System Modeling: A Foundation for Costing Through-Life Availability Provision

Ettore Settanni, Nils Thenent, Linda Newnes

System Modeling: a Foundation for Costing Through-life Availability Provision

Ettore Settanni, Nils E. Thenent, Linda B. Newnes

Department of Mechanical Engineering, University of Bath, United Kingdom

E.Settanni@bath.ac.uk

Abstract Under performance-guaranteeing contracts, such as availability-based contracts, the Original Equipment Manufacturers (OEMs) have become increasingly concerned with understanding and managing the cost of their commitment to deliver specific results to customer through-life. However, current approaches to cost estimating hardly offer more than sheer claims of the existence of a link between cost and organizational performance – no matter whether products, services or product-service-systems (PSS) are at stake. This paper presents an intermediate step towards a computational structure explicitly linking cost and performance for PSS. A PSS is represented formally as a system combining assets and activities delivering the results OEMs are committed to through-life. Inter-temporal aspects of PSS provision which typically define the successful delivery of an asset's availability are taken into account. Network formalism and principles derived from Input-Output Analysis are employed to base PSS cost estimation on a representation of a PSS as a 'system'.

Keywords: Product-Service-System, Availability contracts, Through-life costing, Systems, Input-Output Analysis, Defence aerospace.

1. Introduction

Availability-based contracts that provide incentives to guarantee the usability of engineering systems are seen as a desirable alternative to purchasing individual items and then supplementing them with support arrangements [1]. An Original Equipment Manufacturer (OEM) – if not a third party service provider – takes responsibility for all or most of the cost of delivering a result to the customer by means of a combination of assets and through-life activities commonly referred to as Product Service Systems (PSS) [2].

An in-depth analysis of the Through-life Costing (TLC) literature has highlighted the methodological challenges arising from PSSs [3]. To summarize, the current approaches to estimate the cost of PSS deal with one cost object at a time, i.e. one product or service characterized by a set of features, and assume that all the relevant costs directly relate to it. They fail to recognize that 1) the results delivered by a PSS are not just designed into an individual end-item. Rather, performance is attained through the actions a business undertakes, their effectiveness and efficiency; and 2) in the presence of multiple deliverables within certain organizational boundaries, the consequence of a series of decisions taken independently is not necessarily the sum of the effects of each individual decision, and may not result in an immediately observable change in cash flows.

This research illustrates an intermediate step towards a computational structure for costing PSS concerned with the formalized system representation in TLC. Unlike product-by-product analysis incumbent in TLC, performance is rendered in terms of undertaken actions, their purposes, the output delivered and necessary preconditions. In this way, performance and cost can be linked in the flow of work through an organizational system, and dealt with simultaneously. In the remainder of this paper, the need for a 'system' approach is discussed first. Then, the principles for obtaining a mathematically treatable representation of the system investigated that can be used for PSS costing are detailed. Additional steps from system representation to PSS costing are left to further research.

2. Need for a 'System' Approach

The concept of PSS embeds that of 'system'. A system is a combination of interacting elements organized to achieve one or more stated purposes. Within a PSS the relevant system is what delivers the results OEMs are committed to as an outcome of a specific combination of assets and through-life activities. Examples include complex engineering services such as providing the availability of aircraft or major aircraft sub-systems [4].

For the purpose of cost estimation a system – even a PSS – tends to be entirely characterized in terms of the architecture and properties of the physical entities needed to carry out the system's functions. Less attention is paid to another domain, called the 'process' domain, which is essential when trying to understand certain system behaviors. It concerns the actions or operations performed within or by the system and their mutual relationships [5]. System-thinking and process-thinking are indeed intertwined [6]. This is evident especially for service processes [7], and PSS [8]. Also, a formalized system representation often relies on process representation techniques – including IDEF0, UML and Petri Networks to mention but a few [9]. Ma et al. [10] summarize the advantages and disadvantages for a variety of such representation techniques with a service operations outlook. In the field of cost estimation a system approach is often claimed. However, it is not the case that formal system representation and modeling always play an explicit role in the cost analysis (see [11]). In the absence of a formalized system approach, priority is given to chasing accurate cost estimates in the same way as 'goodness of fit' is chased in forecasting uncontrollable external events [12] (see for example [13]).

Linking system/process-thinking and cost becomes more important if the aim in cost estimation is to improve cost consciousness i.e., consciousness of the cost implications of the actions taken [14]. When cost consciousness is at stake, cost is no longer deemed an intrinsic property of e.g., a product or service. Rather, it is an "emergent property" of the context in which products or services are designed and delivered [15]. Hence, the primary rationale for developing a cost model becomes to translate the interrelated consequences of changes occurring in such a context into cost metrics, through a consistent and transparent representation of that context.

Causal understanding has to precede the estimate of costs. The development of such an understanding rests on the representation of the quantitative flow of goods and services delivered by organizations, whereas money serves as a meta-language merely providing a value representation of that flow [16]. Based on the flow of goods and services the virtual cost flow paths within stated organizational boundaries can be determined [17].

Research on system/process-thinking in TLC is rather sparse. Only a few TLC studies conceptually identify a system through means-ends relationships between the operations or activities performed within or by that system [18, 19]. Applications include defense aerospace [20], and PSS [21]. In most cases, however, there is lack of published detail on how the links and mutual dependencies between the operations or activities constituting the system affect the computation of cost. To overcome these limitations, TLC can be based on a technological model of the enterprise or supply chain, implemented through the formalism of Input Output Analysis (IOA) [22].

A technological model is a model which relates to the notion of technological knowledge as detailed process understanding [23]. IOA has been originally meant to represent economic systems such as whole national economies. However, IOA can also handle particularly intricate technical-economic systems consisting of mutually interconnected stages, such as production-inventory systems [24], thus making it potentially suitable for modeling such a PSS as the provision of availability. The theory of IOA owes greatly to Nobel Laureate Wassilly Leontief, whose belief that "…partial analysis cannot provide a sufficiently broad basis for fundamental understanding", coexisted with that that uncritical enthusiasm for formidable mathematical formulation is too often prone to concealing lack of substantive content. IOA guarantees a balance between formalization, which is important for general validity to be proved mathematically, and computability, which is important for relevance to be proved empirically [25].

3. A System Representation for PSS Cost Estimation

Prior to estimating cost an understanding of the causal relationships has to be developed. This is a matter of formally representing a PSS as a 'system' i.e., identifying the boundaries and scope of the analysis; and within those boundaries the actions taken, their dependencies, the input resources required and the outputs delivered by each action. Inputs and outputs leading to the outcome(s) the system is meant to achieve can be "goods" (products or services) or "bads" (by-products or 'waste') [17].

For illustrative purposes, consider a hypothetical PSS delivering the availability of end-items such as military aircraft (A/C) [26], or A/C LRUs (Line Replaceable Units). As an example, Fig. 1 illustrates a range of outcomes that such a PSS may deliver in the case of a Multi-functional Display (MfD), and where this research stands. Focus is on the sustainment of end-items (the provision of which remains outside the system boundaries), the aim of which is guaranteeing they are in operable and committable state for certain missions (also outside the system boundaries) over a certain time-span.

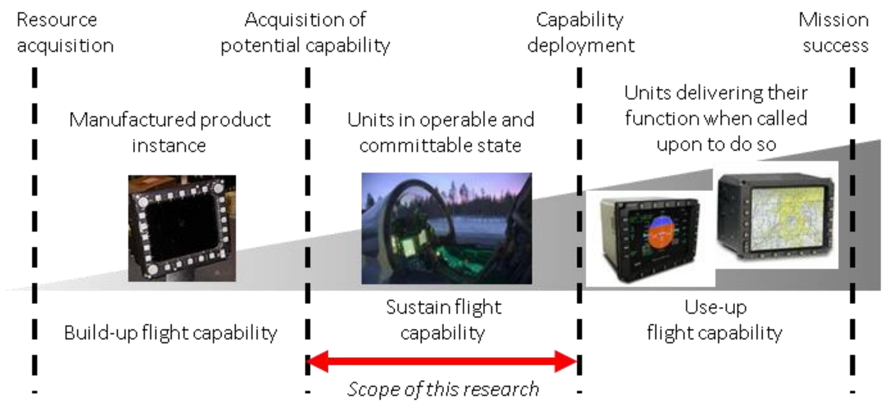

Fig. 1. Example of PSS deliverables for MfD availability.

Fig. 2 shows the structure of the main end-item involved in the PSS. Proceeding clockwise, it shows the structure of the sustaining operations delivering the availability of such an item in terms of means-ends – or supply-demand – relationships using IDEF0. At this stage, the aim is to provide a structured representation of the modeled system without committing to a specific modeling language (e.g, SysML etc.).

First, a single-block context diagram defines the boundaries and scope of the system studied. Outside the boundaries are the exogenous factors i.e., those factors the provision of which is not deemed controllable, and hence left outside the analysis. Not only goods and services may be acquired from outside the system boundaries, but also conditions may be externally imposed on the system functioning, and the system's functions may be delivered outside its boundary. Then, the context diagram is detailed progressively through child diagrams. All the items involved, as well as the flows between the activities the PSS consists of, can be expressed in terms of a common, fictitious metric called 'capability units' – *c.u*.

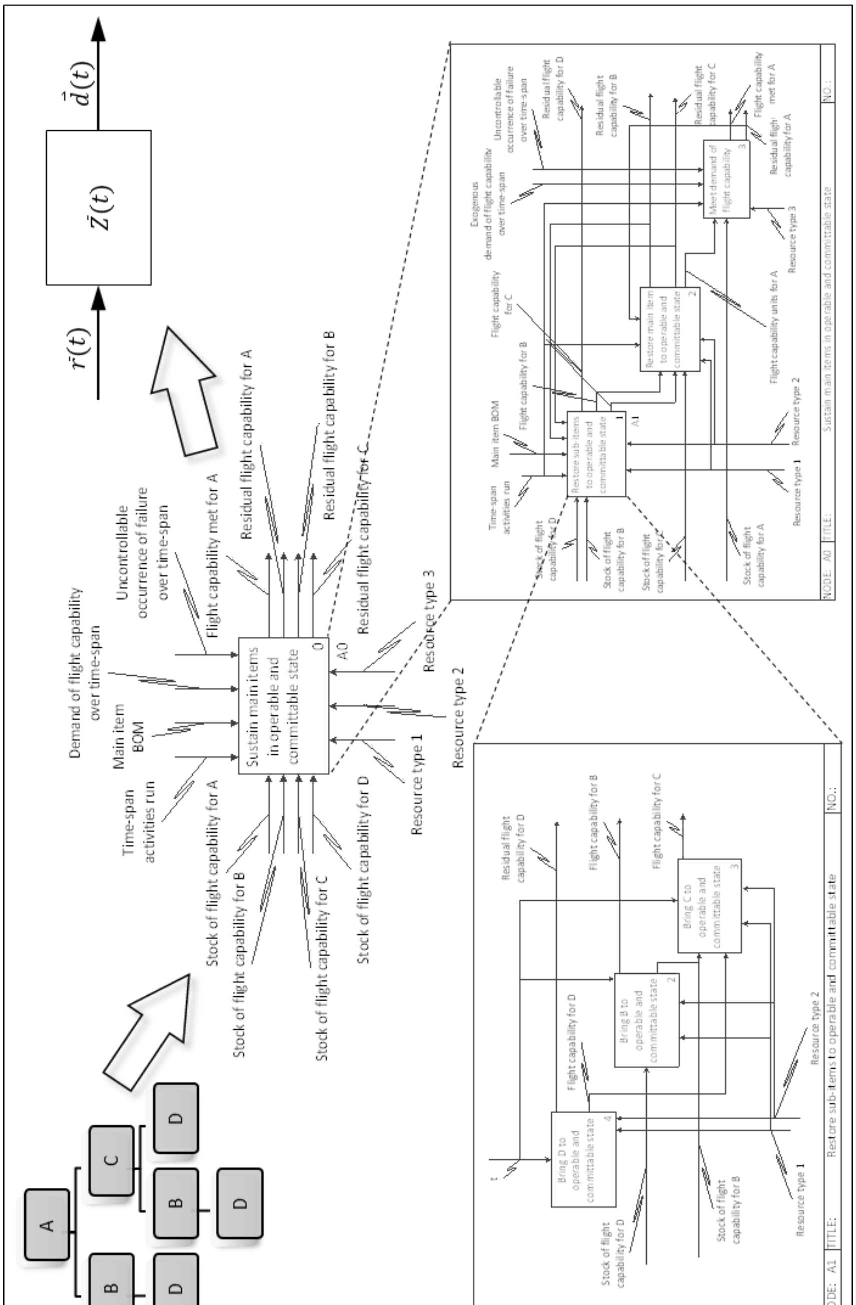

Fig. 2. From product structure, through an IDEF0 PSS representation, to time dimension.

Capability units may be thought of as flyable hours (sorties, cycles etc.) equivalent to a top-level item (whole A/C or LRU) or sub-items. For example, a fleet of two A/C each of which has a life-cycle capability of flying 2 missions worth 25c.u. can be pooled as an initial "stock" of 100c.u. at time "zero". If a mission having duration 1 time unit is called at time 1, and nothing goes wrong the stock is depleted of 25c.u. leaving a residual capability of 75c.u. A failure occurrence (assumed here to be a completely uncontrollable event) when the mission is called again, would deplete the stock of capability of 50c.u. instead (i.e., one grounded A/C and one spare A/C flying the mission). In this sense, a failure acts like an additional (although wasteful) "demand" of capability. Shortage of capability triggers activities generating more capability units – e.g., by restoring the main item or sub-items into an operable and committable stage.

Although each activity has its lead time, activities are not time-phased in an IDEF0 blueprint. The latter can be thought of as a "picture" of a system taken using a conveniently long "exposure time", which corresponds to the system's total active period i.e., the time-span these activities run. In the presence of non-zero lead times, however, activities must be triggered a number of time units in advance of the time a certain demand of flight capabilities occurs. To introduce this dynamics, an Input-Output based production-inventory system for multi-indenture items [24] is adapted to the PSS of interest. The model is modified so that 1) it fits a specific framework for IOA known as "supply-use"; and 2) dynamics is induced similarly to the time-distributed systems' activities approach in IOA [27]. Only discrete time is of interest here.

Let n be the number of activities the PSS is composed of. Let θ_j be the lead time for the j-th activity $(j = 1 \dots n)$**.** Let τ be the total active period's length. For each discrete time t $(0 < t \leq \tau)$ the relevant system can be described in terms of the following multi-period balance of quantities:

$$\mathbf{r}(t-1) + \mathbf{V}_t(0)\mathbf{s}(t) = \sum_p \mathbf{U}_{t-p}(p)\mathbf{s}(t-p) + \mathbf{y}_t + \mathbf{r}(t) \qquad (1)$$

where p is the time lag ($-\theta \leq p \leq 0$, $\theta = max\{\theta_j\}$), and $t-p$ is the delivery time ($0 < (t-p) \leq \tau$).

The $n \times n$ time-distributed "*use*" matrix $\mathbf{U}_{t-p}(p) \equiv \left[u_{ij}(t) \cdot \delta_{\theta_j,-p}\right]_{n\times n}$ records for each activity j its direct requirements of input i $(i = 1 \dots n)$ supplied by another activity within the system $|p|$ time units prior to the delivery time $t-p$ i.e., at time *t*. The corresponding quantity $u_{ij}(t)$ is then multiplied by the Kroneker symbol taking values $\delta_{\theta_j,-p} = 1$ if $\theta_j = -p$ and 0 otherwise. The $n \times n$ time-distributed "*supply*" matrix $\mathbf{V}_t(0) \equiv \left[v_{ij}(t)\right]_{n\times n}$ records for each activity j its gross output of i delivered at time *t*. By assumption, an activity's output is entirely delivered θ_j time units ahead the fulfillment of the necessary preconditions (e.g., the provision of inputs). These matrices recording supply and use flows can be combined to give the system's net output as follows:

$$\begin{cases} \mathbf{Z}_t(0) = [\mathbf{V}_t(0) - \mathbf{U}_t(0)] & \text{for } p = 0 \\ \mathbf{Z}_t(-p) = [-\mathbf{U}_{t-p}(p)] & \text{for } -\theta \le p < 0 \end{cases}$$

The $n \times 1$ vectors $\mathbf{r}(t-1)$ and $\mathbf{r}(t)$ are, respectively, the beginning and final inventories of each activity's outputs at time *t*. For $t = 1$ the values of the beginning inventory $\mathbf{r}(0)$ are known and serve as initial conditions. The $n \times 1$ vectors $\mathbf{s}(t-p)$ and $\mathbf{s}(t)$ are the unknown activity levels at each delivery time, and at each time *t* respectively. Finally, the $n \times 1$ vector $\mathbf{y}_t$ is the demand of system's outcomes imposed exogenously at each time *t*. In our case it should be further distinguished into 'good' demand of units in operable and committable state, and 'bad' demand due to e.g., failures: $\mathbf{y}_t = \mathbf{y}_t^G + \mathbf{y}_t^F$. Equation (1) is developed for $t = 1 \dots \tau$. Let $\mathbf{I}$ be an $n \times n$ identity matrix and $\mathbf{0}$ a null matrix of appropriate dimensions:

$$\begin{bmatrix} \mathbf{Z}_1(0) & \mathbf{Z}_1(1) & \cdots & \mathbf{Z}_1(t-1) & \cdots & \mathbf{Z}_1(\tau-1) & -\mathbf{I} & & & & & & \\ & \mathbf{Z}_2(0) & \cdots & \mathbf{Z}_1(t-2) & \cdots & \mathbf{Z}_1(\tau-2) & \mathbf{I} & -\mathbf{I} & & & & \mathbf{0} & \\ & & \ddots & \vdots & & \vdots & & \ddots & \ddots & & & & \\ & & & \mathbf{Z}_t(0) & & \mathbf{Z}_1(\tau-t) & & & & \mathbf{I} & -\mathbf{I} & & \\ & \mathbf{0} & & & \ddots & \vdots & & & & & \ddots & \ddots & \\ & & & & & \mathbf{Z}_\tau(0) & & \mathbf{0} & & & & \mathbf{I} & -\mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{s}(1) \\ \mathbf{s}(2) \\ \vdots \\ \mathbf{s}(t) \\ \vdots \\ \mathbf{s}(\tau) \\ \mathbf{r}(1) \\ \mathbf{r}(2) \\ \vdots \\ \mathbf{r}(t) \\ \vdots \\ \mathbf{r}(\tau) \end{bmatrix} = \begin{bmatrix} \mathbf{y}_1 - \mathbf{r}(0) \\ \mathbf{y}_2 \\ \vdots \\ \mathbf{y}_t \\ \vdots \\ \mathbf{y}_\tau \end{bmatrix}$$

or, in compact terms:

$$[\mathbf{Z} \quad \mathbf{\Phi}] \begin{bmatrix} \mathbf{s} \\ \mathbf{r} \end{bmatrix} = \mathbf{d} \tag{2}$$

The problem becomes finding the elements of $\mathbf{s}$ as the minimum nonnegative integers such that the entries of $\mathbf{r}$ are non-negative:

$$\begin{aligned} &\text{minimize } \mathbf{z} = \mathbf{1} \cdot \mathbf{s}(1) + \cdots + \mathbf{1} \cdot \mathbf{s}(\tau) + \mathbf{0} \cdot \mathbf{r}(1) + \cdots + \mathbf{0} \cdot \mathbf{r}(\tau) \\ &\text{subject to:} \\ &\begin{bmatrix} \mathbf{Z} & \mathbf{\Phi} \\ \mathbf{F} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{s} \\ \mathbf{r} \end{bmatrix} = \begin{bmatrix} \mathbf{d} \\ \mathbf{0} \end{bmatrix} \\ &\mathbf{s} = \text{integer} \\ &\mathbf{s} \ge \mathbf{0}; \mathbf{r} \ge \mathbf{0} \end{aligned}$$

where $\mathbf{1}$ is a unity vector of appropriate dimension. $\mathbf{F}$ is a matrix of the same size as $\mathbf{Z}$, which contains a set of constraints. These constraints are such that an activity *j* cannot deliver its output unless there is time for doing so. For $t = 1 \dots \theta$ diagonal matrix $\mathbf{D}_t \equiv [d_{jj}]$ is defined such that $d_{jj} = 1$ if $\theta_j \le t - 1$ and zero otherwise. Hence: $\mathbf{F} = \begin{bmatrix} \mathbf{Z}_1(0) \cdot \mathbf{D}_1 & \cdots & \mathbf{0} & \\ \vdots & \ddots & \vdots & \mathbf{0} \\ \mathbf{0} & \dots & \mathbf{Z}_\theta(0) \cdot \mathbf{D}_\theta & \end{bmatrix}$

Alternative approaches to the multistage, mixed-integer linear programming used here (e.g. [24]) can be more effective for the mathematically literate, yet less practical to implement e.g., using spreadsheets. The algorithm can be applied to the example in Fig. 2. The example features a PSS consisting of four activities ($n = 4$). Each activity brings either the main-item (A) or the sub-items it is made of (B, C, D) into an operable and committable state. Assuming for simplicity the use matrix remains constant over time $\left[u_{ij}(t)\right]_{n\times n} = \left[u_{ij}\right]_{n\times n}$ and so does the supply matrix $\left[v_{ij}(t)\right]_{n\times n} = \left[v_{ij}\right]_{n\times n}$ the following hypothetical numerical values (all expressed in *c.u.*) are assumed:

$$\left[u_{ij}\right]_{n\times n} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{bmatrix} 0 & 0 & 0 & 0 \\ 800 & 0 & 0 & 0 \\ 400 & 600 & 0 & 0 \\ 0 & 1200 & 1700 & 0 \end{bmatrix} \end{array}; \quad \left[v_{ij}\right]_{n\times n} = \begin{array}{c} \\ A \\ B \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cccc} A & B & C & D \end{array} \\ \begin{bmatrix} 200 & 0 & 0 & 0 \\ 0 & 600 & 0 & 0 \\ 0 & 0 & 850 & 0 \\ 0 & 0 & 0 & 900 \end{bmatrix} \end{array}$$

The beginning inventories for each item in terms (all expressed in *c.u.*) are $\mathbf{r}(0) = [170 \quad 920 \quad 2650 \quad 4800]^T$. (Superscript T means matrix or vector transposition). Finally, the hypothetical values for the lead times of each activity (expressed in discrete time units) are $\left[\theta_j\right]_{1\times n} = [2 \quad 1 \quad 3 \quad 2]$. Fig. 3 shows the values for activity levels $\mathbf{s}$ and capability stock levels $\mathbf{r}$ given the exogenous demand for flight capability (including "bad" one i.e., due to thing going wrong) shown at the bottom (for the main item only), over a discrete time-span ($\tau = 8$).

4. Conclusion and Need for Future Work

This research lays the foundation of an original, formalized system representation for use as a preliminary step for PSS costing. It draws on principles developed in disciplines like IOA and inventory modeling, which are not taken into account in current approaches to PSS cost estimation. The insights associated with a rigorous and transparent quantitative approach to model PSS as 'systems' are meant to support the improvement of *cost consciousness*.

The approach developed here requires a distinction between what can, or has to be included within the system's boundaries, and what is deemed exogenous to the system and hence uncontrollable. The focus on the provision of flight capability and the introduction of *c.u.* as fictitious units represents an assumption. However, it has allowed to show how the principles of inventory modeling which are well-developed for products apply to more generic "functional units", suitable for representing the intermediate and final results delivered by a PSS. The approach that has been illustrated here is in generic form, and is taking a deterministic standpoint. Topics of co-production and inefficiencies/waste generation have been left aside.

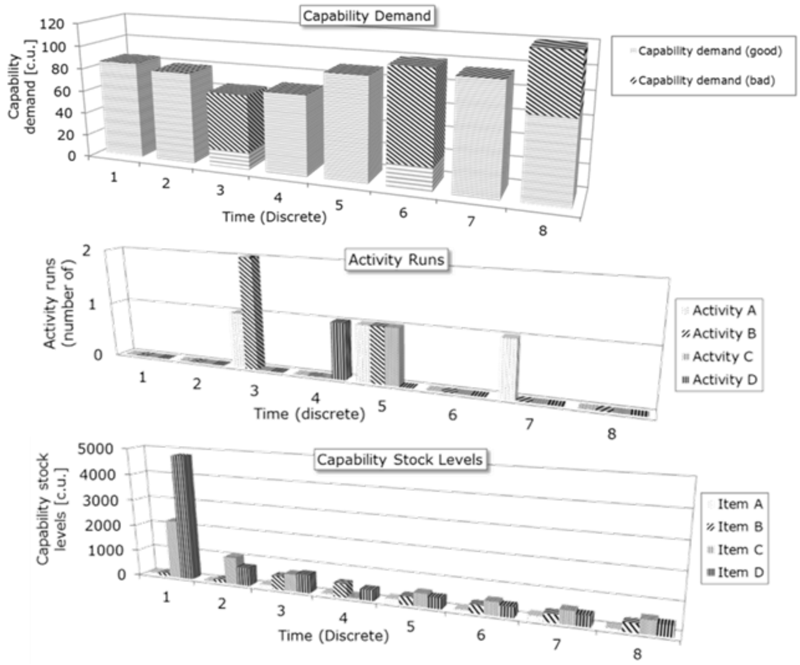

Fig. 3. Inter-temporal behavior of hypothetical PSS: main aspects.

These aspects can be taken into account as the basic model presented here grows into a costing model consistent with the Input-Output technological approach to TLC suggested in the field of sustainability management by [22]. Further work is necessary to address potentials and limitation of the proposed model through its application to an industrial context. Future research must also address what needs to be known about a PSS, for example, in order to link concepts such as technological maturity and obsolescence to changes over time of the technological knowledge about the system's inputs and outputs.

Acknowledgments The authors gratefully acknowledge the support provided by the Department of Mechanical Engineering at the University of Bath, the Innovative electronics Manufacturing Research Centre (IeMRC) and the Engineering and Physical Sciences Research Council (EPSRC) for funding the research.

References

1. Meier, H., Roy, R., Seliger, G.: Industrial Product-Service Systems—IPS2. CIRP Ann-Manuf. Technol. 59, 607–627 (2010)
2. Tukker, A., Tischner, U.: Product-services as a research field: past, present and future. J Clean Prod 14, 1552–1556 (2006)
3. Settanni, E., Newnes, L.B., Parry, G.C., Goh, Y.M.: A conceptual model to address the methodological challenges of costing through-life availability. Working paper (2011)

4. Ng, I.C.L., Parry, G.C., Wild, P., McFarlane, D., Tasker, P. (eds.): Complex engineering service systems. Concepts and research. Springer, Berlin (2011)
5. Bartolomei, J.E., Hastings, D.E., Neufville, R. de, Rhodes, D.H.: Engineering Systems Multiple-Domain Matrix: An organizing framework for modeling large-scale complex systems. Syst. Engin. 15, 41–61 (2012)
6. Emblemsvåg, J., Bras, B.: Process thinking — a new paradigm for science and engineering. Futures 32, 635–654 (2000)
7. Batista, L., Smart, A., Maull, R.: The systemic perspective of service processes: underlying theory, architecture and approach. Production Planning & Control 19, 535–544 (2008)
8. Kim, Y.S., Lee, S.W., Koh, D.C.: Representing product-service systems with product and service elements. In: Howard, T.J., McAloone, T.C., Hansen, C.T. (eds.) Proceedings of the 18th International Conference on Engineering Design (2011)
9. Aguilar-Saven, R.S.: Business process modelling: Review and framework. Int J Prod Econ 90, 129–149 (2004)
10. Ma, Q., Tseng, M.M., Yen, B.: A generic model and design representation technique of service products. Technovation 22, 15–39 (2002)
11. Valerdi, R.: Heuristics for Systems Engineering Cost Estimation. IEEE Systems Journal, 5, 91–98 (2011)
12. Makridakis, S.G., Wheelwright, S.C., Hyndman, R.J.: Forecasting. Methods and applications, 3rd edn. John Wiley & Sons, New York (1998)
13. Roy, R.: Cost engineering: why, what and how? Decision Engineering Report Series, Cranfield University (2003)
14. Lindholm, A., Suomala, P.: Learning by costing: Sharpening cost image through life cycle costing? International Int J Prod Perform Manag 56, 651–672 (2007)
15. Field, F., Kirchain, R., Roth, R.: Process cost modeling: Strategic engineering and economic evaluation of materials technologies. JOM-J Min Met Mat S 59, 21–32 (2007)
16. van der Merwe, A.: Management accounting philosophy II: The cornerstones of restoration. Cost Management 21, 26–33 (2007)
17. Möller, A.: Material and Energy Flow-Based Cost Accounting. Chem Eng Technol 33, 567–572 (2010)
18. Emblemsvåg, J.: Life-cycle costing. Using activity-based costing and Monte Carlo methods to manage future costs and risks. Wiley, Hoboken, N.J (2003)
19. Mévellec, P., Perry, N.: Whole life-cycle costs: a new approach. International Journal of Product Lifecycle Management 1, 400–414 (2006)
20. Davis, N., Jones, J., Warrington, L.: A framework for documenting and analyzing life-cycle costs using a simple network based representation. In: Proceedings of the Reliability and Maintainability Symposium, pp. 232–236. (2003)
21. Kimita, K.: Cost evaluation method for service design based on Activity Based Costing. In: Proceedings of the 7th International Conference on Manufacturing Research (2009)
22. Settanni, E., Tassielli, G., Notarnicola, B.: An Input–Output technological model of Life Cycle Costing: computational aspects and implementation issues in a generalised supply chain perspective. In: Burritt, R., et al. (eds.) Environmental Management Accounting and Supply Chain Management, pp. 55–109. Springer, Dordrecht (2011)
23. Bohn, R.E.: Measuring and Managing Technological Knowledge. Sloan Manage Rev 36, 61–73 (1994)
24. Grubbstrom, R.W., Tang, O.: An Overview of Input-Output Analysis Applied to Production-Inventory Systems. Economic Systems Research 12, 3–25 (2000)
25. Augusztinovics, M.: What Input-Output is about. Structural Change and Economic Dynamics 6, 271–277 (1995)
26. Hollick, L.J.: Achieving shared accountability for operational availability attainment. In: Proceedings of the Reliability and Maintainability Symposium, pp. 247–252 (2009)
27. ten Raa, T.: The economics of input-output analysis. Cambridge University Press, Cambridge (2005)