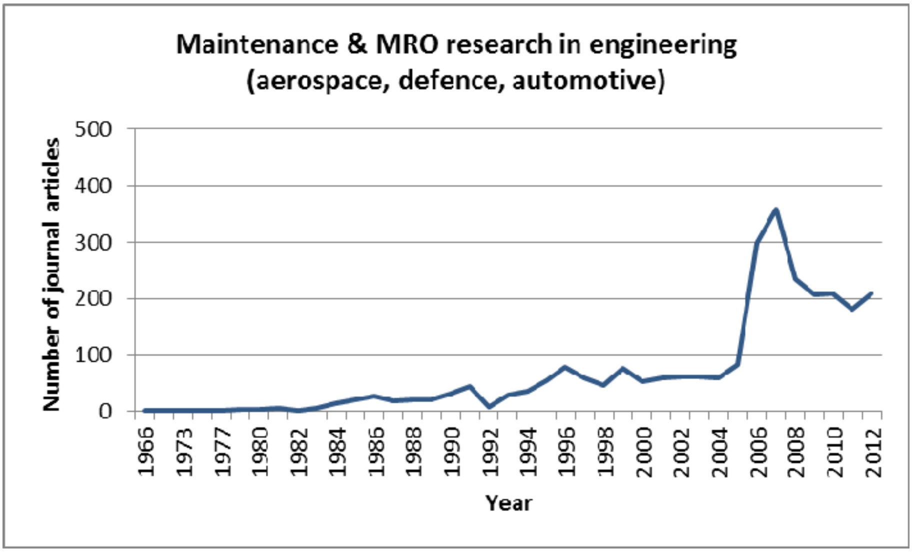

Fig. 1. Number of publications in maintenance and MRO

There are a number of dedicated research centres within the area, which highly influence the publications, including: EPSRC Centre for Innovative Manufacturing in Through-life Engineering Services (UK), Integrated Vehicle Health Management Centre (UK), Aviation Services Research Centre (China), Fraunhofer Innovation Cluster MRO in Energy and Transport (Germany), Center for Advanced Life Cycle Engineering (USA), Luleå Railway Research Center (Sweden) and The Center for Intelligent Maintenance Systems (USA).

2.2 Shifting Customer Targets: The Role of Contracts

The IPS^2 literature classifies the types of business models into three categories [1, 3]. Firstly, the function-/product-oriented model concentrates on selling the product in a traditional manner, while additional services are included (e.g. maintenance, repair). The second model, known as use-/availability oriented (e.g. Contracting for Availability – CfA), focuses on selling the use or availability of a product that is not owned by the customer (e.g. leasing, sharing). Thirdly, the result-oriented model offers the sale of a result or capability instead of a product (e.g. selling parts instead of the facility for manufacturing them). These models can be subdivided into several individual business models, where the models differ for various reasons (e.g. ownership of product, payment method, supply of operating personnel) [3]. However, it is worth recognising that there is currently an emphasis in industry to enter into CfA type agreements [4].

When the solution provider takes decisions such as whether to bid for a contract or accept one when offered, they need to do so based on an understanding of the uncertainty in maintenance for the duration of service delivery [5]. This necessitates better prediction of uncertainty for IPS^2 than has been typical of traditional contracts in the past because the contract timescales are much longer, and ownership of uncertainty has been transferred from customer to the solution provider - typically on a fixed-cost basis [4, 5]. Furthermore, as major agreements with large financial burdens, driven by cost and schedule estimates, can be agreed at the bidding stage, there is a need to apply rigorous steps to take account of the influence of uncertainty on cost [6].

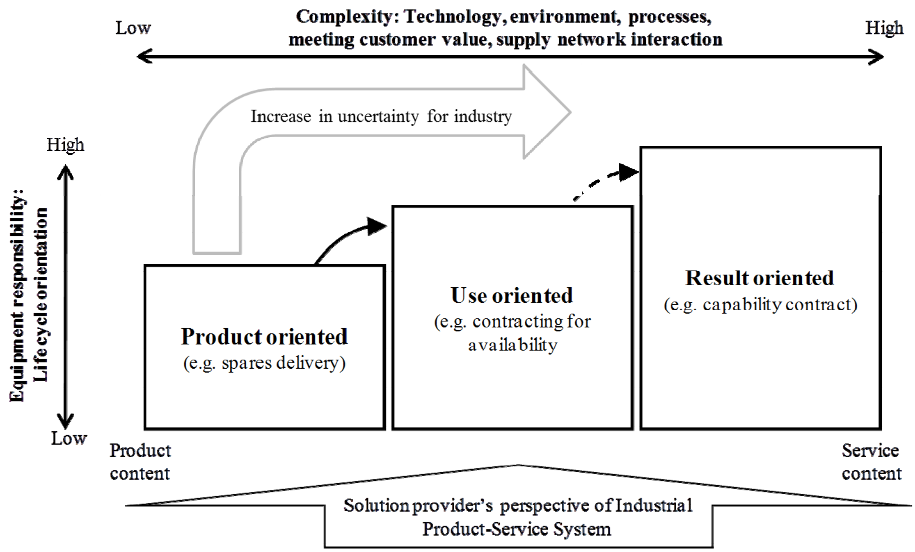

Fig. 2. Uncertainty and types of solutions in IPS^2 [5]

The IPS^2 context offers a larger set of uncertainties that industry needs to manage, due to the enhanced scope and complexity of the service solution being offered [5]. Some of the areas to consider include assessing the performance and the requirements of the service delivery, and the enhanced dependence on external sources. For instance, obsolescence is increasingly becoming challenging to manage and is creating large cost implications. Obsolescence, which is most often experienced in electronics equipment's, refers to the state of being which occurs when an object, service or practice is no longer available even though it may still be an effective technical solution [7]. Its mitigation requires an integrated supply chain and flexibility in the design of equipment with a view on how to tackle the obsolescence issues that may arise in a planned or unplanned manner. Driven by such aspects the delivery of service is less well understood at the early stages compared to the traditional model, due to the increase in the experienced uncertainties [5].

Table 1. Types of contracts and associated challenges in IPS²

	Contract type		
Contract name	*Fixed price contract*	*Cost plus contract*	*Performance based contract*
Characteristics	- Maximum risk on suppliers - Greatest incentive to reduce cost - No performance incentives	- Risk is shared - Least incentive to reduce cost - Moderate performance incentives	- Moderate risk on suppliers - Moderate incentive to reduce costs - Greatest performance incentives
Challenges	- Inaccurate cost estimates, - Technological unknowns, - Changing requirements - High financial risks	- Adequate cost control that promotes cost sustainment and reduction - Cost overruns experienced often	- Accurate estimate of % for pain/gain share - Adequate penalty and incentive limits - Risk of not meeting performance

CfA are currently being awarded on the basis that they span the manufacturing and in-service phases of the CADMID lifecycle but the bids are often prepared and submitted in earlier phases [5]. The move towards CfA has followed an iterative transition, which has experienced a shift from providing the traditional business model into spares inclusive maintenance contracts (e.g. product oriented), CfA (e.g. use oriented) and contracting for capability (e.g. result oriented), as represented in Figure 2. The traditional business model stands at one extreme where the product and the service are considered separately and the service is an add-on feature to products that are sold. Roy and Cheruvu [3] identified different IPS² contract types from the literature and various industries, as illustrated in Table 1. These are classified into three types: fixed price, cost plus and performance. Fixed price contracts, concentrate on delivering the solution at the agreed price and pose the highest risk option for the solution provider. As a result, adequate measures (e.g. technology adoption) need to be taken in order to reduce cost and control service delivery. The cost plus approach introduces risk sharing between the customer and the solution provider, where costs/savings are shared for certain scenarios as specified in the contract. Thirdly, performance contracts are highly driven by incentives and promote further collaboration along the supply chain. Among these approaches, there is an emphasis to agree fixed price contracts, which can span the whole lifecycle of the equipment. Table 1 also presents the major challenges that are experienced across all the presented contract types. Datta and Roy [6] highlighted that the main parameters considered during the process of agreeing contracts are responsibility, cost of performance and incentives.

2.3 Targets of Maintenance in IPS^2

Maintenance is currently increasingly being included as part of the OEM's responsibility for most fixed priced long-term contracts that guarantee the performance of the system [2]. Therefore manufacturers are beginning to enhance maintenance activities to reduce the whole life cost [4,5]. The wide range of maintenance activities include inspection, testing, measurement, adjustment, repair, upkeep, fault detection, replacement of parts, servicing, lubrication, and cleaning. The service system for maintenance consists of materials (parts), tools, people and equipment/machines [2]. Furthermore, an infrastructure needs to be built, which varies from deterministic production models into one that copes with high variability. This infrastructure needs to cater for the material flow, storage, repair, transportation, communication and information systems [5]. Due to these reasons it has commonly been suggested that delivering after sales service is more complex than delivering the products themselves. The service delivery process is challenged by uncertainties that arise from demand and supply. McManus and Hastings [8] defines uncertainty as "things that are not known, or known only imprecisely", where it encompasses aspects including "liability to chance or accident," "doubtfulness or vagueness," "want of assurance or confidence; hesitation, irresolution," and "something not definitely known or knowable". The uncertainty in demand may occur from the complexity (dependent on know-how) of the delivered equipment, the machine usage conditions/environment, or usage levels, along with the customer's willingness to pay. From a schedule point of view, the solution provider faces challenges particularly in terms of meeting reliability, maintainability, and availability targets that are typically agreed at the outset of agreeing a contract [5]. As follows, the sources of cost reduction will depend on materials and labour requirements (driven by failures) and the confidence in estimating these [6]. Labour is considered in terms of skill level and scale of labour requirements. Material estimates tend to be based on similar historical projects and follow the equipment breakdown structure. The estimated labour and materials demonstrate performance related targets, which are driven by meeting cost and schedule targets. Figure 3, illustrates a framework for targets in maintenance, which are associated with increasing predictability (driven by technologies), availability (driven by reliability) and reducing or sustaining cost (driven by strategies/contracts/failure). On the other hand, the uncertainty in supply may be influenced by supportability, resource availability and the capacity across the service supply chain [9]. As follows, service quality is a function of the scale and scope of customer demand and supplier capacity to respond to the demand.

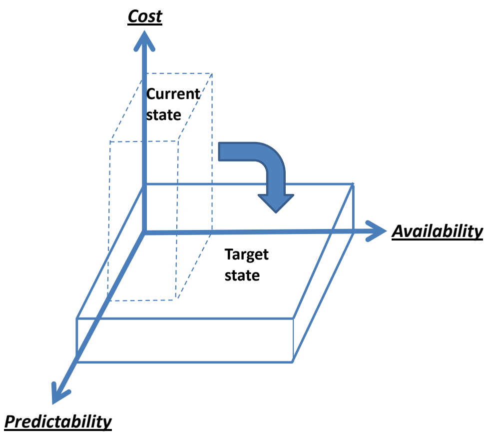

Fig. 3. Current vs Target state performance for IPS² contract

2.4 New Challenges for Maintenance in IPS^2

The shift in maintenance requirements promotes new challenges for industry. The solution provider needs to account for the performance driven requirements and predict the life cycle of components. This requires detailed uncertainty management through information flow between the customer and solution provider about the equipment health [10]. This is necessary in order to derive proactive maintenance strategies that reduce life cycle cost. Also, extending the life cycle and adequate application of MRO holds an important role in achieving reduced costs, and meeting performance requirements. The flow of data and the feedback across projects facilitates establishing maintenance cost models at the earliest possible phases of the lifecycle and evolves as the lifecycle progresses and in agreeing new contracts [6]. However, it is essential that companies take account of the new challenges that are driven by uncertainties. These relate to the new uncertainties experienced with agreeing CfA and involve, for example, the role of availability on cost, payment based on performance, end user equipment usage, change in capability requirements, supplier

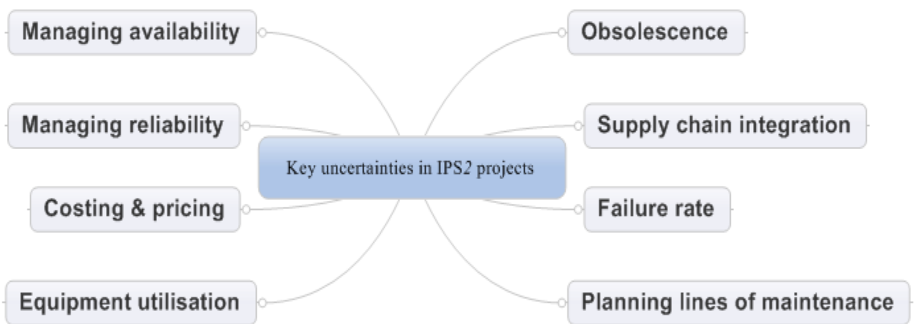

Fig. 4. Key uncertainties in IPS^2 projects (Adapted from [5])

dependence, and training for availability [5]. In addition to many other reasons, accurate prediction of such new challenges is proving to be demanding in developing reliable cost and schedule estimates for contracts. In order to further emphasise the issues Figure 4 lists the key uncertainties that have been highlighted by four organisations in the defence industry that are involved in IPS^2 projects [5]. Failure rate, managing obsolescence and gathering data about equipment utilization emerge as some of the key areas to focus on.

3 Emerging Themes for the Future of Maintenance

It is increasingly recognized that the in-service phase of the life cycle creates the largest amount of cost. Maintenance, which is a driver of in-service costs, to a large extent cannot be avoided due to a number of reasons such as consumables, wear, plug and play technology upgrades, and standardization of interfaces. As a result the customer has become increasingly interested in minimizing the cost of whole life cycle ownership of assets. On the one hand, strategies have moved towards reduction of maintenance (e.g. schemes to avoid failure – design for zero failures), and higher predictability (e.g. visualize future wear) that drives availability. Such aspects need fundamental questions to be answered including:

1. Is it possible to avoid replacing “consumable” components (e.g. engine oil, windscreen wipers)?
2. Is it possible to prolong the life of systems and components?
3. Is it possible to avoid the replacement/refurbishment of worn components?
4. Is it possible to eliminate wear?
5. Is it possible to reduce maintenance activity through improved autonomy?
6. Is it possible to predict and build in possible upgrades of parts/systems during the design process?
7. Is it possible to have modularity to insert new capabilities with developing technologies?

On the other hand, the significance of cost has promoted changes in contractual arrangements. Like so, the literature has emphasised that ownership and use/employment (e.g. CfA) are increasingly being separated. Research within this area has focused on the role of the bidding stage. For instance, research has been made to incorporate the influence of uncertainty [5], and of obsolescence [7] to cost, and to provide guidance on contract selection [3]. Furthermore, standards certification has also been an area of interest where research has been conducted for cost engineering related terms [10]. It is worth recognizing that the shift towards services has generated further aftermarket business opportunities for the solution provider and supply chain. The following section provides a detailed account of the emerging themes for maintenance, as illustrated in Figure 5.

Failure is the tip of the iceberg where maintenance has a role to reduce the impact of many issues such as wear, play, slackness, leakage, dust, dirt, corrosion, deformation, adherence of raw materials, surface damage, cracking, overheating, vibration, noise and other abnormalities. Developing a detailed maintenance plan can assist in handling of component and system failure. This particularly becomes essential in IPS^2

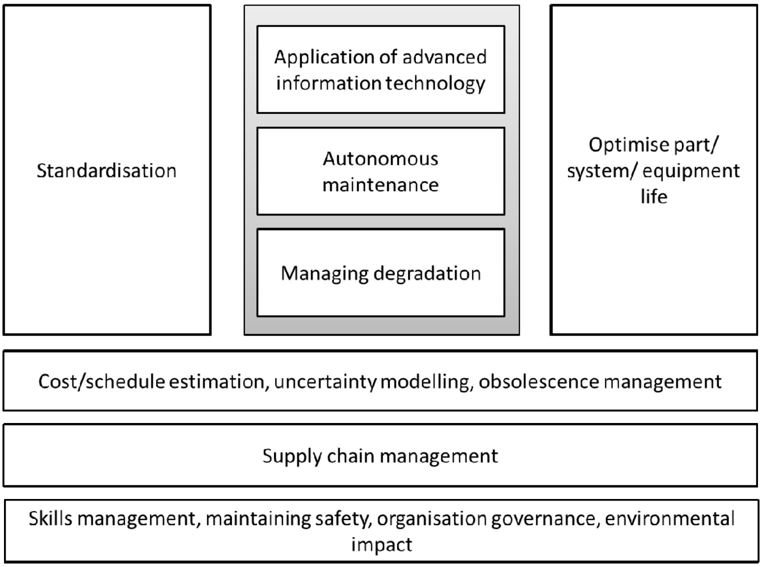

Fig. 5. Overview of future themes for maintenance within an IPS² contract environment

in order to meet the cost pressure and performance requirements. Adequate measures taken can assist in achieving fewer failures and unplanned breakdowns, the increase in robust diagnoses and prognosis, a shorter waiting time until the system works, a better working environment, and less environmental pollution (e.g. lower energy and raw material consumption). Furthermore, the design and manufacturing phases are increasingly being acknowledged to drive the impact on the service provision, whilst feedback from the service is progressively playing a key role for each of these phases.

3.1 Standardisation

Putting in place a mechanism for standardization, supports with determining technical specification, quality management for an engineering project or a safety standard and with many other aspects [10]. Furthermore, it may result in early adoption of novel technologies, reduced costs, improved uptime and to avoid major disasters. Within the maintenance area standards are required in a number of areas including [11]:

1. Interoperability of diagnostics data
2. Quality of diagnostic systems and data
3. Backward compatibility
4. Maintenance using remote monitoring
5. Wireless protocols for system monitoring and remote repair
6. Obsolescence management
7. Terminologies for new technologies
8. Whole life costing

In order to achieve these targets there is a need to perform a gap analysis on the existing standards landscape, to develop a delivery plan to fill the gaps and to educate regulatory bodies on the direction to be followed.

3.2 Application of Advanced Information Technology

Maintenance as a concept has experienced a major philosophical transformation from the traditional view of "fail–and–fix" maintenance practices to "predict–and–prevent" e-maintenance based strategies. This has promoted a network based architecture that shares, integrates and synchronizes the vast number of maintenance and reliability applications to gather and deliver asset related information as designed. This network of information sharing is illustrated in Figure 6. The network refers to the link between the customers operations and the feedback that is collected from remote customer sites and analysed in order to plan suitable maintenance steps. A key role that assists the flow of information is enabled by e-maintenance. This can be achieved using Personal Digital Assistant (PDA) devices that enhance the applicability of mobile maintenance management [11]. The main technologies that assist the application of e-maintenance include the internet, wireless devices, smart tags, micro-size MEMS sensors especially designed for maintenance purposes and low-cost online lubrication analysis sensors [11]. Also, information processing tools enable the continuous data flow through a distributed and collaborative web platform system at the higher end of the processing hierarchy. These assist in re-designing maintenance strategies in a cost effective and environmentally friendly manner. Such approaches have been comprehensively reported in the literature, however Redding et al., [12] highlight that the application of such technologies has in comparison been below expectations. Though, it is expressed that there is a large desire to adopt such technologies.

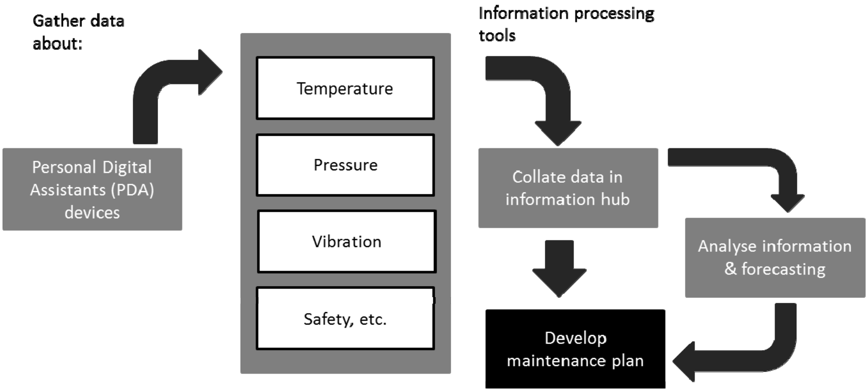

Fig. 6. Process of information gathering

Sensors may be in the form of wired or wireless sensors, whilst both have commonly been acknowledged to offer large potential to sense, store, and analyse equipment data to predict health status [11]. However, the reliance on sensors for condition monitoring requires robust and reliable sensors and data processing. In parallel a shortcoming has been observed with sensor failures happening between the time intervals of check-ups [13]. Additionally, within the nuclear power plant context, issues have been observed with electromagnetic and radio frequency interference (EMI/RFI), cyber security, and installation issues such as the coverage of the wireless signal [13]. Redundancy has been considered to be an approach where a wired sensor is used as the primary source, whilst in the case of a breakdown (e.g. due to a loss-of-coolant accident) wireless transmission of data may offer a more reliable option.

Increasingly commonly are sensors which collect information about vibration and apply diagnostics techniques that enable the trending of equipment health. However, the shortcoming of the approach lies in the cost of full physical check-ups. Apart from the technology requirements, there is also a need for vibration experts, who are typically highly educated and costly. Thus, a cost-benefit analysis is required in order to decide whether adding a sensor to the monitoring program will be beneficial. It is also worth recognizing the value of reducing uncertainty and facilitating the delivery of IPS² that meets cost and performance targets.

3.3 Optimise Life

The maintenance strategy needs to facilitate the optimization of the life cycle of the equipment. For this purpose the future of maintenance will need to concentrate on a) developing suitable simulation approaches; b) schemes that facilitate adaptability; c) modular maintenance and d) disposal decision making [11]. Figure 7 shows an overview of these concepts.

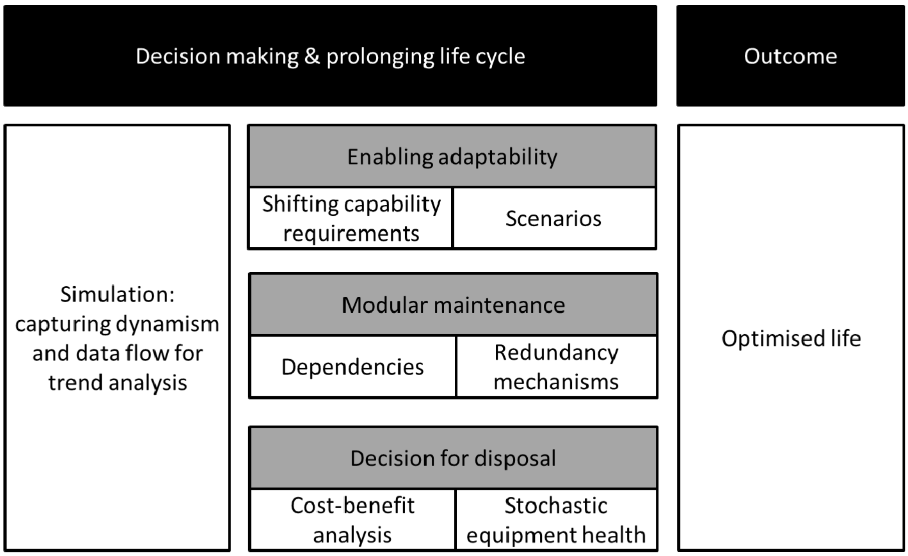

Fig. 7. Achieving optimized life

During the life cycle of maintenance, with up to date information about the equipment health, suitable simulation approaches need to be adopted in order to develop trend analysis and to predict reliable life expectations. Various techniques such as a

Bayesian probabilistic approach and Markov chains have increasingly been applied [11]. In particular the Bayesian approach is gaining much interest due to its ability to dynamically update data based on the monitoring of outcomes on specified model parameters and thus revising the probability of damage for each substructure. The parameters may be directly related to the process such as temperature, pressure, vibration or humidity, or be higher level descriptors such as process safety, efficiency, or level of output [14]. This approach allows the tracking of gradual changes, such as fatigue and corrosion, and offers the opportunity to detect issues at an early stage well before the risk of failure. As an outcome such information enables to determine the spare parts demand and supply schedules to reduce time and amount of maintenance.

A common feature of the life cycle is the need to modify the equipment because of changes in capability requirements, affordability issues, or technological advancements for example. However, recognizing the costs of change at the outset and the implications on the duration of the life cycle are challenging. In order to reduce these challenges researchers have applied rule-based systems to define the potential range of modification strategies [11]. Though, building a comprehensive scope of modification strategies and recognizing the dynamic nature of this scope is also challenging. For this purpose, optimization studies have a valuable role in guiding decision making with such issues. Nevertheless, selecting optimal rule refinements is an unsolved problem that requires further research.

Modular maintenance refers to a procedure that allows replacement of major assemblies, called modules, with a minimum of amount of expenditure and time. Furthermore, the removed modules follow a cycle by being returned to the repair facility, bench test, repair, and inserted back in to the equipment [9]. However, designing this procedure is challenging because one has to consider the sub-modular cost structures that capture the dependencies between various components and modules in the system. It is also important to design suitable redundancy mechanisms and appropriate schemes to resolve maintenance issues such as obsolescence.

Decision making for disposal is also challenging and requires simulation studies that take account of the stochastic nature of the condition of the equipment. The optimal point for disposal occurs when the carrying cost exceeds the disposal cost. There are a number of aspects that need to be considered including (a) product recovery operations require expensive and skilled labour; (b) timing and quantity of discarded products; (c) cost of recovered components resulting from the unpredictable disposal of products and stochastic demand; (d) costs originating from surplus inventory; (e) stock-outs causing lost sales; (f) disposal cost of leftover and obsolete inventory; (g) competition from OEMs, and (h) restrictive environmental regulations [15].

3.4 Autonomous Maintenance

Autonomous maintenance means developing capability within a high value system to maintain itself and also developing maintenance systems that collaboratively provide autonomous capability to perform maintenance on a high value system with minimum human intervention. This improves robustness of a system and influences the ability to meet performance and cost targets. Among autonomous maintenance approaches self-healing is highly attracting attention. Self-healing systems aim to mitigate, detect and recover from failures [16]. The initial step involves defining an appropriate architecture that specifies components, their relationships within a system coupled with topology (with number and placement of components in a system). This architecture helps to mitigate the effects of failures by providing guidance with increasing system redundancy. Subsequently, failure detection techniques are applied and involve monitoring component health and uncertainty analysis in order to realize the remaining life in a reliable manner. This leads to recovery techniques, which define actions to a component in order to address suspected failures. Self-healing systems comprise consistent mechanisms that provide a means to maintain a synchronized state among distributed components by propagating state changes to remote components. Research has concentrated on robotics and software development that establishes connections between failure and healing mechanisms [16]. Furthermore, large engineering systems in safety critical situations already have a level of self-diagnosis (built in self-test or BIST) and self-fix, if not self-immobilisation to prevent more serious damage. However, the migration of self-repair to lower value systems is a process which engineering is just beginning. Future research will need to concentrate on solutions that are easy, cheap and quick to adopt.

3.5 Degradation

Degradation refers to the process of deterioration of characteristics of an object with time; gradual decline in quality; breakdown of matter due to the impact of external forces in conformity with the laws of nature and time. The degradation issue could be categorized in to component and system level. At the component level the degradation mechanisms are wear, cracks, corrosion etc. At the system level the degradation manifests as no fault found (NFF). Given the variety and complexity of mechanisms, there is a need to understand their drivers and ways to mitigate their implications.

In the process of investigating the mechanisms there is a growing interest in realising NFF. NFF refers to system or component that has been returned to the manufacturer or distributor for warranty replacement or service repair, but operates properly when tested in laboratory environment [11]. Investigations have shown the occurrence of NFF in coupled whole systems with electronic, electrical and mechanical sub-systems. Solutions have always proved difficult. The root causes can be diverse and many are specific to particular industries, but the problem can occur from incorrect diagnostic techniques or tests, poor training, incorrect processes, operational pressures poor design. The costs can be significant particularly when assets are now being contracted at a fixed price per hour of their availability. An investigation by the Royal Air Force showed some 60,000 man-hours being attributed to nugatory maintenance activity on NFF. Similar wasted efforts will be occurring in the Army and Navy, Railways, Wind Turbines and High-end car industries. There are three different classes of NFFs, all of which will be addressed here: a) Intermittent faults, a fault is indicated but 'goes away' a short time later, b) Integration faults, a component or subsystem works fine on test but shows faults when incorporated with other systems and

c) BITE (Built-in-Test Equipment) indicates a fault but there is insufficient information available to locate the exact unit or component to be replaced [11]. Various technologies can be employed to investigate NFF decisions including environmental test chamber and, intermittent fault detection, as shown in Figure 8.

Fig. 8. Technologies for the system and component level degradation reduction

3.6 Additional Themes

Apart from engineering based issues that are faced in maintenance there is also interest in more soft issues including how to design the skill set to deliver the maintenance solution, how to structure the organization to meet the requirements, maintaining safety and how to organise the supply chain. There is also growing interest in aligning with environmental requirements. In particular, the role of maintenance in meeting regulations is a challenging area that requires further research. Furthermore, from a financial point of view, with the wide application of carbon trades the significant role of maintenance in producing environmental pollution will be further assessed and may yield financial benefits to trade pollution. Maintenance does not only have a role to ensure reliability of equipment, but it also requires consideration of providing a safe and healthy environment for the maintainers [17]. The maintenance requirements due to failures and failure expectations within the plant are evolving and the potential risks are transforming. Future research will need to assist in assessing the technical risks but also in determining what is acceptable risk by society.

4 Concluding Remarks

Maintenance as a service is a major driver for the whole life cost of an IPS²project. There are new and revised challenges in the form of customer requirements and uncertainties that needs addressing to make an IPS² project a success. Some of these aspects relate to meeting availability requirements, managing reliability, obsolescence mitigation, achieving supply chain integration, supporting and guiding customer equipment utilization. Maintenance activity needs to further develop to address these additional challenges and that could be achieved through technological and organizational development. The major technological trend in the maintenance that is expected to influence the future includes application of advanced information technology, autonomous maintenance, managing degradation and mechanisms to optimize life. Also, there is an increasing need to standardize the maintenance terminologies and technological processes to support the supply chain and implement best practice.

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