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Research Article

Performance Assessment of Product Service System from System Architecture Perspectives

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New business models in complex engineering products have favoured the integration of acquisition and sustainment phases in capability development. The product service system (PSS) concept enables manufacturers of complex engineering products to incorporate support services into the product's manufacturing and sustainment lifecycle. However, the PSS design has imposed significant risks to the manufacturer not only in the manufacture of the product itself, but also in the provision of support services over long period of time at a predetermined price. This paper analysed three case studies using case study research design approach and mapped the service elements of the case studies to the generic complex engineering product service system (CEPSS) model. By establishing the concept of capability distribution for a PSS enterprise, the capability of the CEPSS can be overlaid on the performance-based reward scheme so that decision makers evaluate options related to the business opportunities presented to them.

1. Introduction

Recent trend around the world among the owners of complex engineering systems such as aircraft or oil refinery is to include consideration for the sustainment of the system at the very early stages of system development. According to the Defence Materiel Organisation in Australia [1], the asset acquisition project is considered a continuum of four phases, which can be generalised as a capability systems lifecycle as shown in Figure 1. The goal is to ultimately attain desired capability levels that can be measured as a performance outcome of systems in-service.

There are two different contracting regimes in Figure 1.

(i) System acquisition agreements including functional and performance specification of the final system, that is, the tendering and contracting activities in the acquisition phase.

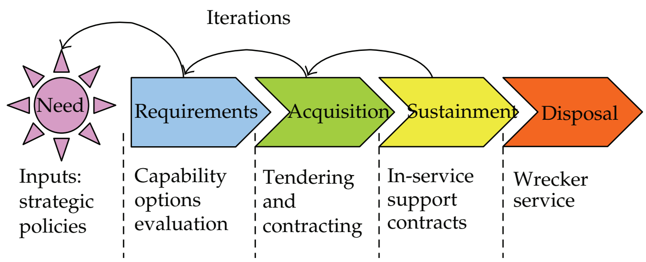

Figure 1: Capability systems lifecycle.

(ii) Sustainment agreements specifying outcomes and performance requirements for in-service support, that is, the in-service support contracts in the sustainment phase.

Although it is still early stage process development, the Australian Defence intends to adopt a more integrated approach by contracting for acquisition and sustainment simultaneously in some of their new system acquisitions.

Similarly, the Ministry of Defence [2] in UK is managing a general shift in defence acquisition away from the traditional pattern of designing and manufacturing successive generations of platforms. Instead, a new paradigm centred on support, sustainability, and the incremental enhancement of existing capabilities from technology insertions has evolved with the emphasis increasingly on through life capability management. The new approach to acquisition is built around the objective of achieving

(i) primacy of through life considerations;

(ii) coherence of defence spend across research;

(iii) development, procurement, and support,

(iv) successful management of acquisition at the departmental level.

From the industry's point of view, this shift in defence acquisition process means longer, more assured revenue streams based on long-term support and ongoing development instead of a series of big "must win" procurements [3]. Observation on other industry sectors shows similar changes in the manufacturing and sustainment of complex engineering products such as an oil refinery and mining machinery [4].

Traditionally, management of sustainment services is the responsibility of the asset owner, after the product is commissioned. Most asset owners simply take the recommended schedule of the manufacturer, either by in house service department or by a maintenance services contractor. The strategy is to minimise expenditure that should be spent on the asset [5]. Therefore, classical services and maintenance plans are designed on the principle that mean time between failures is a constant and hence the focus is to replace components before it fails. Typically, service activities including inspection, adjustment, and replacement are scheduled in fixed intervals [6]. Due to multifaceted relationship between operating context and characteristics inherent in the complex system, these intervals may not be optimised [7]. On the other hand, reliability-centred maintenance regime has been developed to plan actions in maintenance based on advanced understanding of the reliability of the system [8]. In addition, many other factors are also influencing the operations of the asset [9]. Many service decisions on assets are therefore made on rules of thumbs rather than using analysed system performance data. Many complex systems are left vulnerable with high risks of failure.

A new service business model known as "performance-based contracting" has emerged in recent years as one of the favourable choice of contracting mechanisms for the public sector and asset intensive industries [10]. Under performance-based contracting approach, a contractor offering systems support services needs to design an operation and support system that is sustainable, fits for the purpose, and demonstrates its value for money. The advantage of performance-based contracting is the sharing of benefits for both sides of the business. Efficiency gains are shared between the contractor and the owner of the business [11]. In this regards, original equipment manufacturers have significant advantage over other service providers because they know their product well. Many equipment suppliers have taken the opportunity to expand into offering after sales services to customers [12].

A manufacturer of complex engineering system entering into this kind of contract takes a lot of risks with the contract. For example, the new contracting framework by Defence Materiel Organisation [13] contains several elements of incentives and penalties. Application of these elements depends on the actual system performance results within four bands.

(i) *Performance Band I.* System performance result is below the required performance level. Contract payment is reduced proportionally to the actual performance outcomes as a disincentive.

(ii) *Performance Band II.* Result is poor but may be tolerable for short term only. Contract payment is significantly reduced proportionally to the actual performance outcomes with a more rapid reduction ratio until reaching zero.

(iii) *Performance Band III.* Result is totally unsatisfactory and represents an irrecoverable failure. No payment is made and other remedies may be applied.

(iv) *Performance Band IV.* Result of the achieved performance equals or exceeds the required performance level. An optional performance incentive may be paid in addition to the agreed value.

In this new service business model, risks exist throughout the whole of life of the product. How can the manufacturer know in advance what performance he/she can achieve at the conceptual design phase of the product life cycle? Which performance band is the system going to operate? There are many factors affecting system performance, for example, new deployment requirements, or change of software operating system, and so forth. The technology in the system is already very sophisticated. The model adds further complexities of sustainment and lifelong services in the commercial contract. These represent several layers of uncertainties in the commitment on the part of the service provider. A decision support methodology that can reduce such uncertainties in the life of the asset is required. This paper is motivated by the fact that new business paradigm emerging in the service sector has demanded a new set of principles and knowledge to assist the manufacturing industry. A new product and service enterprise architecture is proposed in this paper and verified by three past service systems design projects, with case study research design methodology. Based on the new architectural model, an assessment methodology that can be used for assisting decision makers to evaluate options available to them in regards to the business opportunities presented to them is proposed.

2. Product Service System

The shift of complex engineering products manufacture to service-oriented business environment has necessitated research in developing a new business model [14]. Abe [15] studied a service-oriented solution framework designed for Internet banking and described the new research as “service science”. The concept of product service system (PSS) was initially developed around the optimization of sustainability criteria to operations, maintenance, and environmental related issues around the product [16]. The PSS concept extends, on the basis of an existing complex product, the provision of support services on that complex product when it is in operation. Bairnes et al. [17] presented a clinical style survey of contemporary practices in PSS and subsequently defined PSS as a special case of servitization. It is obvious that there are commercial benefits for companies to move into continuous services and support operations of the complex products they manufacture. In addition to the technical requirements of supporting a complex engineering system, a key feature of the new PSS model is the extension of product offering to service offering. A service system comprises people and technologies that adaptively adjust a system’s value of knowledge while the system changes in its lifecycle [18].

One of the key questions emerged from this approach is the uniqueness of service requirements. Every complex engineering product is different and hence it is fair to say that each PSS is customised. Johansson and Olhager [19] examined the linkage between goods manufacturing and service operations and developed a framework for process choices that enable joint manufacturing and after-sale services operations. Study showed that moving into services-oriented business could have significant financial implications to the company [20]. In a performance-oriented service system, decisions for optimization can be quite different from maintenance oriented service concepts. For example, in order to reduce time of service to customers, Shen and Daskin [21] suggested that a relatively small incremental inventory cost would be necessary to achieve significant service improvements. Hence, to develop service systems that can handle this type of business requirements, companies should build common business functionalities as shared services so that they can be reused across lines of business as well as delivery channels [22].

When compared to traditional support arrangements, PSS concept changes a contractor’s roles and responsibilities by shifting the support service to customer focus. Under service-oriented arrangements, the service provider is responsible for the full spectrum of support, including ownership, sustainment, and operation of assets. Furthermore, contracting arrangements will include incentives and penalties against levels of support service or delivery. The service provider will need to think differently and design the output solutions that deliver the desired outputs as well as generating profit. This is a different type of business with unfamiliar contractual metrics and risks. In PSS, the emphasis is on customisation of solution designs to meet service needs and create new values of use for the customer [23].

A performance-based contract in PSS will include incentives and penalties against levels of support service or delivery as discussed before. Hence, the service contractor should have a thorough understanding of how the system works and how the supporting systems around the asset provide the services to achieve the desirable performance [24]. Due to this highly individualised nature of service, no one performance-based contract is the same. The support system then becomes a one-off development which imposes significant system design issues to both asset owners and contractors.

A service contract often involves active interaction within the supply chain and with the customer. In a service environment, it is normal that a new separate enterprise is formed from several independent, collaborating enterprises. There are many risks in this strategy, for example, there are risks in collaboration, confidentiality, intellectual property, transfer of goods, conflicts, opportunity loss, product liability, and others. To minimise the risks for the new service enterprise, enterprise engineering researches provide an enterprise architecture framework as a common starting point. The study of enterprise architecture in the last decade has been on how enterprises can be designed and operated in an environment when the enterprise missions and objectives are clear. They assumed that one can follow the common engineering practice of well established sequences of steps: design, implementation, operation, and decommission phases [25]. The rationale to use enterprise engineering methodologies to guide these steps is to minimize enterprise design modifications and associated rework of the system governing information and material flows [26]. A PSS as discussed in this paper is a dynamic system. Any unplanned change to the enterprise is an impact of uncertainty to enterprise performances. The enterprise architecture (EA) approach provides a structured system to manage services activities, for example, promote planning, reduce risk, implement new standard operating procedures and controls, and rationalize manufacturing facilities [27]. Hence, this paper uses an EA approach to understand the enterprise under which the product and related services are managed and to assess the performance of the PSS.

3. Architectural Approach

An enterprise architecture defines methods and tools which are needed to identify and carry out change [28]. Enterprises need lifecycle architecture that describes the progression of an enterprise from the point of realisation that change is necessary through setting up a project for implementation of the change process. Denton et al. [29] specified an information technology route map that enabled rapid design of IT solutions to automate some business processes for service supply chains. Therefore, it is crucial to use a systematic design methodology that helps the management developing well-defined policy and process across the organisational boundaries and implements the changes in all enterprises of the service supply chain.

However, traditional enterprise architectures are based on top down approach. They emphasized on uniformity throughout the organization. As such, the structure is inflexible. Changing the structure in order to respond to fast changing dynamic issues for in service engineering systems will be too long to fix any problem [30]. Two issues in using standard enterprise architecture to model service and support systems are identified.

Inwards Modelling

Existing enterprise architectures contain functions, data, staff, resources which are inwards looking and focus on internal company issues. There is very few, if any, modelling constructs for interaction with other systems.

Static, Snapshot View of Present and Future

EA modelling methodology is based on the understanding that it is a snapshot of the enterprise at certain point in time. Service systems are dynamic organisations. There are frequent staff movements, external environment changes, customer changes, and change of use context. The static nature of existing EA is incapable of handling changes as anticipated in real service systems.

In order to support decisions on business opportunities by enterprise architectural approach, the PSS enterprise should have the following characteristics.

Measurement of Performance and the Development of Metrics That Can Be Supported by Technology

The PSS will be operated in parallel with the complex engineering system. Service is qualitatively different to the familiar product-based approach where hard artefacts are delivered to the asset owner. Service is a negotiated exchange with the asset owner (and operator) to provide intangible outputs that are usually produced together with the asset owner. A service is usually consumed at the time of production. Services cannot be transferred to other asset owners in the same way that products can. Hence, the development of appropriate performance metrics is essential and most of these are supported by advanced information and computational technologies.

Use of Proven Enterprise Architecture That Incorporates Broad Range of Engineering Disciplines

PSS incorporates system design knowledge that draws upon principles derived from a wide range of engineering disciplines including systems engineering, logistics engineering, project management, information systems, and many others. The knowledge helps the system support engineer to take into account as many constraints as possible during the system design phase. These constraints are imposed by the environment in which the complex system and the business are operating.

Sustainability Capability That Manages Risks in the Support Contract

The performance-based services are characterised by the need to create value for both asset owner and the service provider. As such both sides are treated as coinnovators in the design of the PSS. Many decisions are made based on incomplete data rather than fully analysed data set. There are a lot of risks, both from the point of view of data availability, as well as subjective human judgement and communication.

When customers want to outsource a service function, capturing the requirements is the real challenge for human intelligence and ability to manage what we know, what other people know, and what nobody knows [31]. A modelling construct that has more human interaction characteristics is required.

SHEL model has been developed from analysing and modelling human interaction with physical and project activities [32]. Chang and Yeh [33] applied the SHEL model to describe the structure of the air traffic control system and its interface to human operators. The research findings provided practical insights in managing human performance interfaces of the system due to changes in its operating environment. Felici et al. [34] applied the SHEL model to deal with the definition of the requirements for a new railways traffic control system. Lei and Le [35] evaluated risks of human factors in flight deck system. They used a SHEL model and found five most significant factors on the risks in the system.

Extending from traditional enterprise modelling methodology, Chattopadhyay and Mo [36] modelled a global engineering services company as a three-column progression process that was centred on human engineering effort. Chattopadhyay et al. [37] developed a business model for virtual manufacturing with particularly emphasis on the need for intense collaborative network for a variable-variety, variable-volume and manufacture to order situation with provisions for recycling and reverse logistics. The concept was further developed as an aggregated model resembling nature's atomic and molecular interaction after studying the supply chain in China [38]. These new attempts to incorporate human participation in modern global enterprises have highlighted the effect of new information and communication technologies in bringing the human dimension in enterprise architecture to a dominated position.

As seen from the literature, the SHEL model has particular focus on local, operational level of the enterprise. It does not have the support of engineering methodology to ensure repeatability and sustainability of the system. Likewise, traditional enterprise architecture methodology tends to ignore human interaction and becomes difficult to describe vibrant enterprises in the services sector. It is logical to develop a new enterprise model for services that combines traditional enterprise architecture with SHEL concept. We propose this new complex engineering product service system architecture as shown in Figure 2.

Figure 2 shows that a PSS for complex engineering products should be a four–dimensional system architecture: product, process, people, and environment. This is in contrast to conventional enterprise modelling methodologies that had significant influence to system development thinking in the 1990s. The new architecture covers the additional "changing" aspect of service system by integrating the concepts of product, process, people to changes in environment over time. The four dimensions are interlinked and affecting one another. The architecture provides a focus for consolidating existing knowledge of designing a service system as well as an instrument for projecting future requirements in a system so that new features can be developed in an orderly fashion.

4. Case Study Research Design

Case study research is particularly useful in identifying specific characteristics that affect system performances. Serra and Ferriera [39] identified four strategy pillars in five case studies of well-known multinational corporations. In supply chain case study research, Seuring [40] surveyed 68 papers related to supply chain sustainability and supply chain performance and concluded that more supply chain cases should be documented and reviewed. Lewis et al. [41] researched three case studies in the energy and maintenance management practices. They found that the link between different service requirements should be better understood when the teams worked together for service solutions.

However, extracting the theoretical essence of a PSS is not a trivial exercise from studying a wide variety of cases. For example, Holschbach and Hofmann [42] used case study evidence from eight manufacturing and eight service companies. They found that companies did not use quality management for externally sourced business services to its full potential. There were major difficulties in determining quality failures, standardization, and quantity of service. Zhang et al. [43] carried out a structured literature review on the influence of ICT in supply chain management. They found that despite inconsistency in reported findings in this field of research, there were general positive performance outcomes of supply chains due to ICT system development. Kucza and Gebauer [44] investigated the forms of servitization of products could help global manufacturing firms to develop new service-based and relationship-based value propositions for customers. Four such forms were identified: integrated and ethnocentric; integrated and polycentric; separated and polycentric; and separated and geocentric.

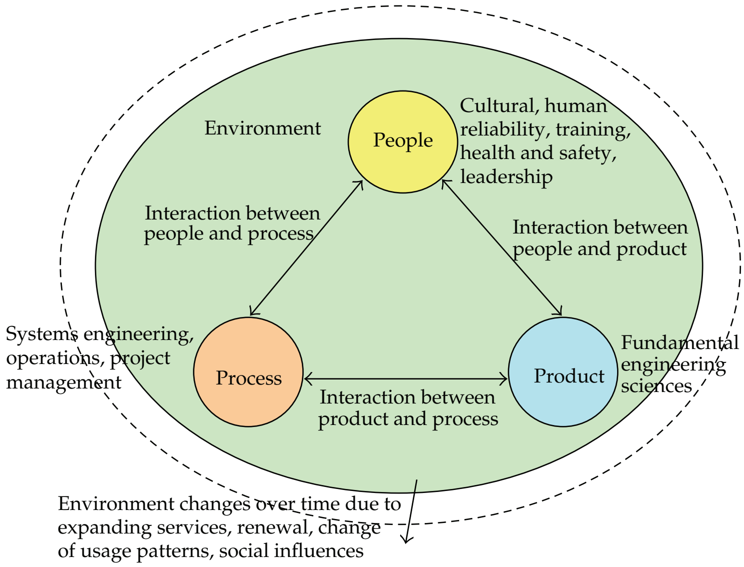

Figure 2: Complex engineering product service system (CEPSS) architecture.

One of the most difficult issues in the case study research is the definition of unit of analysis. Grünbaum [45] provided a useful elaboration of the concept by examples of generic case studies based on modifications of Yin's [46] case study design. Huang [47] interviewed top management of 40 SMEs in Taiwan on their perceptions of IT components in business and found five internal strategic factors inhibiting top management support in IT adoption. M. Bielli and A. Bielli [48] presented a conceptual model of a SMEs network in the European project CO-DESNET. The coordination of distributed and autonomous agents characteristics of the collaborative enterprise clusters was represented by suitable models such that global performances could be evaluated. The model was validated by a case study outlining a transition to the Net Economy of SMEs in Italy.

In this paper, three case studies are described and their key features are highlighted. The cases are earlier forms of PSS representing various degrees of success in creating new businesses for the equipment suppliers. The ad hoc systems established at the time of these cases provide good examples for benchmarking current thinking of the design and implementation of PSS. These cases are chosen because the parties in the cases have tried to apply a defined enterprise infrastructure that links different parts of the service system working in conjunction with the product. Subsequently, the service system has to be re-designed and tailored to characteristics of the product or the enterprise itself.

Data collection for this type of case study research depends on the relationship of the researchers and the parties in the cases. In all cases, the author of this paper has had varying levels of participation in the cases.

5. Case Studies

The products in the three cases are complex engineering systems. Case 1 is a computer controlled plasma cutting machine that can cut steel plates up to 50 mm thick. The machine has been sold over the world. Case 2 is a chemical plant that is designed and built by a

Japanese engineering company. In order to support the customer with minimum costs, the support system was designed to use the Internet, which was evolving at the time when the project was done. Case 3 is a defence case in which the ship builder formed a service consortium to continue its business after the ships were built. Evaluation and analysis of the cases will be based on the CEPSS model presented in Figure 2.

5.1. Case Study 1: Signal-Based Condition Monitoring System

System health monitoring plays a critical role in preventative maintenance and product quality control of modern complex engineering products. The effectiveness of management can directly impact their efficiency and cost-effectiveness. A condition monitoring system monitors the products using various classical methods of signal analysis such as spectrum or state-space analyses [49]. Maintenance decisions are then made according to the prediction of system performance.

Using time-based signals available from normal machine sensing mechanisms, a CNC machine manufacturer in Australia developed a remote condition monitoring system for plasma CNC cutting systems with the aim of servicing the customer anywhere in the world via the Internet. Figure 3 shows the network structure of the system known as ROSDAM [50]. All ROSDAM-enabled machines were configured as servers that had functionality communicating with the global master server. Information about the operation of the machines was captured through individual companies' database. The significantly improved sources of information enabled the product manufacturer to decide the best option that supported operation and maintenance of the plasma cutting machine from a distance.

In this case study, new elements were required to be developed and integrated with the product, that is, the CNC plasma cutting machine. These elements are mapped to the CEPSS model as shown in Table 1.

5.2. Case Study 2: Global Operation Support Services

Complex assets are normally built from a large number of components and involving a large number of engineers and contractors. In the past, customers as plant owners usually maintain their own service department. However, the increasing complexity of the plant and operating conditions such as environmental considerations require service personnel to have a higher level of analysis and judgment capability. Rathwell and Williams [51] used Flour Daniel as the study platform and validated the use of enterprise engineering methodology for creating services that support operations of chemical plant. The study showed that significant efficiency gain could be achieved in the design and implementation of the service system through systematic enterprise modelling analysis.

In managing the design and manufacture of a chemical plant for their customer, Kamio et al. [52] established a service virtual enterprise (SVE) with several partner companies around the world providing after-sales services to a customer (Figure 4).

Each partner in Figure 4 was an independent entity that was equipped with its own unique capabilities and competencies, assuming responsibility to perform the allocated work. The SVE was designed as a "hosting service" which had a broad range of services including plant monitoring, preventive maintenance, trouble-shooting, performance simulation and evaluation, operator training, knowledge management, and risk assessment. Participants of the virtual enterprise had well-defined roles and responsibilities.

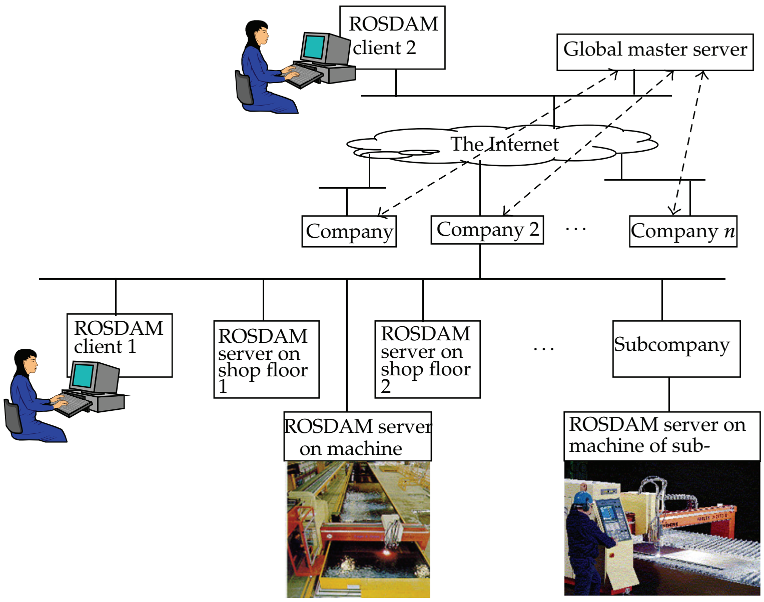

Figure 3: Signal-based condition monitoring service system network structure.

Table 1: Mapping of service elements in case 1 to CEPSS.

Element	Description	Mapped to CEPSS
On machine signal-based diagnostics capability	A new diagnostics software module based on chaotic theory and digital signal processing was developed to assist identification of faults.	Product
Communication networks and IT systems based on client-server model	The controller of the machine was significantly changed from a normal standalone operating system to one that can act as a server in a network environment.	Product-People
Knowledge sharing—transform customer data to information to knowledge	New data processing algorithms were developed as software modules that were required to process data on machine to knowledge useful to enhance operational efficiency.	People
Engineering information integrated for supporting more effective customer service	Engineering information such as bill of material, machine configuration management, parts inventory, and resources planning were integrated from different sources including CAD, MRP, and various manufacturing sources to create seamless operation database for the machine.	Process
The new system design requires upgrade of field products	Field upgrade for machines that were already installed at customers' location was progressively rolled out according to contracted maintenance schedules.	Product-Environment

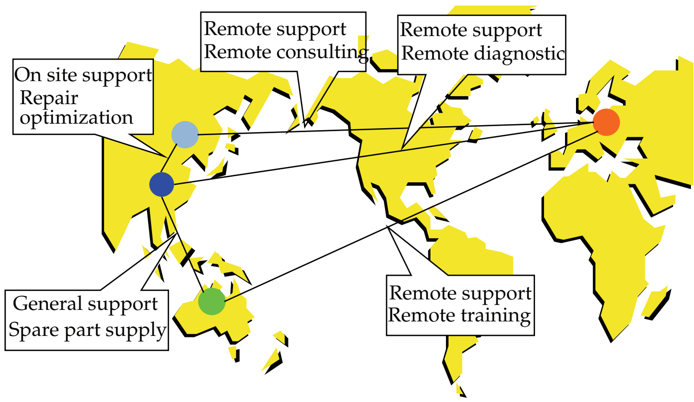

Figure 4: A global service virtual enterprise.

An essential element in the design of a service enterprise is to develop efficient system architecture and provide the right resources to the right service tasks. By synchronising organisational activities, sharing information and reciprocating one another's the technologies and tools, each partner in the service enterprise will be able to provide services that would have been impossible by individual effort. The PSS therefore requires properly designed components to support the use of technology in the provision of support services to customers.

In this case study, in order to operate the SVE, new service elements were developed. They are listed and mapped to CEPSS in Table 2.

It should be noted that the engineering product remained the same as it was designed initially. There was no noticeable engineering change required on the product itself in order to implement the support service offered by SVE.

5.3. Case Study 3: Ship Service System

The ANZAC Ship Alliance (ASA) could be thought of as a virtual company with shareholders comprising the Australian government and two commercial companies, one of which was the ship builder. The primary goal was to create best value for money [53]. The primary goal of ASA was to manage all changes and upgrades to the ANZAC Ships [54]. The Alliance was a "solution focused" company where the staff of the ANZAC Ship Alliance Management Office would develop change solutions but the detailed design is undertaken by the "shareholders" drawing upon their existing and substantial knowledge of the ANZAC Class.

Prior to the development of ASA, Hall [55] developed a highly integrated documentation and configuration management system that served the on-going need of ten ANZAC class frigates. Over the life time of the asset (30 years), changes due to new technologies, people and defence requirements are inevitable. The organisation structure of ASA can be described as shown in Figure 5.

In this case study, the enterprise was not set up as a legal entity. There was no formal binding agreement among the partners in ASA. In the language of virtual enterprise, the

Table 2: Mapping of service elements in SVE to CEPSS.

Element	Description	Mapped to CEPSS
Intercompany communication networks and IT systems	New IT and communication systems were installed to enable intercompany exchange of information as well as personal interaction.	Process-People
Work items synchronized within the project across companies	Work items were analysed individually so that the link from individual level to group level can be streamlined ensuring minimum duplication of work and conflicts.	Process
Change of human organisation role	The relationship within a SVE was definitely different from a totally authoritative company structure. A much more flexible human organisation structure was established.	People
Global access by customer	The SVE was implemented on the Internet. At the time of the development of this PSS, the Internet was still not entirely effective in some parts of the world, and this environmental constraint imposed significant challenges on the SVE development.	Process-Environment

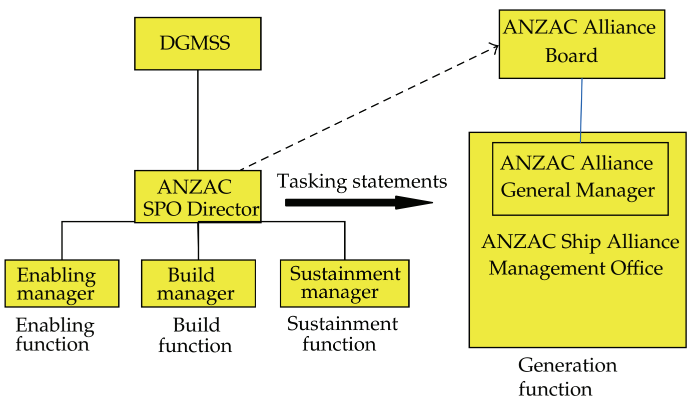

Figure 5: Organisation structure of ANZAC Ship Alliance.

partners were loosely linked organisations such that everything done in the ASA is based on trust. The new service elements that were developed on this premise were listed in Table 3.

From the point of view of the ship builder company, the ASA was an unprecedent business environment that no one knew exactly how to operate. There were some upgrade projects as continuous support initially. After several years of operation, the ASA entered into a new material support program focusing on supplies and shore facilities.

Table 3: Mapping of service elements in ASA to CEPSS.

Element	Description	Mapped to CEPSS
New procedures and legal processes	All parties joined the ASA with the understanding of a set of business rules. (i) All parties win or all parties lose (ii) Collective responsibility, equitable sharing of risk and reward (iii) All decisions based on "best for project" philosophy (iv) Access to resources, skills, and expertise of all parties (v) All financial transactions are fully open book (vi) Encouragement of innovative thinking—outstanding outcomes These nontraditional business rules imposed challenges on the ASA as the service system of the ships.	Process
Ownership of product-related services rested with ASA	The enterprise was a joint development of several companies and hence the ownership of the product-related services had to be resolved. This issue settled at the end but as all participants were in the defence business environment, and the customer was a partner of ASA, the "company" structure at the right hand side of Figure 5 was able to provide sufficient background understanding for the people to rely on.	Process-Product
Secondment of staff from the three partner organisations	As the "company" status was eventually accepted, the need to develop a set of processes that is acceptable to all staff (who were all seconded from the partner organisations) became urgent. A lot of time was spent in synchronising practices and culture originating from individual companies. There was confusion in the first year among the staff of the participating organization about the nature of ASA. This issue was resolved through a number of ASA workshops.	People-Environment

6. Performance-Capability Assessment

From the foregoing case studies, the subsystems and interactions between the subsystems of the CEPSS model are represented by specific elements in the cases. Table 4 summarises the relevance of the cases in a matrix.

When a PSS enterprise is created by three interdependent subsystems under the CEPSS model, the ability of the total PSS in meeting the performance expectation of the customer will depend on how the capability of each of the subsystems is designed and the effect of the environment on the execution of these subsystem capabilities. Theoretically, for each of the subsystems in a CEPSS enterprise, it is possible to devise some measures of enterprise capability in relation to the outcomes that can be produced by the capability. These methods include survey, interviews, system audit, comparative analysis, human resources

Table 4: Applicability of cases to elements and interactions of CEPSS.

	Product	People	Process
Product	Case 1		
People	Cases 1 and 2	Cases 1, 2, 3	
Process	Case 3	Case 2	Cases 1, 2, 3

records, and so forth. This type of capability assessments are bound to have certain degree of uncertainty. In addition, the enterprise capability will change over time due to changes in people, process, and product.

Likewise, by way of aggregation of subsystem capabilities, the capability of the PSS can be benchmarked against the theoretical capabilities required to achieve expected performance, an assessment of the potential achievement can be made at the outset, when the PSS enterprise is established. Due to the uncertainties as explained above, the probability of the PSS enterprise's achievement can be expressed in terms of the frequency of success of this capability meeting specified performance metrics.

Using case 1 as an example, assuming all other capabilities are able to deliver to the required performance standards, the improved service elements can be assessed using a 5-point scale of 1 to 5 where 5 represents most certain and 1 represents rarely meeting expectation as shown in Table 5.

The ratings in Table 5 are for illustration only. Since most ratings are above average, the PSS in case 1 is assessed as likely to meet customer expectation. With an assessment of the capability against expectation outcomes, the probability of the service contract being successful can then be determined from the contractual terms.

As an illustration, if the Defence Materiel Organisation four-band performance incentive/penalty scheme is used, the capability distribution can be overlaid on the achieved performance axis as shown in Figure 6. The capability distribution (in dotted curve) represents the probability density of the enterprise achieving a performance level on the x-axis. Different risks and probabilities of a PSS contract can then be identified as shown in Figure 6.

Several decisions can be made using this assessment outcome. For this discussion, the CEPSS contractor is the prime contractor who is a major engineering company working with the client on a new complex engineering system within the capability systems lifecycle shown in Figure 1. Using the performance-capability assessment methodology, the CEPSS contractor has visibility on what risks are likely to incur in its current proposal.

First, based on this information, the CEPSS contractor can decide whether to go ahead with the enterprise capabilities he/she has. This is a go and no-go decision scenario. The contractor will have to decide in conjunction with other concurrent opportunities, which may be assessed by the same PSS opportunity assessment methodology or other means.

Second, if the risk level is too high, the CEPSS contractor can increase his/her enterprise capabilities by raising the contract price to cover the costs, or by implementing organisational improvements such as lean and six sigma. In the latter case, the time factor of the CEPSS will be brought in to map the change of capability over time.

Third, the CEPSS contractor can identify the shortfall capability areas and collaborate with other prime suppliers in the industry. The performance capability assessment is then modified as the overall performance capability of the combined CEPSS consortium. The contractual detail of the coalition arrangement is outside the scope of this paper [56].

Table 5

CEPSS	Element	Customer expectation	Assessed capability	Rating
Product	On machine signal-based diagnostics capability	Diagnose the causes for all (100%) of reported problems.	The new signal diagnostics capability only provides high level fault analysis.	3
Product-People	Communication networks and IT systems based on client-server model	Obtain online support information at any time.	Connection to the master server depends on the Internet	5
People	Knowledge sharing—transform customer data to information to knowledge	Receive correct advice all the time.	Fault trees based on past records sometimes contain conflicting cases	4
Process	Engineering information integrated for supporting more effective customer service	Identify suitable machine configuration and spare parts.	Support system is integrated with product design database which requires minor interface development.	4
Product-Environment	The new system design requires upgrade of field products	Upgrade as minimum cost and within reasonable time.	Establish a separate group within the company responsible for upgrade requests.	5

A mapping of potential changes over time in capabilities of other parties should also be considered, as highlighted by the CEPSS model.

Fourth, the CEPSS contractor can consider boosting its core capabilities by mergers and acquisition with other companies. This case is more complicated since consideration of which companies to acquire depends on strategic alignment requirements. However, this option will represent an immediate shift of the capability distribution to the right. The only concern is whether the new organisation can be restructured and operated effectively and quickly enough for executing the PSS contract [57].

7. Conclusion

New business models in delivering capabilities from the operations of complex engineering products such as aircraft, ships, and refineries have favoured the integration of acquisition and sustainment phases of the products. The product service system (PSS) concept enables manufacturers of these complex engineering products to incorporate support services into the product's system capability lifecycle. These services are substantially more complex than routine, reliability-based maintenance or spare parts support. Unfortunately, in the past decade, researches in the development of support systems have been fragmented. There is no unified body of knowledge specifying the methodologies that can naturally lead to the design of a support solution for any scenario. This situation prompted this study.

The new type of service business model, which is represented by performance-based contracts, focuses on the performance of the complex engineering product during operations in terms of timeliness, availability, maintainability, and sustainability costs in the product's complete lifecycle from conception, design, manufacture to disposal. Ultimately, the service

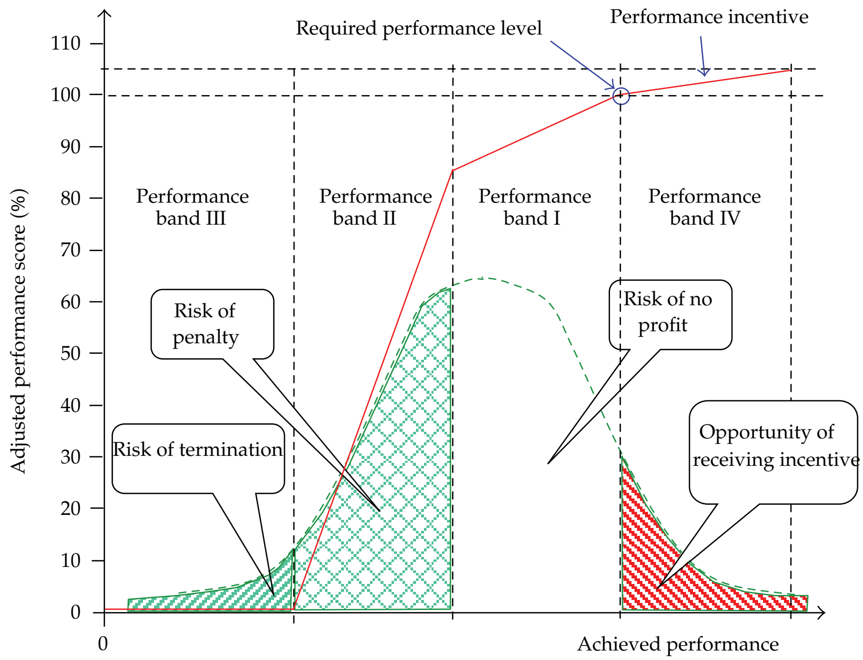

Figure 6: Performance band and risks in the PSS contract.

business model is expected to provide long-term benefits to both contractor and customer due to efficiency gains. However, the PSS itself has imposed significant risks to the contractor not only in the manufacture of the product, but also in the provision of support services over long period of time at a fixed reward scheme with a lot of unknowns. A successful PSS enterprise requires an analysis methodology that can assist the contractor to estimate the performance outcomes of the PSS.

In this paper, three case studies are analysed using case study research design approach to investigate a new complex engineering product service system (CEPSS). CEPSS combines the conceptual elements in the SHEL model with the systematic enterprise architecture modelling approach. Service elements of the three case studies have been mapped to CEPSS. Through this mapping, the CEPSS can be broken down into subsystems. Capabilities of the subsystems are readily assessed against customer expectation using qualitative methods such as opinion surveys. Once the capabilities are known, they can be overlaid on the performance-based incentive/penalty scheme so that different risk levels can be assessed as a decision support tool. Decision makers can then use this information to select options related to the business opportunities presented to them.

This paper is a preliminary investigation of the fundamental question: what service elements should be developed in the new PSS environment? Investigation using case study approach so far seems to show that the capability of the PSS can be assessed by an aggregated evaluation of these service elements and hence the expected performance of the service system can be estimated. However, the complexity of the system cannot be ignored. Further research is required to create a consistent scoring framework that can be applied across different risks and engineering systems. Naturally, more case studies on a broad range of engineer products would be necessary, while validating of the CEPSS using a more quantitative, evidence-based approach against these cases is vital to the development of a quantitative consistent scoring framework.

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