Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2) Conference, Cranfield University, 1-2 April 2009, pp200

Uncertainty challenges in service cost estimation for product- service systems in the aerospace and defence industries

J. A. Erkoyuncu[1], R. Roy[1], E. Shehab[1], P. Wardle[2]
[1]Decision Engineering Centre, Cranfield University, MK43 0AL, Bedfordshire, UK
[2]BAE Systems Integrated System Technologies, Eastwood House,
Glebe Road, Chelmsford, CM1 1QW
{j.a.erkoyuncu, r.roy, e.shehab}@cranfield.ac.uk, phil.wardle@baesystems.com

Abstract
Contracting for availability is expected to become more prevalent for product -service systems (PSS) in the aerospace and defence industries. These contracts tend to transfer responsibilities for the operational phase from the customer to the supplier. In parallel, with operational life spans spanning several decades, the ability to deal with uncertainty in cost estimation for support activities is becoming critical. This paper outlines challenges within this process derived from literature as well as issues that were highlighted during interviews with four major defence and aerospace organisations.

Keywords:
Product Service Systems, uncertainty, cost estimation, service

1 INTRODUCTION

The product-service system (PSS) approach, which integrates products and services to varying degrees, has lately attracted interest in the defence and aerospace industries as a candidate for availability contracting. In these industries the technical-PSS (t-PSS) concept applies where this is defined by the major characteristics of relatively higher monetary value of product core, a physical product core that is integrated with services, and a business to business relationship [1]. Examples that have followed this trend are the 'Total Care' and 'Power by the Hour' packages offered by Rolls-Royce which are focused on provision of in-service support against performance measures such as equipment availability. Taking a PSS approach drives a life cycle view of system provision for suppliers. This in essence creates a number of challenges that are illustrated in Figure 1.

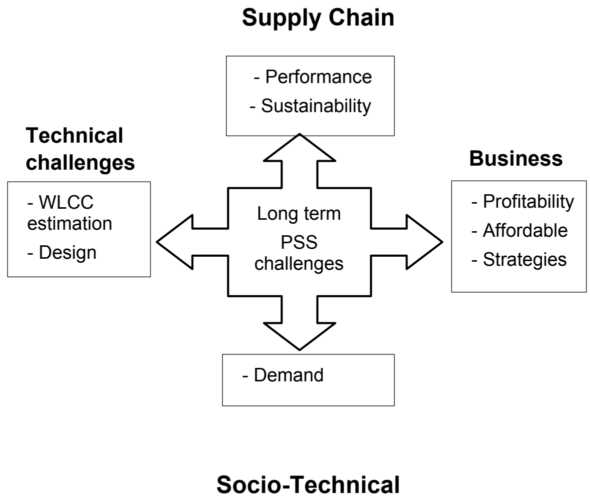

Figure 1. Long term PSS challenges (Adapted from Shehab and Roy [2])

Equipment availability is a function of its mean time between failure (MTBF) and mean time to repair (MTTR). MTBF is a characteristic of equipment design and is generally independent of the arrangements for in-service support, but MTTR depends directly on the support solution which can be characterised in terms of process, outcomes, and cost. Process includes detection of failures (including planned and unplanned maintenance) and rectification (including repairs, overhaul, retro-fitting, upgrades and obsolescence management) [3].

Under traditional contract arrangements suppliers are typically paid according to the throughput of 'spares and repairs' and other transactions such as mitigations for obsolescence. The sales value of each transaction with respect to costs incurred, which may be negotiated case-by-case, determines the supplier's profitability whilst transaction throughput determines the affordability for the customer. The throughput is under the customer's control and they will typically manage their demand rate within internal budgetary constraints, e.g. by prioritising transactions and dealing with simple cases in-house.

Under availability contracting arrangements the MTTR or other performance criterion is made the essence of the contract. At the time of bidding, the supplier offers a fixed price to the customer whilst assuming responsibility for estimating the cumulative number of transactions needed to sustain the MTTR. The supplier must accept the risk that, if they underestimate the number of transactions necessary, profitability will be reduced. Such estimates need to anticipate a range of contributory technical, commercial, financial, and behavioural risks and uncertainties that are exacerbated because of the need to look-ahead over a long period of time. The affordability for the customer is now independent of demand rate but they still have an interest in using this measure as a basis for comparing offers from alternative suppliers to achieve the best value-for-money.

Risk is the threat of a loss (e.g. financial, timescale, or performance) from an unwanted event. Uncertainty is the difference between an anticipated or predicted outcome (e.g. a cost estimate) and the confirmed outcome (e.g. the actual cost). To be able to handle uncertainty, one needs to examine its sources. Broadly, these are incomplete information, disagreements between information sources, imperfect communication, and variation in circumstances.

The PSS sets the context for this study in which the goal of the research is to enhance rigour in cost estimates by means of better handling of uncertainty, particularly during the in-service phase. Availability contracts, which are the commercial arrangements under which the PSS is procured and delivered, take the whole life perspective of the equipment/system life cycle. In essence, when the PSS supplier 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 profitability over the duration of the lifecycle including the inherent uncertainty.

This necessitates better prediction of uncertainty for availability contracts 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 supplier - typically on a fixed-cost basis. Figure 2 illustrates how the main concepts within this paper are interlinked.

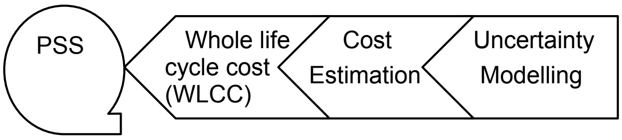

Figure 2. Inter-linkage of concepts in the paper

The research covered by this paper focuses on defining the current practice in uncertainty modelling in cost estimation, highlighting some of the major estimating uncertainties arising from the shift to contracting for availability and challenges incurred in incorporating service uncertainty into cost estimation. It has been conducted within the Product-Service System Cost Project (PSS-Cost) at Cranfield University.

Section 2 explains the methodology; Section 3 gives the outcome of a literature review on key concepts to the paper. Section 4 describes the current practice in uncertainty modelling for cost estimation, service uncertainties in availability contracts and the major challenges for industry. Sections 5, gives conclusions and implications for further work.

2 METHODOLOGY

The research commenced with a literature review to understand the drivers of the move towards service oriented contracts within the defence and aerospace industries. Subsequently, the research aimed to understand how the concept of WLCC has become associated with, and necessary to, the PSS approach. The literature review also briefly covered trends in cost estimation methods including uncertainty prediction, although such prediction at the in-service phase was found to be very limited.

The main databases used were ProQuest, Scopus, Web of Knowledge, Science Direct, EBSCO, and Google Scholar. No specific limit was set in terms of date of publication during the search process but the references found were all published between 2001 and 2008. This may be due to the field's short history. The following key words were used in the search: (whole life cycle) cost estimation, bid phase, uncertainty definition, uncertainty modelling, product service systems, service, service cost estimation, service cost uncertainty.

The outcome of the literature review was used to devise semi-structured interviews with four major partners in the project. These comprised three defence companies and one defence customer (UK MoD). The research with the partners was designed to confirm which of the techniques for uncertainty prediction suggested by the literature review were actually being used, to capture experience of their use, and to elicit challenges for future research. The questionnaires used in the interviews were piloted with BAE Systems' sponsoring manager.

A total of over 33 hours of semi-structured interviews were conducted with cost engineers, project managers, support managers, engineering managers, and functional experts (e.g. on risk and uncertainty). The PSS-Cost project members mostly attended the interviews together, apart from interviews that were held with functional experts. As a result, the linkages among research topics core to the project (design rework, obsolescence management, uncertainty and affordability assessment) were better understood. The duration of each interview did not exceed two hours. The researchers took notes during each interview and observations were reflected back in the form of a report for validation. The interviewees shared documents with the researchers prior to interviews to speed-up the process of learning about current practices in the collaborating industrial organisations. Some interviews focused on enhancing understanding of these documents. The range of current practices included: stakeholder involvement in the bidding process, life cycle management frameworks, software and engineering estimation guidelines, service definition elements in availability contracts.

Owing to the limited time that industrial participants could provide the researchers needed to select their questions carefully. To begin with, these included basic questions to confirm shared understanding of the definitions of terms such as uncertainty and risk, the elaboration of types of uncertainties, and the way uncertainties change during the lifetime of an availability contract.

Results from interviews were analysed by developing mind maps designed to highlight commonalities and differences in current practices and challenges experienced across the projects studied. These were again reflected back for validation.

The deliverable outputs at the end of year one of the PSS Cost project (December 2008) comprised reports on (1) the state of the art in cost estimation, (2) key challenges in cost estimation within the defence and aerospace industry, and (3) candidate activities for improvement in years two and three.

3 LITERATURE REVIEW

3.1 PSS and service

PSS offerings have generated interest in the defence and aerospace industries because of (1) pressure in national defence budgets in most countries including the UK, (2) the UK defence customer's ambition to transfer financial uncertainty from itself to industry, and (3) UK industry's ambition to grow its share of the diminishing defence budget in terms increased span across both the lifecycle (e.g. CADMID[1]) and defence lines of development (e.g. TEPIDOIL[2]).

These specific interests in the PSS approach on the part of the defence and aerospace industries are backed-up by others in industry at large. In the literature these include environmental benefits and system level cost reductions.

These benefits are driven by increasing effectiveness in utilisation of equipment [4] and an emphasis on the

---

[1] The Concept, Assessment, Demonstration, Manufacture, In-service, Disposal cycle has been used by the United Kingdom Ministry of Defence (MOD) since 1999, when it was devised as part of the Smart Procurement initiative, since replaced by Smart Acquisition, to deliver equipment capability within agreed performance, cost and time parameters.

[2] The United Kingdom's defence lines of development are training, equipment, personnel, information, doctrine and concepts, organisation, infrastructure and logistics

functionality and capability of the combined product-service system rather than the product itself [5, 6, and 7]. Furthermore, contracting for availability helps achieve value for money through co-creation of value between supplier and customer [8]. The most recent research looks at how the desire for co-creation of value is driving traditional product suppliers to transition into service delivery organisations.

3.2 Whole Life Cycle Cost (WLCC)

When considered in a rigorous manner WLCC analysis guides formulation of the PSS proposition during the bidding process from the technical, economic, and contractual perspectives and helps analysts to compare alternative propositions by taking account of all future costs. Technical metrics may involve functionality, performance, effectiveness, reliability, maintainability, supportability, or recyclability. Economic metrics may include initial cost, affordability, or profitability. An availability contract may make reference to any of the technical or economic metrics.

WLCC analyses offer better uncertainty assessment techniques, which are limited in standard methods [9]. Better consideration of uncertainty improves the chances of actual cost outcomes being within cost predictions, and this in turn allows contingency for uncertainty to be taken out of the price quoted by the supplier to a customer. This is beneficial to the supplier, especially in industries that have tight competition [10], because it improves their position against competitors. In the defence industry, the importance of the reliability of a cost estimate has increased since the public procurement policy was put in place during the 1980's [9]. This policy put the concept of 'value for money' at the forefront.

Despite these motivating factors the overall growth in adoption of WLCC has been relatively slow [10]. This can be attributed to a number of factors. For instance, estimators tend to be sceptical about adopting emerging techniques for WLCC estimating whose efficacy is unproven. Also, in committing one self to a long lasting contract, difficulty arises when the uncertainties in the estimate exceed the nominal profit. Other reasons for the slow uptake may be attributed to the short term view of management and/or the influence of reward systems that favour lower costs on an immediate basis [10]. A systematic approach that enables the risk and uncertainty in WLCC estimates to be reduced will enhance uptake in the industry [9].

75 to 80 percent of the WLCC is often committed before contract award, or shortly after, because the early design activity must scope the product solution and service solution concurrently owing to interdependency. In fact this behaviour is often driven by requirements in the customers request for proposal that ask for early visibility of the WLCC predictions.

The percentage uncertainty in cost estimates for the product solution (including development, manufacturing, testing, integration, certification, and acceptance) is often much less than that of the support solution.

Furthermore, by the time cost outcomes become evident in the first year or two of the support phase it is difficult to modify the support solution from either the technical or contractual viewpoint (e.g. in the event that it becomes necessary to pre-empt predicted cost overruns). Some availability contracts mitigate this problem by means of the 'evergreen renewal' principle that permits re-negotiation at intervals, e.g. every five years for a thirty year contract, but this is not seen as an ideal solution.

For these reasons it is a priority to address uncertainty in the cost estimating of the support phase of availability contracts, and to prepare initial estimates at an earlier phase of the lifecycle than under traditional arrangements where the product solution and support solution are decoupled under separate, sequential contracts.

It was noted in the course of interviews conducted by the PSS Cost project team that disposal or termination rarely form part of either traditional or availability contracts in the defence and aerospace industry. The prediction of costs and consideration of uncertainty for this phase of the lifecycle is therefore not covered here but remains an opportunity for further work.

3.3 Representation of WLCC

The segmentation of the life cycle enables a cost breakdown structure (CBS) to be produced for use in allocating budgets to individual cost centres and recording actual spend. The approach taken in developing the CBS may be variously driven by a legacy structure, customer requirement, the product breakdown, project organisation, or functional organisation. Ideally, industry would like to work towards CBS standardisation but this is difficult to achieve. In practice, estimators apply their experience to map data from one CBS to another in order to inform future estimates from data collected on past projects.

It is inherent in the process of retrieving data from past projects, possibly as long as several decades ago, that the original knowledge of the scope of each element will have been lost. The cost estimator typically mitigates this by applying his/her own experience and researching the experience of others but, particularly in the defence and aerospace industries where project lifecycles can exceed a working lifetime, better knowledge management techniques are required so that this understanding can be persisted without relying on the memory of individuals.

3.4 Cost estimation methods

The stages of the lifecycle for the PSS, for example as in the CADMID cycle, are widely varied in scope and scale and require a variety of methods to most effectively predict the respective costs. Three well-recognised methods are mentioned in [11] and a fourth has been identified from research conducted under the PSS Cost project:

- **estimating by analogy:** reads-across the cost outcomes from past projects having similarities with the one being estimated, traditionally used for the non-recurring engineering costs during development and unit cost during manufacture.
- **activity based costing**: identifies activities in an organisation and allocates the cost of each (e.g. in terms of man-hours, facilities, and materials) to products and services according to their actual consumption.
- **the parametric method:** derives cost estimating relationships (CERs) that can predict cost as a function of the basic attribute(s) of an item (e.g. weight, volume, complexity) [12]. Models in this group include regression analysis, fuzzy logic, and neural networks [13].
- **extrapolation:** particularly for operational and support phases, experience from prior contracts (e.g. spares and repairs) can inform projections of future costs when the incumbent supplier now needs to estimate for follow-on availability contracts.

Selection of the method largely depends on the available data. Relatively new methods such as fuzzy logic and evidence theory [13, 14, 15] are available but have not been widely adopted in industry because the uncertainty in the estimates is too large to assure the supplier of profitability and the customer of affordability. Ideally, more than one method is applied to a given estimating challenge, and this in itself can reduce uncertainty in the prediction of cost.

3.5 Uncertainty in cost estimation

The understanding of the level of uncertainty in the available data, such as a cost estimate, is an important factor in making reasoned decision [16], such as when the customer is choosing between the PSS solutions offered by alternative suppliers.

Well-established techniques have been developed to manage uncertainties in predicted costs that arise during the development and production phases of the PSS lifecycle (e.g. owing to technical, financial, timescale, and quality factors). Much research has applied methods that derive from general probability theory to establish suitable methods for particular scenarios in estimating uncertainty. Uncertainties in predicted costs that arise during the in-service phase have, however, proved more difficult to manage (e.g. owing to obsolescence and supply chain disruption).

Understanding of risk and uncertainty was shaped by social scientists Frank Knight and John M. Keynes who raised definitions for these terms. In 1921 Frank Knight differentiated between them. Risk is concerned with the loss that might arise (e.g. cost, time, or performance) depending on whether a given event may or may not happen. Uncertainty is concerned with events which are certain to happen (e.g. obsolescence) but whose effect is hard to predict (e.g. the number of obsolescence events over the lifetime of the PSS and the cost of their mitigation).

Figure 3, depicts the way in which the accuracy of cost predictions for a given scope of supply, such as the support solution being discussed here, improves over time as the uncertainties are progressively resolved. Such depictions frequently show cost predictions bounded by high (straight line) and low (dotted line) confidence levels, e.g. 90% and 10% respectively.

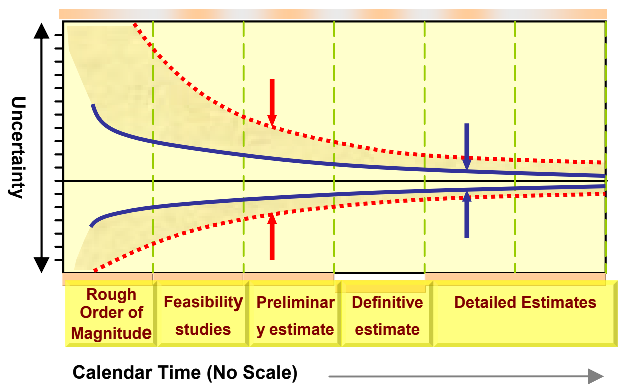

Figure 3. Estimating accuracy trumpet [17]

4 IN-SERVICE PHASE COST UNCERTAINTY: INDUSTRIAL PERSPECTIVE

Interest in becoming service oriented is certainly evident amongst suppliers and customers in the defence and aerospace industries. However, in seeking to devise, negotiate, and deliver availability contracts that are both profitable for the supplier and affordable for the customer, an expanded set of uncertainties need consideration compared with those arising from traditional contracting arrangements. This is driven by the transfer of uncertainties from the customer to the supplier. This section, by taking an industry perspective, aims to highlight current practice in integrating uncertainty into cost estimation, describes the major factors that influence uncertainty in availability contracts, and indicates the key challenges that are faced in the defence and aerospace industries at the bidding stage.

4.1 Current practice in uncertainty and cost estimation at the bidding stage

Based on the industrial interviews it was found that availability contracts 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.

The in-service phase for current contracts typically runs from ten to thirty years but there is often an 'evergreen renewal' arrangement in the terms and conditions which allows the contract to be re-baselined at shorter intervals, typically five years. On each iteration of this interval the estimating uncertainties become smaller as experience of cost outcomes increases and the time to contract completion decreases.

Depending on the concept of the PSS solution, the individual equipments of which it is comprised may have a shorter design life than that of the PSS as a whole. This approach can mitigate problems such as obsolescence at the equipment level provided the successor equipment has the same form, fit and function, i.e. on the "open architecture", "open standards" principle. In these circumstances it can be helpful to consider uncertainties on two levels – first at overall PSS level, and second at equipment level. Furthermore, each level has its own CADMID lifecycle.

For a PSS of significant size (e.g. £100 million or greater in contract value), industry tends to start working on design solution and in-service support solution as long as three to four years before winning a contract, i.e. at the concept or assessment phase of CADMID. During these phases a number of technical and business reviews are conducted to assessing the feasibility, affordability, and profitability of the potential project. These reviews, which take place on a cross-functional basis (e.g. engineering, procurement, operations, commercial, and finance) inform decisions such as "bid / no bid" and whether to accept an availability contract for the manufacturing and in-service support phases if offered.

Cost models are established at the earliest possible phases of the CADMID lifecycle and are evolved as the lifecycle proceeds. Lower levels of detail are progressively added to the design solution and in-service support solution, e.g. by clarifying and elaborating requirements of the PSS with the customer, by performing trade studies to examine design or in-service support solution options, and by producing derived requirements to capture design decisions.

Although it is usually possible to enumerate risks and uncertainties early on in this process, the challenge for industry is to quantify them sufficiently, and with adequate levels of confidence, to support discussions on affordability (with the customer) and profitability (internally and with the supply chain). For example, cost estimates at the concept phase are based on high level assumptions and use parametric or analogy based tools. It is often not until the assessment stage or later, when the maturity of the design is progressing, that it becomes possible to quantify uncertainty by means of the more accurate estimating methods.

This challenge can be characterised slightly differently for each of the bidding scenarios in the UK defence and aerospace industries. These are:

- The competitive situation: the price that the customer agrees is governed by the competition in the market
- The single bid situation: the price is established through negotiation between customer and supplier. This involves the customer having visibility of the supplier's costs and cost-to-price calculation including profit margin.

The trend from traditional contracting towards availability contracting sustains the challenge for suppliers to be confident in the affordability of their offering (e.g. to be assured of both winning the bid in the competitive situation, and of winning the value-for-money argument with the customer in the single bid situation). It has also increased the challenge for them to be confident in their own profitability as a result of the transfer of risk and uncertainty from customer to supplier, particularly in the single bid situation.

The usual response of industry to these challenges is to manage uncertainty using a framework as illustrated in Figure 4. Each step has an overlap with the next and may require individuals to return to previous steps to make updates (e.g. in the light of new data) or to consider new uncertainties that had not been previously identified.

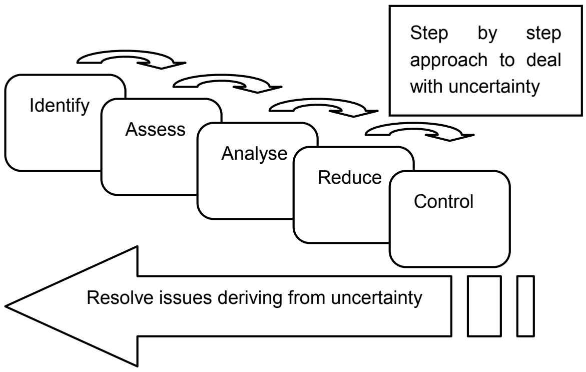

Figure 4. Managing uncertainty

The uncertainty associated with a cost estimate at a terminal node in a CBS is ideally expressed as a probability distribution with "minimum", "maximum" and "most likely" costs and is typically represented as a line item in for example a Microsoft Excel spreadsheet.

The estimate at a terminal node typically refers to an equipment cost in the manufacturing phase of CADMID (e.g. development or manufacture of a "line replaceable unit", a "hardware configuration item", or a "software configuration item"), or a service operation / transaction in the in-service support phase (e.g. spares and repairs).

Equipment costs in the manufacturing phase are typically associated with one-off non-recurring engineering tasks or unit production. They are often aggregated at higher levels of the CBS using Monte Carlo simulation tools such as the riskHive suite [19], the Predict! suite [20], or Crystal Ball [21].

Support costs in the in-service phase typically arise repeatedly. These are often aggregated using tools that can simulate the rate of occurrence. Examples include Vari-Metric [22], OPUS 10 [23], or Tecnomatix PSST [24] which contains a suitable database developed in collaboration with BAE Systems[3].

Estimating practitioners in both the supplier and customer communities have a preference for commercial tools because this simplifies verification and validation of cost models. Unfortunately, commercial tools are not always able to cope with specific circumstances, for example the phased introduction or withdrawal of platforms from a fleet concurrent with mid-life update and/or technology refresh and/or spares scavanging. In this case special-to-purpose models in Microsoft Excel (or similar) are required and investment in verification and validation for these must be accomodated in the cost of bidding.

Although risk management is outside the scope of this paper, functional experts interviewed in the industry highlighted difficulties in segregating uncertainty and risk in cost estimation. This means that, in some instances, risks and uncertainties are incorrectly categorised and may cause unreliable cost estimates. Furthermore, this problem does not only occur when risk registers are first created at the beginning of projects because they may change their categorisation with time. Driven by time constraints (e.g. tight timescales during the bidding phase), some suppliers find that there is insufficient time to analyse risks and uncertainties sufficiently.

4.2 Service uncertainty in availability contracts

Moving from traditional contracts towards those based on availability necessitates consideration of a wider set of uncertainties. There are two major drivers for this:

- Additional uncertainties arising from the in-service phase of CADMID. Under traditional arrangements these additional uncertainties were managed under follow-on contracts signed towards completion of the manufacturing phase (e.g. for spares, repairs, training services, obsolescence management, technology refresh, and disposal). Under availability contracts consideration of uncertainties is bundled and concurrent for both suppliers and customers. There is also the challenge of offering new services that were not traditionally offered (e.g. training).
- Availability contracts also demand 'left shift' of the point-in-time at which some uncertainties are addressed yet the information needed to resolve some of them may not have been developed at bid time (e.g. the design of the support solution cannot be firmed-up before the product solution has been designed, the supplier's initial assumptions on in-service environment have to be clarified and confirmed, and the boundary between supplier and customer responsibilities may not have been negotiated).

These drivers necessitate better consideration of the types of uncertainties at the bidding stage to facilitate cost estimates having the best possible accuracy. Based on interviews with industry the major categories of uncertainties concerned are illustrated in Figure 5.

[3] The PSST tool in combination with the BAE Systems database was formerly known as RAMLOG.

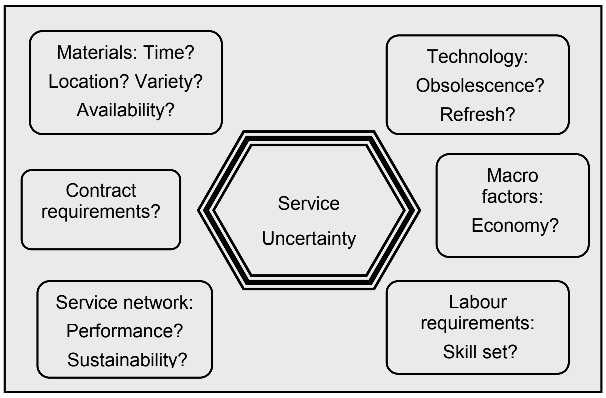

Figure 5. Types of uncertainty

4.3 Challenges in incorporating service uncertainty into cost estimation

Efficient consideration of uncertainty in cost prediction is essential in order that availability contracts can be successfully negotiated and delivered in the future. The evidence from both the literature review and the industrial interviews is that uncertainty is driven by both the lack of information and poor timeliness in its availability. Along with this aspect, provision of new services requires the development of a new knowledge set for suppliers. This section presents a number of key challenges highlighted during interviews:

- Equipment reliability (MTBF), repair time (MTTR), and the demand rate for spares are important sources of uncertainty in the support costs for a PSS. Even if the performance criteria for an availability contract are not directly based on these metrics the uncertainty involved in them will affect performance indirectly. The challenge is to improve prediction of these drivers.
- At all phases of the CADMID cycle, and particularly at the in-service support phase, the ability to deliver the contracted level of performance is highly dependent on the supply network. Sustaining performance of a supply network is a challenging task. Furthermore, the long duration of availability contracts increases the chance of disruption(s) occurring.
- Improved monitoring of supply chain performance would give greater opportunity for proactive intervention before problems arise, and hence reduce uncertainty. This concept is inspired by Earned Value Management (EVM) as applied at the manufacturing phase of the CADMID cycle but the concept will need adaptation for the in-service phase.
- The need for improved estimating techniques that can take account of the increased range and scale of uncertainties typical of availability contracts compared to traditional contracts.
- To be able to agree support based contracts it is necessary to have a common understanding between the customer and the supplier of the uncertainties. This is a particularly challenging aspect which requires a synergy in approaches to consider uncertainties. This may be achieved by means of a common framework utilized to capture uncertainties at the bidding stage.

5 CONCLUSIONS AND FUTURE WORK

The trend towards availability contracting adds to the challenges faced by the defence and aerospace industry in estimating long term contracts with sufficient accuracy. A substantial element of this challenge is the uncertainty that attaches the in-service support phase of the contract which, at the time of bidding, can extend several decades into the future.

To improve understanding of this challenge this project proposes to develop a list of generic uncertainties and potential mitigations that typically apply to availability contracts, and to test this with the industrial collaborators.

At the same time, the suppliers are often invited to take on additional scope such that they increasingly need to take a holistic view of the contracts and focus less on intermediate deliverables and more on overall outcomes. This increase in scope can introduce additional sources of uncertainty.

One of the major sources of uncertainty that lies outside the control of the supplier is supply chain disruption, yet in the limit, the supplier must accept the cost impact of supply chain failures and the responsibility of resolving these. As part of future research the PSS Cost project will develop an estimating framework for availability contracts that encapsulates management of supply chain disruption within the estimating methodology. The research will particularly focus on reflecting the dynamic nature of service supply chains.

6 ACKNOWLEDGMENTS

The authors would like to thank the EPSRC, Cranfield IMRC for funding this research. The continued support given by Industrial Collaborators is also appreciated.

7 REFERENCES

[1] Tukker A., Ursula T., (2006) "Product Service as a research field: past, present and future. Reflections from a decade of research" *Journal of Cleaner Production.* 14(17), pp 1552-1556

[2] Shehab E.M. and Roy R., (2006) "Product-Service Systems: Issues and Challenges", *The 4th International Conference on Manufacturing Research (ICMR 2006)*, Liverpool John Moores University, 5th – 7th September 2006, pp 17-22

[3] Ling D., Roy R., Shehab E., Jaiswal J., Stretch J., (2006) "Modelling the cost of railway asset renewal projects using pair wise comparisons", *Proceedings of the Institution of Mechanical Engineers, Part F, Journal of Rail and Rapid Transit, IMechE,* 220(4), pp 331-346

[4] Mont O., (2002) "Clarifying the concept of Product service system" *Journal of Cleaner Production,* 10, pp 237-245

[5] Ayres R.U., (1998) "Towards a zero emissions economy" *Environment Science Technology*, 32(15), pp 366- 367

[6] Maxwell D., Vorsty R., (2003) "Developing sustainable products and services " *Journal of Cleaner Production,* 11, pp 883-895

[7] Baines T., Lightfoot H., Evans S., Neely A., Greenough R., Peppard J., Roy R., Shehab E., Braganza A. Tiwari, A. Alcock, J. Angus, J. Bastl, M., Cousens A., Irving P., Johnson M., Kingston J., Lockett H. & Martinez V., (2008) "State-of-the-art in product-service systems", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 221 (10), pp 1543-1552

[8] Irene C. L. Ng, 2008, "The pricing and revenue management of service, A strategic approach", Routledge

Advance in Management and Business Studies, Routledge Taylor & Francis Group, pp 81-85

[9] Boussabaine A., Kirkham R., (2004) “Whole Life-cycle Costing: Risk and risk responses” Blackwell Publishing, 1st Edition

[10] Bradley M., Dawson R., (1999) “Whole Life Cost: The Future Trend in Software Development” *Software Quality Journal*, 8, pp 121-131

[11] Asiedu Y., Gu P., (1998) “Product life cycle cost analysis: state of the art review” Internatioal *Journal of Production Research*, 36(4), pp 883-908

[12] Curran R., Raghunathan S., Price M., (2004) “Review of aerospace engineering cost modelling: The genetic causal approach” *Progress in Aerospace Sciences,* 40, pp 487-534

[13] Oberkampf W., Helton J., and Sentz K., (2001), “Mathematical representation of uncertainty”, AIAA Paper 2001-1645, April.

[14] Kishk M., (2004) “Combining various facets of uncertainty in whole-life cost modeling” *Construction Management and Economics*, 22(4), pp 429-435

[15] Harding A., Lowe D., Emsley M., Hickson A. and Duff R., (1999), “The role of neural networks in early stage cost estimation in the 21st century” COBRA 1999: The *Quantitative and qualitative cost estimating for engineering design*“[*Online] Webpage, http://www.rics.org/Practiceareas/Management/Business management/Finance/role_of_neural_networks_19990101.html,* Access date: 12/01/2008

[16] Thunnissen D., (2005), Propagating and Mitigating Uncertainty in the Design of Complex Multidisciplinary Systems, PhD Thesis, California Institute of Technology Pasadena, California

[17] Smart Acquisition 1, Safety and Engineering, “Through life project management” [Online] Webpage, http://www.ams.mod.uk/content/docs/tlmguide/definitn.htm, (Access date: 17/12/07)

[18] Baines T. S., Asch R., Hadfield L., Mason J. P., Fletcher S., Kay J. K., (2005), “Towards a theoretical framework for human performance modelling within manufacturing systems design”, *Simulation Modelling Practice and Theory*, 13, pp 486-504

[19] riskHive suite, [Online] Webpage, http://www.riskhive.com/,(Access date: 10/10/2008

[20] Predict! Suite, [Online] Webpage, http://www.riskdecisions.com/, (Access date: 10/10/2008)

[21] Crystal Ball, [Online] Webpage, http://www.oracle.com/crystalball/, (Access date: 10/10/2008)

[22] Zamperini M. B., Freimer M., (2005), “A simulation analysis of the vari-metric repairable inventory optimization procedure for the U.S. Coast Guard”, *Proceedings of the Winter Simulation Conference,* 4-7 December 2005.

[23] OPUS 10, [Online] Webpage, http://www.systecon.se, (Access date: 10/10/2008)

[24] Tecnomatix PSST, [Online] Webpage, http://www.plm.automation.siemens.com/en_us/products/tecnomatix, (Access date: 11/10/2008)