Through-life costing methodology for use in product-service-systems

Article Classification: Research paper

Abstract

Availability-based contracts which provide customers with the use of assets are increasingly offered as an alternative to the purchase of an asset and separate support contracts. The cost of servicing a durable product is addressed by Through-life Costing (TLC). Providers are now concerned with the cost of delivering outcomes which meet customer requirement using combinations of assets and activities via Product Service System (PSS). This paper addresses the question: To what extent are the current approaches to TLC methodologically appropriate for costing the provision of advanced services, particularly availability, through a PSS? A novel methodology for TLC is outlined addressing the challenges of PSS cost assessment to the 'what?' (cost object), 'why/to what extent?' (scope and boundaries), and 'how?' (computations). Qualitative methods provide a preliminary understanding of how the actions undertaken within the boundaries of the enterprise system enable or hinder service delivery. The principles of Input-Output Analysis are used to produce a mathematically treatable counterpart of the qualitative PSS representation which preserves the system structure. The research provides clarity for those costing availability in a performance-orientated contractual setting and provides insight to the measures that may be associated with it. Whilst seeking to ensure generality of the findings, the application of TLC examined here is limited to a military aircraft platform and subsystems.

Keywords:

Through-life costing; product-service systems; cost estimation; availability contracting; defence and aerospace; input-output analysis

1 Introduction

Through-Life Costing (TLC) has its roots in defence procurement practices and has been extensively applied across several fields (Korpi and Ala-Risku, 2008). Typically, TLC begins with the identification of a long-life asset such as a building, aircraft, a piece of equipment, or one of their constituent parts. With the asset acting as the centre point, a one-off appraisal of the disbursements associated with its acquisition and existence over a time span is carried out (Dhillon, 2010). TLC often involves the designer forecasting how much alternative product concepts should cost as a direct consequence of their features, focussing upon those related to inherent reliability (Newnes et al., 2008). A common assumption in TLC is that the distinction between the Original Equipment Manufacturer (OEM) and its customer's responsibilities for product acquisition and ownership is clear-cut and therefore so are the cost items of concern (Chen and Keys, 2009). Such logic reflects a business context in which the OEM's responsibility is to design and manufacture a product, whilst equipment failure when with the customer provides an additional revenue stream for the OEM after sales and support service. The 'product and support' business model incentivises a 'throw it over the wall' approach with respect to the customer, and is detrimental to product reliability (Caldwell and Settle, 2011).

There have been attempts to challenge the established business model described. With reference to military equipment, it has long been noted that allowing the purchaser's viewpoint to be represented only when contractual reliability requirements are specified does not ensure a satisfactory final deliverable per se (Perrigo and Easterday, 1974). Integrated Logistic Support (ILS) emphases the ability of a weapon system to deliver the output for which it is designed (Galloway, 1996). Long-term service agreements incentivise the usability of an asset while covering all or most of the costs associated with support activities (BS EN IEC, 2009). In particular, availability-based contracts aim to guarantee that an asset performs its function when called upon to do so, and typically uses the ratio between satisfactory operations to downtime as a metric (Jazouli and Sandborn, 2011). Availability-based contracts are increasingly used by engineering OEMs. For example, Rolls-Royce Plc.'s move from selling aircraft engines to selling the availability of its engines has been has been acknowledged as a success story that "…could offer lessons for Britain's other industries" (The Economist, 2011). Similar agreements are also re-shaping the approach to procuring industrial machinery (Hypko et al., 2010), and the development of infrastructure projects through Public-Private Partnerships (Sharma and Cui, 2012).

An advanced service sustains the customers' core business processes and the service delivery system enabling the customer to attain specific beneficial outcomes becomes just as important as the offering itself (Ng et al., 2011; Baines and Lightfoot, 2013). This construct is a knowledge-intensive socio-technical system referred to as Product-Service-System – PSS (Meier et al., 2010).

An OEM transforming to a service provider is concerned with the cost of delivering a result through a PSS (Tukker and Tischner, 2006), for example agreed availability or other performance levels over time. TLC often includes complementary non-monetary performance metrics such as the availability of an item (Ntuen and Moore (1985) provide an early overview). However, attention is placed on a stand-alone product unit and its reliability features which it is assumed, once designed-in, will hold indefinitely. How a product instance operates, fails and is restored to operation is typically described by means of time distributions. Essentially, for modelling purposes the product unit is stripped of its broader delivery, use and support context. Neely (2005) illustrates that performance is attained through a business's actions, their effectiveness (the extent to which customer requirements are met) and efficiency (how economically the resources are utilised). From this perspective the cost of performance is not designed into a product, rather, it is the cost of doing something 'right' from the customer's point of view (e.g. delivering value 'in use' through an outcome – see Ng et al. (2011)), or dealing with the consequences of failing to do so. As such, cost is contained in the flow of work through the organisational system (Seddon et al., 2011).

When dealing with advanced services, in particular availability, provided via PSS academic literature focuses exclusively on the cost of the in-service stage of an individual durable product, without questioning and enriching substantially the overall methodology of TLC. Datta et al. (2010) provide extensive discussion and a framework, but suggest combinations of existing cost estimation techniques for use at a particular product-accompanying service lifecycle stage. Huang et al. (2012) analyse these techniques and identify the challenges of adapting them for the purpose of service cost estimation. In both cases TLC is not presented as an autonomous methodology but is the result of the application of different cost estimating techniques. The distinction between methodology and technique is relevant. Methodology is concerned with 'thinking about how to think', guiding the intellectual process of choosing concepts and deciding how they might be structured, whilst techniques are well-defined ways of 'going about' a problem: like cookbooks, if followed will produce a defined outcome (Wilson, 2001).

The purpose of the research presented in this paper is twofold: first to ascertain whether and to what extent the TLC literature provides sufficient methodological foundation in the case of costing an advanced service delivered by a PSS, particularly availability; and second to outline a methodology for TLC, addressing the challenges of PSS cost assessment related to the '*what?*' (cost object), '*why/to what extent?*' (scope and boundaries), and '*how?*' (computations and metrics). In line with the principles of formal conceptual definitions in operations management (Wacker, 2004), the expected benefit of this research is to avoid that empirical work develops around an ill-defined concept of TLC in availability contracting.

The remainder of this paper is structured as follows. Section 2 presents the research questions and strategy. Sections 3 summarises the state-of-the-art in TLC. Section 4 identifies the challenges of costing advanced services provided through a PSS, and analyses the TLC literature accordingly. In section 5 the findings are discussed and a methodology of TLC outlined. Section 6 summarises the contribution and limitations of this research and links to future work.

2 Research questions and strategy

This paper answers the following research questions:

> *RQ1*: To what extent are the concepts and structures embedded in the prevailing approaches to through-life costing appropriate for costing the provision of advanced services, particularly availability, through a product-service-system?
>
> *RQ2*: How should the intellectual processes of through-life costing for use in product-service-systems look like?

The research strategy followed to address the research questions is shown in Figure 1, and can be summarised in two main steps:

(1) Provide analysis and synthesis of an extended body of literature on TLC at the interface between key fields – management, design and engineering. Both narrative (tables) and meta-synthesis are used to enable comparison between strands of literature which are heterogeneous in terms of methodologies and concepts (Tranfield et al., 2003).

(2) Build on the identified aspects of providing advanced service through a PSS which are a challenge for TLC to set guidelines which stimulate the intellectual process of analysis (Wilson, 2001), and provide directions for future research (Webster and Watson, 2002).

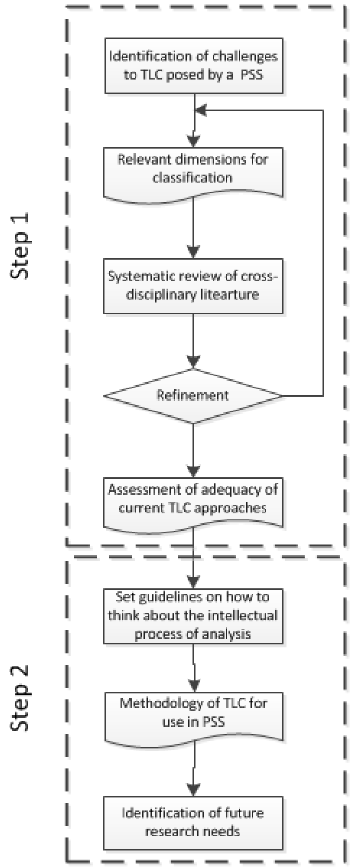
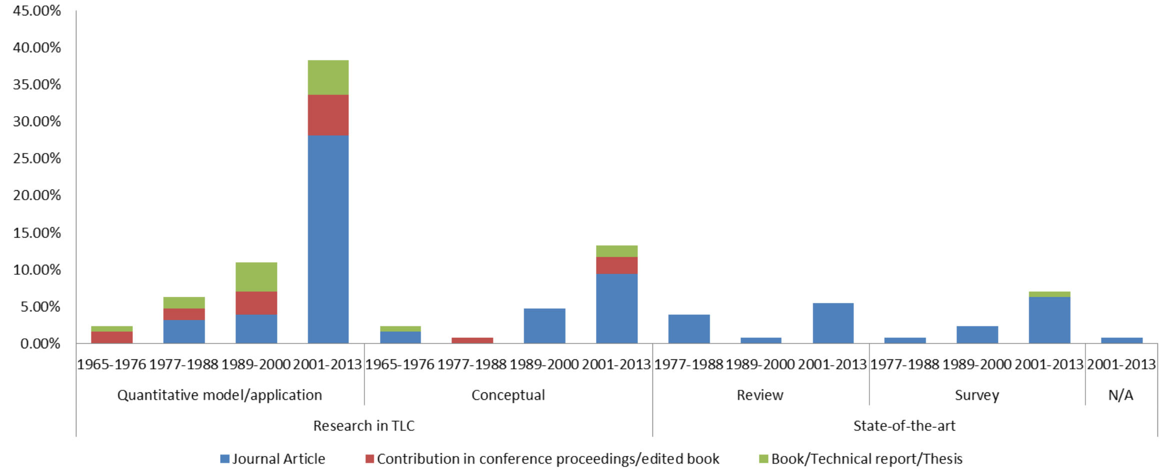


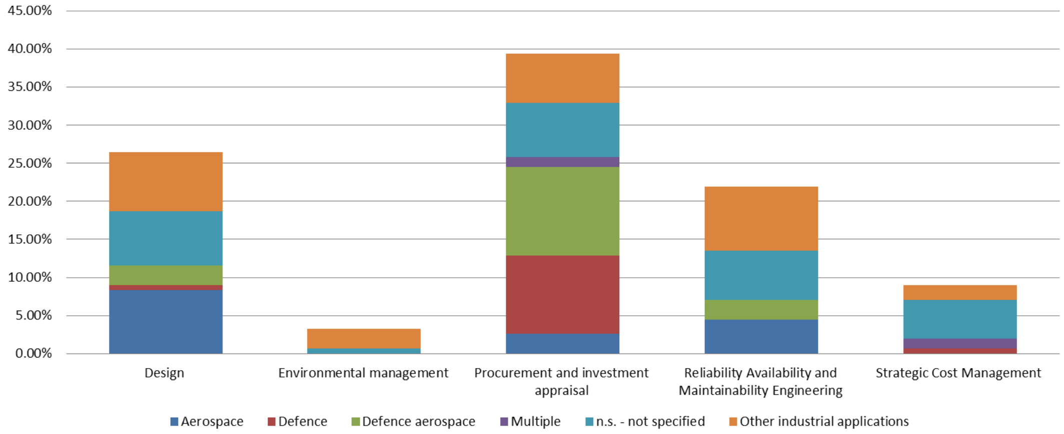
Figure 1 Research strategy flowchart

Figure 2 gives an overview of the composition of the 128 items on TLC reviewed in the first step. The contributions were retained based on the insight they provide into TLC methodology in terms of concepts (theory and frameworks), models (computational structures and metrics) and state-of-the-art (survey and review). Works on TLC within environmental management have been largely excluded due to their specific methodological issues (Settanni, 2008). Finally, applications in which TLC is merely mentioned e.g., to make generic claims on savings associated with particular product designs, were not included.

References have been accessed via keyword searches of librarian services (IEEE Xplore, EBSCO), management and engineering publishers' databases and web-based resources (NATO Research and Technology Organisation, RAND Corporation, and the Management and Accounting Web). The literature features a heterogeneous terminology – the approach being labelled alternatively as e.g., Life Cycle Costing (LCC), Whole-life Costing (WLC), Total Cost of Ownership (TCO). Hence, the search was initiated with the keywords "life" and "cost", and then refined using "availability" or "performance". Whilst no date restrictions have been applied it was noted that the literature on TLC up to the early 1980s was covered extensively (Gupta and Chow, 1985). Each reference is considered as a potential source, which facilitates the identification of the earliest works.



(a)



(b)

Figure 2 Overview of reviewed items: (a) by source type, research type and year; (b) by discipline, and application.

In order to provide focus in terms of case studies reviewed, preference has been accorded to applications of TLC in defence and aerospace – be it whole military aircraft platforms or their subsystems, aero-engines and avionics. This choice takes into account the range of applications already reviewed (Korpi and Ala-Risku, 2008). In addition there is empirical evidence that availability and performance-based contracts are becoming more frequently employed in the chosen sector. For example, the UK Ministry of Defence (MoD), is seeking a substantial move away from traditional support arrangements with industry by means of whole-aircraft availability contracts (Elford, 2011). However, the choice of applications reviewed serves as a lens to focus, and the generality of this research's findings is not restricted to these applications.

3 State-of-the-art

State-of-the-art in TLC includes 27 works, either investigating the extent to which it has been implemented in specific sectors or geographical contexts (Table 1), or literature reviews (Table 2).

TLC is still perceived by industry as an unfamiliar, poorly understood, infrequently implemented concept. Even in defence where TLC originated, it is felt that better knowledge of TLC would increase its use (Tysseland, 2008). TLC use appears easier for organisations that are customer focussed, have adequate Information Systems already in place and are seeking competitive advantage (Dunk, 2004). By contrast, TLC deployment is hindered by use in tendering and aggressive bargaining as a tool to exploit commercial situations (Nicolini et al., 2000). Resistance to TLC can be internal to an organisation. Examples include engineers lacking cost consciousness, or developing private cost systems in response to those operated by accountants that they believe are inaccurate; and top managers focusing on sales prices rather than through-life costs (Shields and Young, 1991).

Literature reviews tend to focus on concepts and methodologies that are specific to domains such as Reliability Availability and Maintainability (RAM) engineering, environmental management, and engineering design. A common assumption is that understanding of TLC is homogeneous across the literature and that the computational aspects are well-known (Christensen et al., 2005). Hence, comparison between TLC studies is often based on whether specific cost items are included or not, regardless of major methodological heterogeneities – see Durairaj et al. (2002); Waghmode and Sahasrabudhe (2011). Few works recognise that computational mechanisms and metrics vary depending on the purpose of each specific study (Sherif and Kolarik, 1981); that many applications are not founded on previous discourse; and that methods adopted have a strong context-specific nature (Korpi and Ala-Risku, 2008).

Table 1 Diffusion and implementation of TLC

Reference	Areas covered					Method(s)			
	Concept investigated	Issues with concept and technique	Issues with implementation in industry	Sector(s)	Geographic context	*Survey*	*Literature*	*Delphi*	*Action research*
(Assaf et al., 2002)	LCC	•	•	Construction	Saudi Arabia	•	•		
(Cinquini and Tenucci, 2010)	LCC (not exclusively)		•	Manufacturing	Italy	•			
(Dunk, 2004)	LCC		•	Manufacturing	Australia	•	•		
(Ellram, 1995)	TCO	•	•	Manufacturing (incl. electronics, and defence aviation)	*not specified*	•	•		
(Ferrin and Plank, 2002)	TCO		•	Manufacturing; Service; Government	United States	•			
(Jackson and Ostrom, 1980)	LCC		•	*not specified*	United States	•			
(James, 2003)	LCC (Environmental)	•	•	Food packaging	Australia	•			
(Lindholm and Suomala, 2002)	LCC	•	•	*not specified*	Finland		•		
(Nicolini et al., 2000)	WLC (not exclusively)		•	Defence and Construction	United Kingdom				•
(Olubodun et al., 2010)	LCC		•	Construction	United Kingdom	•			
(Shields and Young, 1991)	LCC		•	Aerospace and electronics	United States and Europe	•	•		
(Tysseland, 2008)	LCC		•	Defence	Norway	•			
(Xu et al., 2012)	LCC (not exclusively)	•		*not specified*	United Kingdom		•	•	

Table 2 Reviews on TLC

	General contribution				Domain-specific contribution					
	Main topic investigated	Methodological critique	Review of applications	Catalogue (no analysis/ synthesis)	Performance-based contracts	investment appraisal and procurement	Uncertainty modelling	Cost estimation at design	RAM engineering	Environmental management
Reviews of literature										
(Asiedu and Gu, 1998)	LCC, CET	•						•		
(Christensen et al., 2005)	LCC	•					•	•		
(Dhillon, 1981)	LCC			•					•	
(Durairaj et al., 2002)	LCC	•								•
(Erkoyuncu et al., 2011b)*	CET	•			•	•	•			
(Geissdörfer et al., 2009)	LCC					•				
(Goh et al., 2010)	LCC	•					•	•		
(Gupta and Chow, 1985)	LCC			•					•	
(Kaenzig and Wüstenhagen, 2010)	LCC		• Multiple							•
(Keller et al., 2014)	CET	•	• Aerospace			•				
(Korpi and Ala-Risku, 2008)	LCC		• Multiple			•		•		
(Ntuen and Moore, 1986)	LCC	•							•	
(Sherif and Kheir, 1982)	LCC		• Defence						•	
(Sherif and Kolarik, 1981)	LCC	•	• Multiple						•	
Research works with extensive literature review†										
(Cheung et al., 2009)	CET							•		
(Curran et al., 2004)	CET, LCC	•	• Aerospace					•		
(Datta and Roy, 2010)	CET	•			•					
(Dhillon, 2010)	LCC		• Multiple	•					•	
(Hunkeler et al., 2008)	LCC (environmental)	•	• Multiple							•
(Settanni et al., 2011)	LCC	•								•
(Waghmode and Sahasrabudhe, 2011)	LCC								•	

*Refers to TLC indirectly as the cost of the in-service stage of a product.
† Also included in other tables.
CET = Cost Estimating Techniques

4 Literature exploration and analysis

Research on TLC consists of 101 publications, including conceptual (26.7%) and quantitative works (73.3%). Only 17.8% of the reviewed references refer explicitly to a business model based on availability or performance-based contracting.

The exploration and analysis of current research on TLC is structured around the challenges the concept of PSS may pose to the '*what?*' (cost object), '*why/to what extent?*' (scope and boundaries), and '*how?*' (computations and metrics) of TLC, as shown Figure 3.

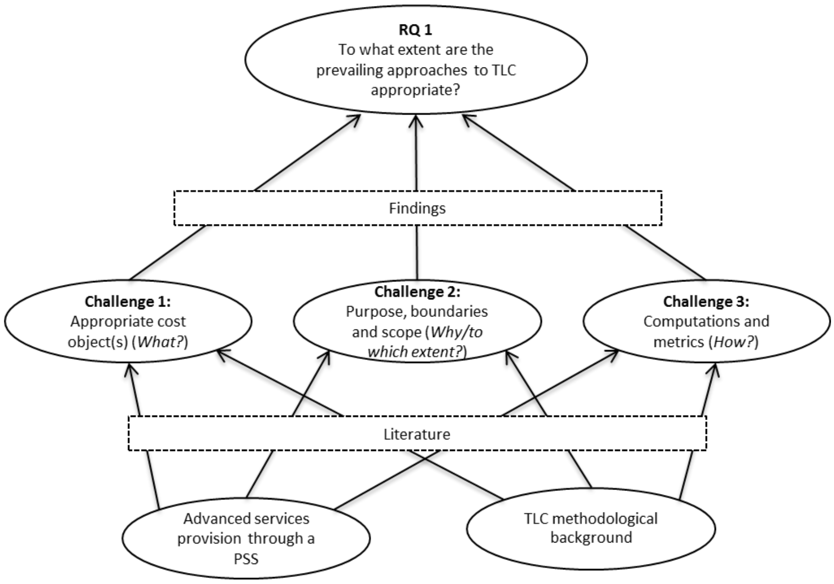


Figure 3: Challenges posed by the concept of PSS to TLC

Each of these aspects is discussed in separate subsections. The reviewed publications have been individually summarised in the Appendix using tables (Table A.1 to Table A.6).

4.1 Cost objects (*What?*)

A cost object is "*…any item, such as products, customers, departments, projects, activities and so on, for which costs are measured and assigned*" (Hansen and Mowen, 2003). From this definition, the unit of analysis for assessing cost can equally be:

- A *process*, that is, an entity delivering a range of products or services (e.g., an assembly line, a flight operation or mission); or
- A stand-alone *instance of product or service* exhibiting certain characteristics (e.g., an assembled fighter jet, a target struck), or even an *instance of time* (e.g., a fiscal year);

A process can be described as a structured collection of interrelated purposeful actions, or operations, aimed to produce a result of value to internal or external customers. It does so by engaging the services of means (inputs) to achieve ends (outputs) under certain operating conditions and over a time interval. Figure 4(a) shows this process structure, and how it replicates at different levels of aggregation. A process' input is referred to as resource to denote a capability acquired from outside the process' boundaries to pursue a course of action (Hansen and Mowen, 2003). A process' output is referred to as outcome to denote some final level of accomplishment resulting from an endeavour (Doost, 1996). Heijungs (2001) provides an extensive discussion, and Aguilar-Saven (2004) an overview of process representation techniques. Figure 4(b) shows cost categories associated directly and exclusively with a standalone instance, without indication of how the means involved result in intermediate and final ends. This indication is missing also in Figure 4(c) where cost categories and output volumes are aggregated over an instance of time.

Placing focus on 'inputs', 'outputs' or 'outcomes' determines what the relevant cost information is. For illustrative purposes, consider the tactical unmanned air vehicle (UAV) program described by Hoyle (2013). Focusing on the program's inputs emphasises the amount of money expected to be spent on equipment and support over the next financial years (say, £160m). However, annual expenditures only express the acquisition of a 'potential' capability to pursue a particular course of action, not what is achieved by that spending (Anagboso and Spence, 2009). Focusing on the program's outputs emphasises the result of the acquisition process (e.g. 54 UAVs procured at £0.34m each). An UAV acquired only represents the means to achieve an end. Analysis of the service outcome (e.g., to deliver target acquisition and reconnaissance services) reveals that the release-to-service procedure for the UAV is still pending, and that an interim arrangement (worth £61.3m) was needed to provide capability via the lease of a different type of UAV.

These alternative views on cost objects lead to the identification of the first challenge:

Challenge 1: *What is the appropriate cost object when costing an advanced service delivered by a PSS?*

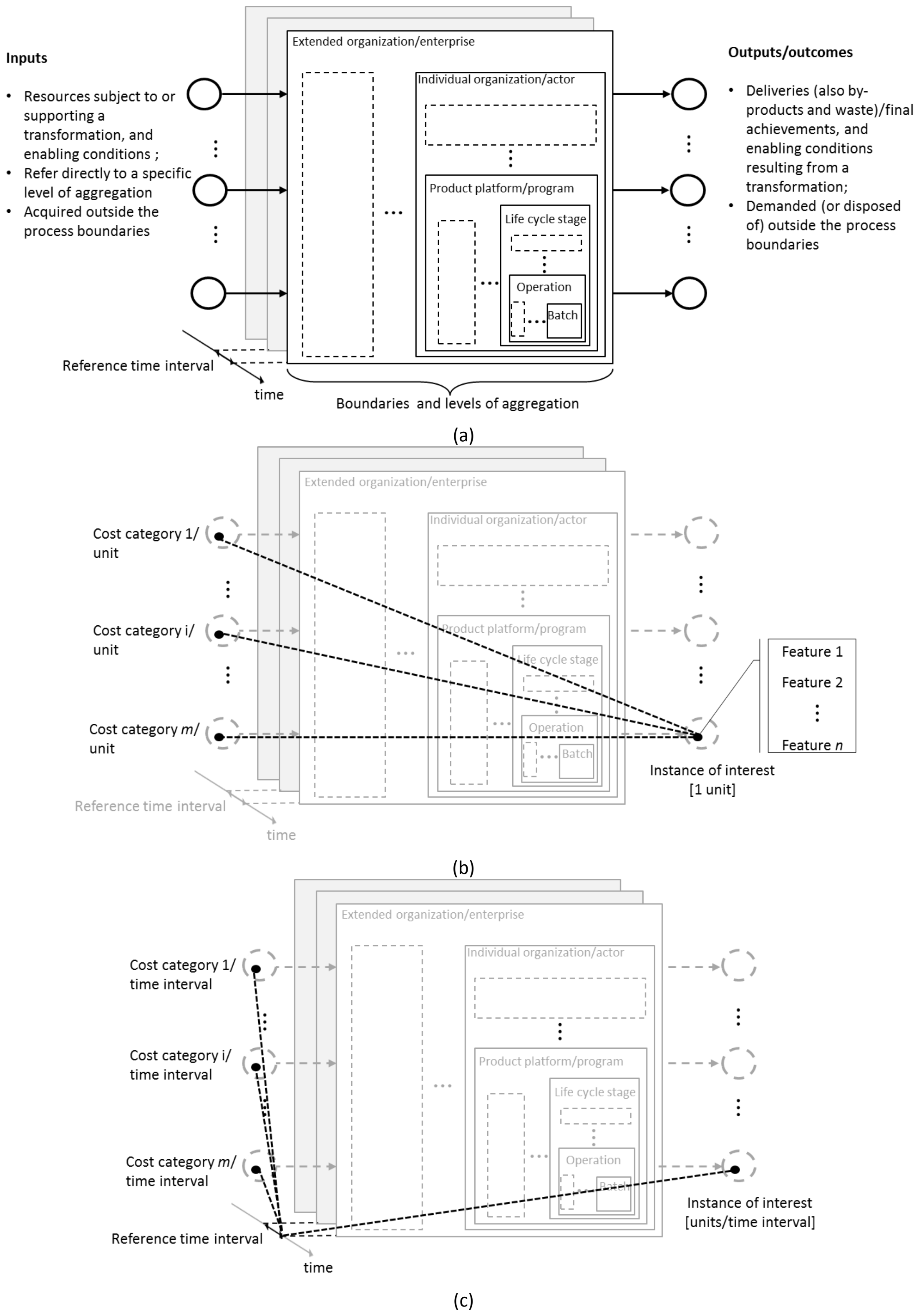


Figure 4 Reference units for cost assessment: (a) a delivery process; (b) a standalone instance; (c) a time interval

Product, service, process and system are intertwined concepts. Sampson (2012) highlights that service is better defined with reference to the work of a process, than by subtracting features from the concept of a product. Batista et al. (2008) suggest that the general principles and characteristics of systems can be applied to the understanding and management of service processes. Thenent et al. (2012) discuss *technological knowledge*, or detailed process understanding, as the foundation to capture the interplay rather than exacerbate the differences between services and the physical artefacts involved in a PSS. Finally, in the field of design, the technical representation of the PSS usually contains indications about the potential functions delivered by the technical system, the interaction between different actors, functionalities and the flows of events (Kim et al., 2011). A PSS cannot be identified with a stand-alone product, service, or process. Rather, a PSS is a specific type of delivery system aiming to meet a service demand (Wang et al., 2013). This is summarised in the following proposition:

> ***Proposition 1**: There is no single appropriate cost object. A PSS is a system potentially involving multiple, interconnected and interacting cost objects simultaneously.*

Using this proposition and the cost objects identified previously and summarised in Figure 5, the literature on TLC was analysed. Figure 6 shows the results of this analysis.

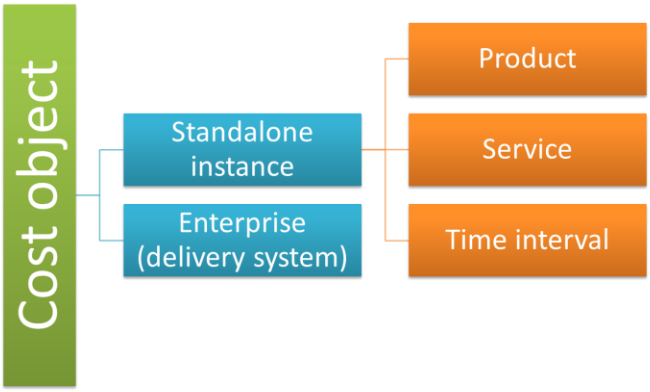


Figure 5 Dimensions for the analysis of TLC literature related to the cost object.

In eight of the reviewed cases the reference unit of analysis was a delivery system (the enterprise), but none examines a PSS. Only two of them are not conceptual works, whilst the remainder are often in fields that are adjacent to TLC, such as Supply Chain Costing (Schulze et al., 2012). Even when activities are explicitly mentioned, for example to refer to the configuration of the maintenance logistics support organisation (Kiang, 1979) or to a company's value chain (Clinton and Graves, 1999) they serve as cost categories, rather than autonomous cost objects, structured through explicit logical relationships within the enterprise.

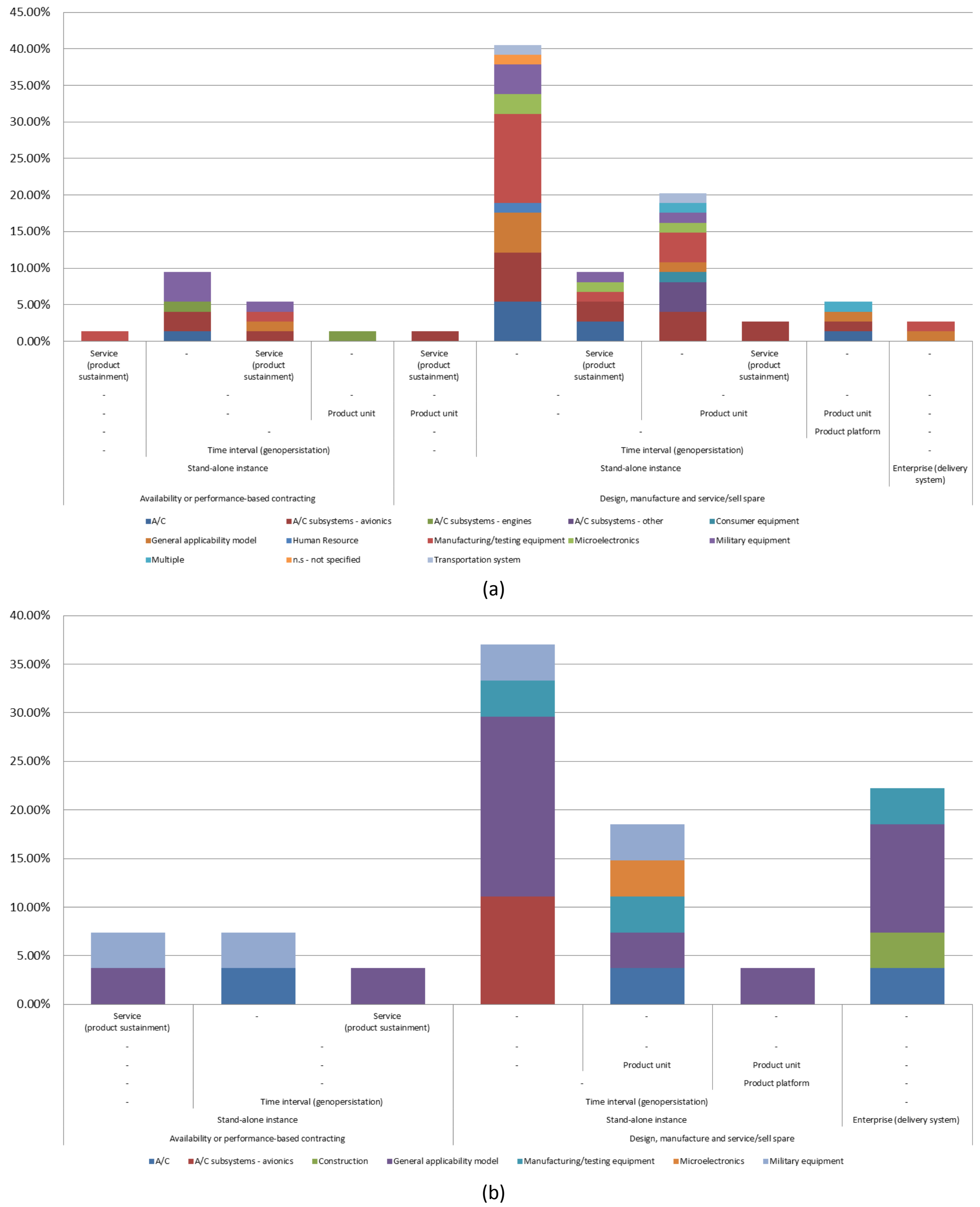


Figure 6: Classification of TLC research according to the cost object(s): (a) quantitative research; (b) conceptual research

The analysis confirms that TLC models deal with one cost object at a time and assume that all the relevant costs are directly related to that object (Emblemsvåg, 2003). In 92.1% of the cases considered, objects were typically one or more of the following: a product unit; a design instance for a product platform or family; an instance of product-related service; an instance of time over which the 'genopersistation' of a product supposedly occurs. The term genopersistation was introduced by Dean (1993) to aggregate the actions of bringing forth, sustaining, or disposing of a product. Also, product and service instances are usually related through a product features only, without otherwise interacting. This aspect of TLC modelling is illustrated in Figure 7 through an IDEF0 diagram (NIST, 1993).

A service instance in TLC can be generalised as the result of either an utilisation or a sustaining event. In the utilisation case, a service is quantified in terms of a product fulfilling its intended function. For example, an utilisation occurrence may engage the services of a specific military aircraft expressed as a number of missions, sorties or flight hours per aircraft (Roskam, 1990). A service rendered by a sustaining event is typically expressed through a one-to-one correspondence with a *failure*, that is, the inability of an asset utilisation occurrence to render its service – see, for example, Sandborn (2013). The cost of a support service instance is then typically multiplied by the frequency of occurrence of the service over a time-span. An instance of service is a cost object in 17% of cases, none of which deals with utilization events. Three of these references identify a PSS with an instance of support service. Expenditures related to utilisation events are typically considered aggregately over a product life-span, and then 'normalised' by the amount of service output (e.g., flying hours) recorded over the same period (Hitt, 1997). In this situation, corresponding to that depicted in Figure 4(c), the service output serves as an allocation base rather than as a cost object.

An instance of time is a cost object in most cases (88%), and the only object in ~50% of cases. Typically, this occurs for investment appraisals where the common assumption is that the monetary value of individual products and services is known and can be associated directly with a time-span. This also occurs in half of the reviewed items concerned with availability-based contracts. For example, Feldman et al. (2009) focus on the time interval over which a socket (an installation location for an avionic Line Replaceable Unit – LRU) is subject to a certain support regime, whilst the cost of individual LRUs, sockets, or maintenance interventions is given.

> ***Finding 1:*** *TLC deals with one cost object at a time, be it an instance of product, service or time. The cost of a PSS tends to be identified with the monetary outflows accumulating over a time-span, namely the time a stand-alone asset is with the user.*

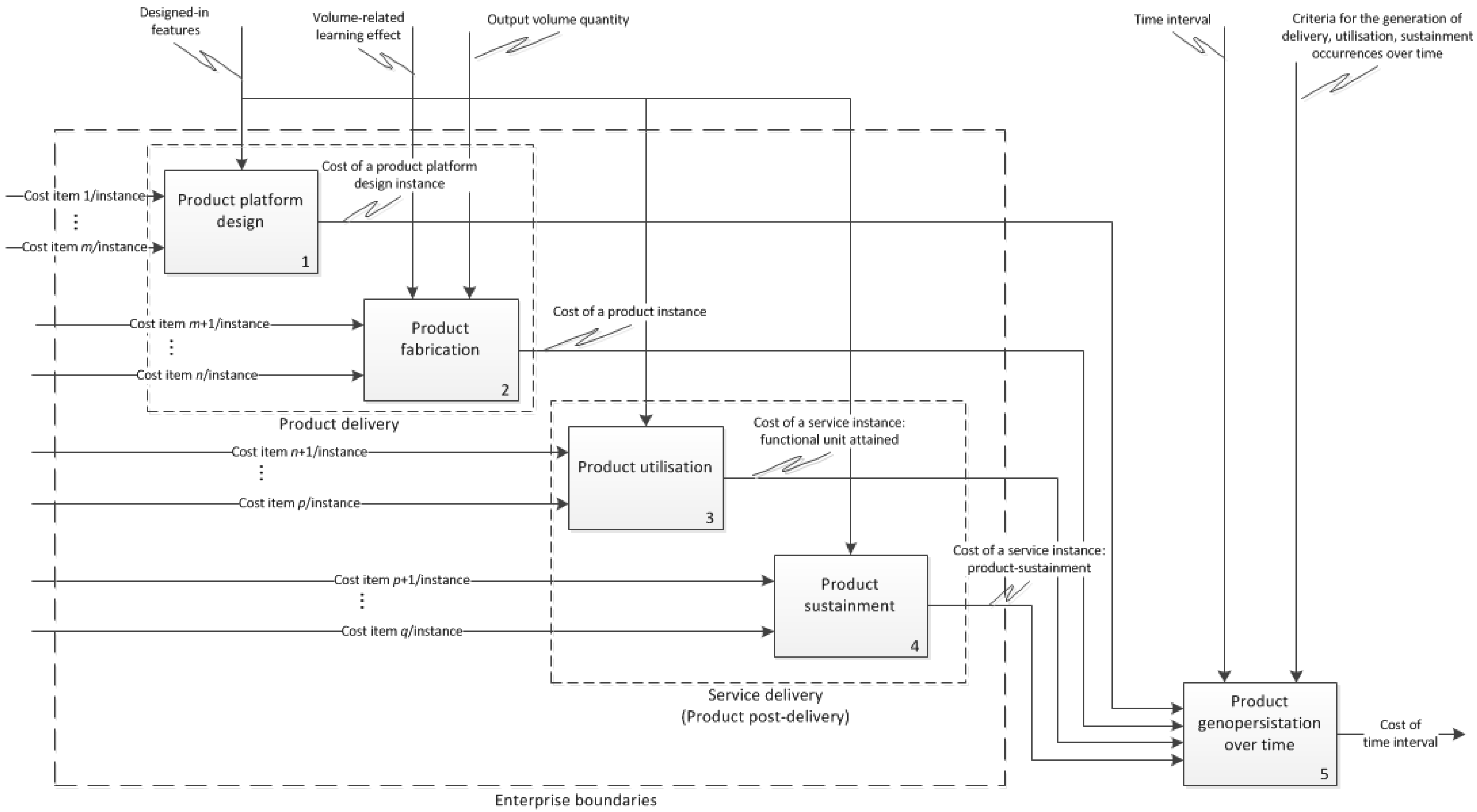


Figure 7 Recurring cost objects in TLC

4.2 Viewpoint (*Why/to what extent?*)

A cost object's cost is calculated for a purpose and is set within a scope. The combination of scope and purpose defines the viewpoint adopted in calculating that cost.

If the purpose is the strategic management of costs, insight is required to create or sustain a competitive advantage within a specific industrial setting by looking both 'inward' and 'outward' to an organisation's suppliers, customers and competitors. The advantage sought tends to relate to efficient resource usage, increased value delivered to the customer and strategic positioning in the marketplace through exploitation of the activities contributing to customer value realisation (Cinquini and Tenucci, 2010). The scope of the analysis is framed in terms of activities undertaken both within the individual firm's value chain and with suppliers upstream and customers downstream (Hansen and Mowen, 2003).

Another purpose is should-cost estimating, that is the generation of a one-time cost estimate independent of specific organisational and industrial settings. It applies when the relationship sought with other actors is of an arm's length type as opposed to a strategic alliance (Ellram, 1996). A typical example is an organisation assessing the fairness of the price a supplier charges by independently calculating a product's should-cost. Another example is the comparison of competing product designs, where a cost estimate has to be generated in the absence of a profound understanding of the product, the methods of manufacture/processes and relationships between processes (Roy, 2003). In this case, knowing cost in absolute terms may not be the main aim, rather, relative accuracy is sought (Sandborn, 2013). The scope of a should-cost estimate may extend beyond the time a product is purchased by a customer, without reliance on insights into value creating activities within and beyond the four walls of the organisation.

The second challenge identified concerns the diversity of purpose and scope in calculating a cost object's cost:

> ***Challenge 2:*** *What is the purpose of costing an advanced service delivered by a PSS? What are the scope and boundaries of the analysis?*

Underlying a PSS is typically an intent to benefit from long-term strategic alliances. An advanced service provider is concerned with monitoring and managing interlinked activities spanning across organisations which continuously meet contracted levels of performance. Upstream, there is a need to align and interact with the supply network. Downstream, the ability to achieve contracted results is subject to the contribution of resources and activities by the customer and the provider, making the boundaries between them more fluid (Ng et al., 2011). The purpose of a PSS may be shared by a diverse network of stakeholders undertaking a complex offset of interdependent activities within the virtual boundaries defined by the concept of *enterprise* (Purchase et al., 2011). Identifying the service-delivering activities and their linkages is necessary in order to adequately address service uncertainty (Erkoyuncu et al., 2011b).

> ***Proposition 2:*** *The scope of a PSS covers interlinked activities performed within and across the organisational boundaries, since the purpose of a PSS is to exploit strategic alliances on a continuous basis. It is also inter-temporal, since the impact of decisions on the state of the PSS at subsequent times has to be considered.*

To address this proposition and the purposes and scopes previously identified, the literature on TLC has been analysed according to the dimensions shown in Figure 8.

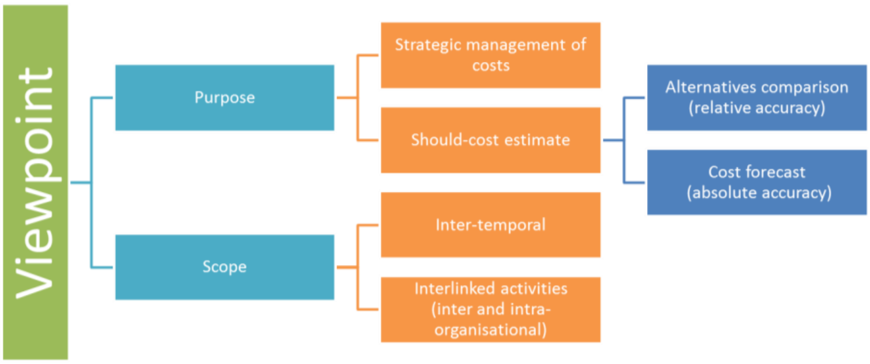


Figure 8 Dimensions for the analysis related to the viewpoint challenge

Table 3 shows different standpoints of “life-cycle” taken in the TLC literature when defining the scope of analysis. A life cycle can be the time-span a product exists – be it the time a unit of product is with the customer; the overall duration of a provider’s involvement over that product; or the time a product platform or family is sold in the market. Another view is that an engineering system progresses through its life-cycle through the actions, performed and managed within the organisations involved. These actions should be expressed in terms of their outcomes, relationships and occurrence (BS ISO/IEC, 2002). Aligning these standpoints is challenging, especially in the absence of explicit links between the activities performed at the enterprise level, which involve multiple products and services simultaneously, and an individual unit of product existing over time.

Table 3 Concepts of life cycle and repercussion on TLC scope and purpose

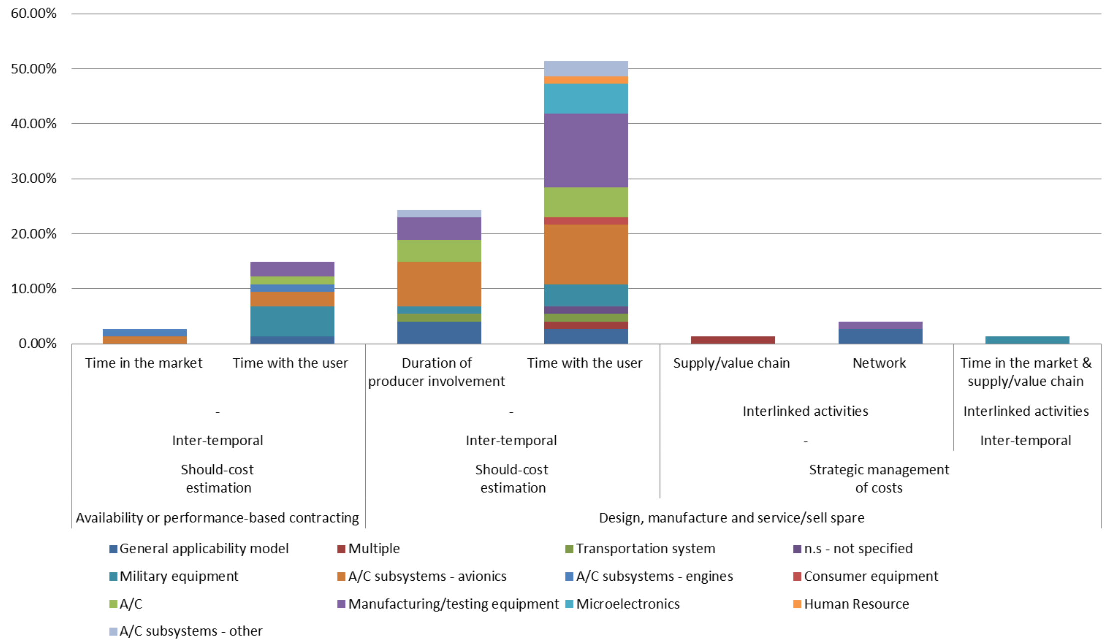
Nature of the life cycle		Standpoint	TLC scope		TLC purpose
			Temporal sequence	Physical sequence	
Inter-temporal	Time-span a product *unit* is with the customer (consumable life)	**Customer's**	Acquisition - - - - - Use Sustainment End-of-life treatment	N/A	Expand the owner's cost analysis over time, beyond the moment a durable good is purchased.
	Duration of the producer's involvement over a single product *unit* (consumable life)	**Overlapping customer-provider's**	Use Sustainment End-of-life treatment	N/A	Expand the producer's cost analysis beyond the moment a product unit is sold.
	Duration of the producer's involvement over a product *platform* (revenue-generating life)	**Provider's**	Design (conceptual to detailed) Manufacture - - - - - Sustain Retire/dispose of	N/A	Expand the producer's cost analysis over time, for the duration of its involvement with a product unit.
	Time-span a product *platform* (or family, brand) is in the market	**Marketing's**	Introduction Growth Maturity Decline	N/A	Monitor and manage costs and profitability as they evolve while a product platform or product family is in the market
Interlinked activities	Linear chain of physically linked steps related to a single product *unit* without any temporal specification	**Value chain's** (**product's,** if organisation-neutral)	N/A	Raw materials extraction Intermediate goods production - - - - - Final goods production Logistics and distribution - - - - - Utilisation Sustainment End-of-life treatment	Extend cost dimension beyond the individual organization through the physical and information flows concerning a product, as defined by inter-organisational relationships. The product perspective is independent from specific economic actors and the relationships between them.

Derived from literature (Emblemsvåg, 2003; Hansen and Mowen, 2003; Hunkeler et al., 2008; Seuring and Goldbach, 2002). “N/A”: not applicable.

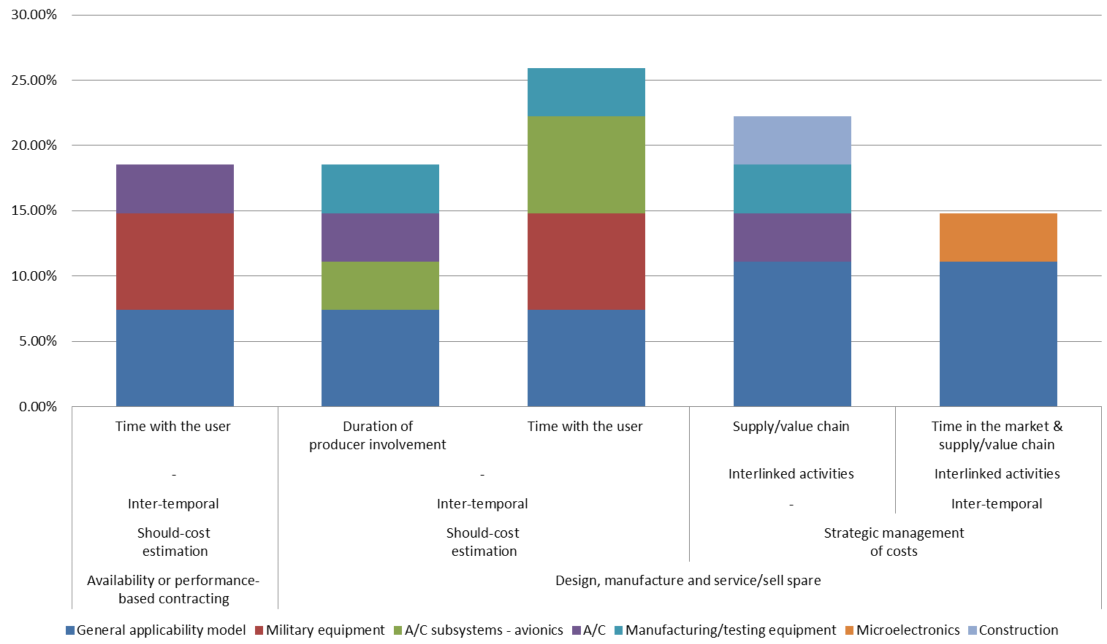
Figure 9 shows that TLC is mainly employed for should-cost estimation purposes (85% of cases), which is physiological in a ‘product and support’ business model. Typically, the aim is to convince the customer of the superiority of one product design over another. This is achieved by showing that a purchasing behaviour that requires higher immediate disbursements will result in savings for the customer while owning, operating and maintaining the product over time. Typical examples include energy-efficient eco-innovations (Kaenzig and Wüstenhagen, 2010) and high-reliability assets like Prognostic Health Monitoring-equipped avionics (Jazouli and Sandborn, 2011). Those works addressing the need to identify and exploit internal and external linkages between activities within TLC are mostly conceptual (66.7%). Also in terms of practical implementation, TLC is the least popular amongst strategic cost management tools (Cinquini and Tenucci, 2010).

Most of the items reviewed identify a life cycle with reference to one unit of product and the time-span such a unit is with the user (60.4%). The producer and market viewpoints on life cycle feature, respectively, in 22.8% and 7% of works. From these viewpoints, a firm is concerned with a product as a platform rather than as a unit. A market viewpoint typically links to a products’ sale volumes, and it has been used also to address the cost ramifications of obsolescence for an electronic product unit (Prabhakar and Sandborn, 2012). Finally, a scope defined in terms of interlinked activities (15% of cases) is less frequently associated with the concept of TLC than it is with adjacent strategic cost management approaches, namely Supply Chain Costing (SCC) and Inter-Organisational Cost Management (IOCM) - see Seuring and Goldbach, (2002). Dean (1993) suggests replacing the concept of life cycle in TLC with that of *genopersistation* to highlight the actions performed rather than the temporal phases. Circa 5% of works conceptually combine time and value-chain based life cycle concepts to show that activities grouped under different life cycle stages are carried out *concurrently* at different times within the enterprise, as in Clinton and Graves (1999).

> ***Finding 2*** *TLC is a one-off, should-cost estimation exercise undertaken by the buying or the selling organisation independently. Its scope tends to be determined as the time-span a product unit exists, rather than the actions performed within the enterprise, their outcomes, relationships and occurrence*.



(a)



(b)

Figure 9 Purpose and scope of TLC: (a) quantitative research; (b) conceptual research

4.3 Computations (*How?*)

From a computational viewpoint, cost assessments differ in terms of cost modelling rationale, underlying concept of cost and use of non-monetary metrics.

The cost modelling rationale determines how the link between a cost object and its cost is established. Building on previous work (Curran et al., 2004) the following categorisation is proposed:

- *Cost inference*: a cost object's cost is a dependent variable with the propensity to be statistically related to the attributes characterising an instance of such an object. Following the rationale that the forecast generation is from past outturns, cost inference models require historical records for the dependent and independent variables involved, making no explicit connection to the company-specific processes;
- *Cost attribution*: causal understanding is developed prior to the cost estimate by relating an output to the input quantities that are, or must have been, consumed for the output to be achieved. Within cost attribution models, money serves as a meta-language, providing a value representation of the quantified flow of goods and services within the enterprise (van der Merwe, 2007).

Cost attribution models are sometimes criticised for being unable to allow for those costs that cannot be identified at the time of making a cost estimate. Cost inference models, by contrast, sacrifice causal explanation facilities assuming that unforeseen costs can be captured if past outturn costs are addressed in aggregate (Pugh et al., 2010).

The understanding of what is 'cost' can also vary (Cooper, 1990):

- *Spending* models identify cost with a measure of disbursement (cash outflows or expenditures) necessary to acquire resources. Such a measure is related directly and exclusively to a specific cost object (one unit of product, one fiscal year etc.). Cost inference models, as well as some cost attribution models exhibit a spending orientation.
- *Resource consumption* models understand cost as a measure of how the services of the resources acquired are engaged to attain some level of accomplishment of the enterprise as a whole. Any aspect affecting the flow of goods and service within the enterprise is relevant, even if it does not directly and immediately affect cash flows or expenditures.

Finally, monetary values may be assigned to cost objects through metrics having an operational focus: non-monetary metrics. Expressions like 'cost drivers' and 'cost estimating relationships' are very common in both literature and practice, but are often a source of confusion (Stump, 1989). Taxonomy of such metrics is difficult so a possible logical grouping is the cost object they identify:

- *Design-related metrics* establish equivalence between a platform-level design and its quantifiable characteristics through continuous variables such as weight and reliability, categorical variables and technometrics (Coccia, 2005);

- *Unit-related metrics* establish equivalence between a unit of product or service and its inputs. Typical examples include direct materials and labour (Hansen and Mowen, 2003);
- *Time-related metrics* establish equivalence between a time-span, the amount of inputs, and one or more product or service outputs. For example, an aircraft fleet fuel consumption and the hours flown in a calendar year;
- *Process-related* metrics quantify the outputs supplied and inputs demanded by each process operating within the relevant boundaries, whereby any process' outputs may be inputs to any other process, for example material and energy flows (Möller, 2010).

Design, unit, and time-related metrics mostly rely on *technical* knowledge, that is, knowledge about a specific technical system, how it operates and fails (Veldman et al., 2011). Process-related metrics rely on *technological knowledge*, as they emphasise an externalised understanding of the relationships between the inputs and outputs of a transformation operated the internal structure of which is only partly known (Bohn, 1994).

Differences in cost modelling rationale, underlying concept of cost and use of non-monetary metrics lead to the identification of the third challenge:

> ***Challenge 3*: *What are the computational aspects of costing an advanced service delivered through a PSS? What are the metrics involved?***

The unresolved debate opposing cost inference and cost attribution models, and the metrics deemed relevant in each, has been extended to the specific case of a PSS (Huang et al., 2012). However, cost attribution models based on resource consumption have been invoked in the service industry where the performance and cost of business processes, especially those experienced directly by customer, is crucial for competitive differentiation (Edwards, 1999). These models would allow a formalised representation of the functions and entities delivering value to the customer through human activities and product behaviour through a PSS (Kimita et al., 2009).

Whilst it is recognised that successful service delivery requires measures focused on outcomes, cascaded throughout the service delivery system, when it comes to availability most research relies on product-related metrics such as Mean Time Between Failure, and Mean Time To Repair (see for example (Baines and Lightfoot, 2013)). These metrics are recurrent in the maintenance performance literature (Simões et al., 2011) but provide little insight into how reliability and availability improvements can be achieved in managing the maintenance process (Smith and Mobley, 2007).

Finally, for computational purposes the relevant metrics can be associated with uncertainty. Uncertainty is associated with something not known with certainty, as opposed to the unknown and is intertwined with a state of loose cause-and-effect relationships that includes both fuzziness and ambiguity (Emblemsvåg, 2011). A probabilistic approach to uncertainty can only address situations characterised by an ambiguity which is due to conflicting beliefs about mutually exclusive alternatives. This uncertainty is said to have an aleartory nature and is identified with inherent variability quantified in terms of consequences and likelihood through absolute counting (Goh et al., 2010). Non-probabilistic approaches such as possibility and subjective probability theory can address fuzziness and other, nonspecific ambiguities. However, most of the identified sources of uncertainty in delivering such services as assets' availability have aleatory nature (Erkoyuncu et al., 2011b).

The above said can be summarised in the following proposition:

> ***Proposition 3:*** *Costing an advanced service delivered through a PSS is a problem of attributing the value of means to the economic activities carried out for the ends to be achieved. Cost results from the interplay between monetary and non-monetary metrics, and uncertainties thereof.*

In considering this proposition and the computational aspects previously identified (Figure 10), the literature on TLC has been analysed. Excluding conceptual works, computational detail is undisclosed or disclosed but not replicable in 72% of the quantitative works, confirming that the methods used in TLC are often unsatisfactory (Korpi and Ala-Risku, 2008).

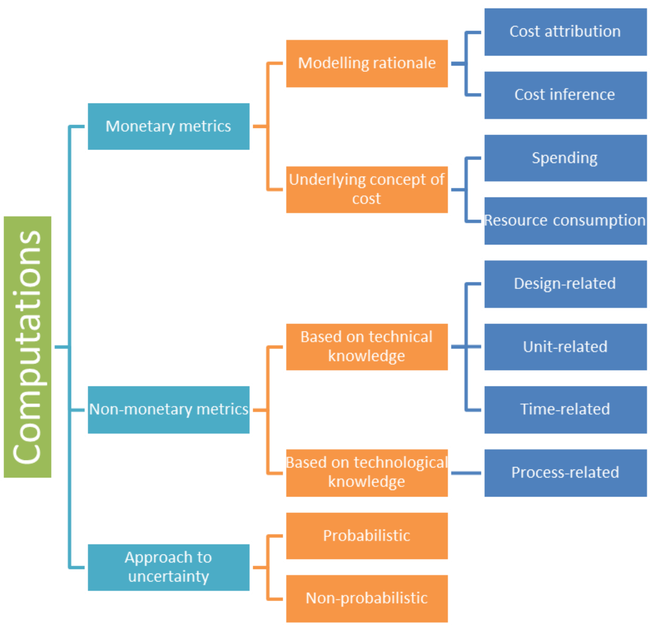


Figure 10 Dimensions for the analysis related to the computations challenge

The computational approaches employed in TLC can be identified as combinations of the aspects discussed above. These are illustrated in Figure 11 and described in Table 4. For example, a Cost Breakdown Structure is identified in Figure 11 through the coordinates 'spending' as underlying concept of cost, 'attribution' as modelling rationale, and 'unit-related' as non-monetary metrics.

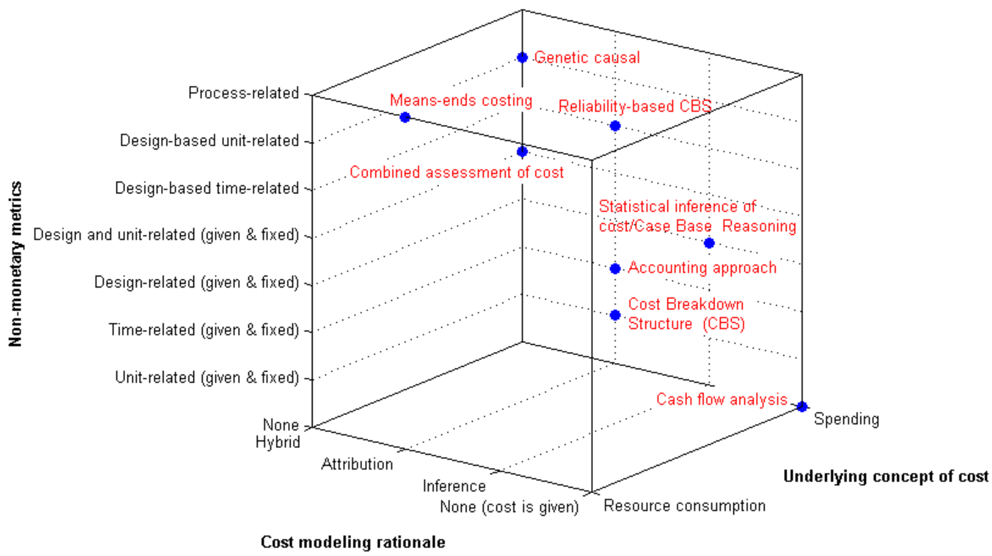


Figure 11 Computational approaches to cost assessment

Table 4 Computational orientation in TLC

Computational approach	Description
Cost breakdown structure (CBS)	Hierarchical decomposition of the direct unit cost of any of the cost objects identified in Figure 7, developed through unit-related metrics which are fixed and given, see for example, Hunkeler et al. (2008).
Genetic causal approach (Gen)	Like a CBS, it is based on a cost attribution rationale. However, the unit-related metrics are expressed analytically as a function of design-related metrics, for example based on principles of statistical inference (Curran et al., 2004).
Accounting approach (AA)	A CBS relating an instance of time with some input and output quantities through time-related non-monetary metrics that are fixed and given (Hitt, 1997).
Reliability-based CBS (REL-CBS)	Establishes correspondence between an instance of time and time-related metrics such as the occurrences of product-sustaining events. These metrics are expressed analytically as a function of logistic variables (failure rates, Mean Time Between Failures etc.) which are specific to a product design (see for example (Sandborn, 2013)).
Statistical cost inference (SI)/ Case-Based Reasoning (CBR)	Although the specific techniques vary, a cost object's cost is estimated comparatively according to the similarity and differentiation of a number of like cases for which the same cost is known (see for example (Kilpatrick and Jones, 1974)). The cost figure of interest is obtained by adjusting an existing case's known cost (Case Base Reasoning – CBR, e.g., (Romero Rojo et al., 2012)).
Means-ends costing	Combines a notion of cost as resource consumption orientation with a cost attribution rationale and process metrics. Handles multiple types of product and service simultanously. Examples include Activity Based Life Cycle Costing (AB-LCC) (Emblemsvåg, 2003), and Input-Output Life Cycle Costing (Settanni and Emblemsvåg, 2010).
Combined assessment (CA)	Simultaneously employ more of the above, for example a cost breakdown structure and statistical cost inference (Cheung et al., 2009).
Cash flow analysis (CF)	The relevant monetary metrics are movements of cash or cash equivalents either given or derived directly with reference to a specific time-span (e.g., £/year, kWh/year × £/kWh etc.). Aggregation over time typically involves discounting (Hansen and Mowen, 2003).

Figure 12 shows the combinations of computational approaches in the reviewed literature. Only 7.9% of the total cases were classified as means-ends TLC models, 5.9% of which are conceptual. Amongst quantitative works, the main contribution is Activity-based Life Cycle Costing (Emblemsvåg, 2003). Claims about Activity-Based Costing (ABC) are made in 20% of cases which either disclose no computational details (Prabhakar and Sandborn, 2012) or consist in fact of a direct cost breakdown (Kayrbekova et al., 2011). The remaining 92.1% (97.3% of quantitative TLC models) focus on a concept of cost as a measure of spending rather than of resource consumption, drawing on the 'direct variable' cost encountered only because an asset is being built or used (Fiorello, 1975). Within these studies one or more of the following cost objects is assessed separately:

- A time-span: it may be directly associated with cash flows that are given (12.9%), or inferred statistically or via Case Based Reasoning (7.9%). Alternatively, it is broken down into given amounts of inputs (18.8%), see for example Hunkeler et al. (2008), and outputs (4%) used for cost normalisation. For *reliability-based* TLC models (42.7%) the breakdown consists of the number of occurrences of product-sustaining events over a time-span. Finally, a combined assessment is used in 4% of cases, none of which are quantitative;
- The cost of designing and developing a product platform is considered in 4% of cases, 3% of which through statistical inference or Case Base Reasoning and 1% through Cost Breakdown Structure (CBS);
- The cost of a product unit is assessed in 30.7% of cases. Of these, 45.2% employ CBS; 6.5% a genetic causative approach; 19.4% statistical inference; 9.7% Case Base Reasoning; and 19.4 % (mostly conceptual) a combined assessment.
- The cost of an individual product-sustaining service is assessed in 15.8% of cases. Of these, 56.3% use a CBS, for example Kayrbekova et al. (2011). A service CBS approach has also been suggested to deal with a PSS in the context of availability contract (Datta and Roy, 2010); 12.5% use Case Base Reasoning, for example, Romero Rojo et al. (2012) propose a model of avionic obsolescence cost for use in PSS contracts, in which the base cost of resolving an obsolescence issue must be known; the same number of cases features statistical inference, and combined assessment. Only one reference applies the genetic causal approach to service cost estimation (Early et al., 2012).

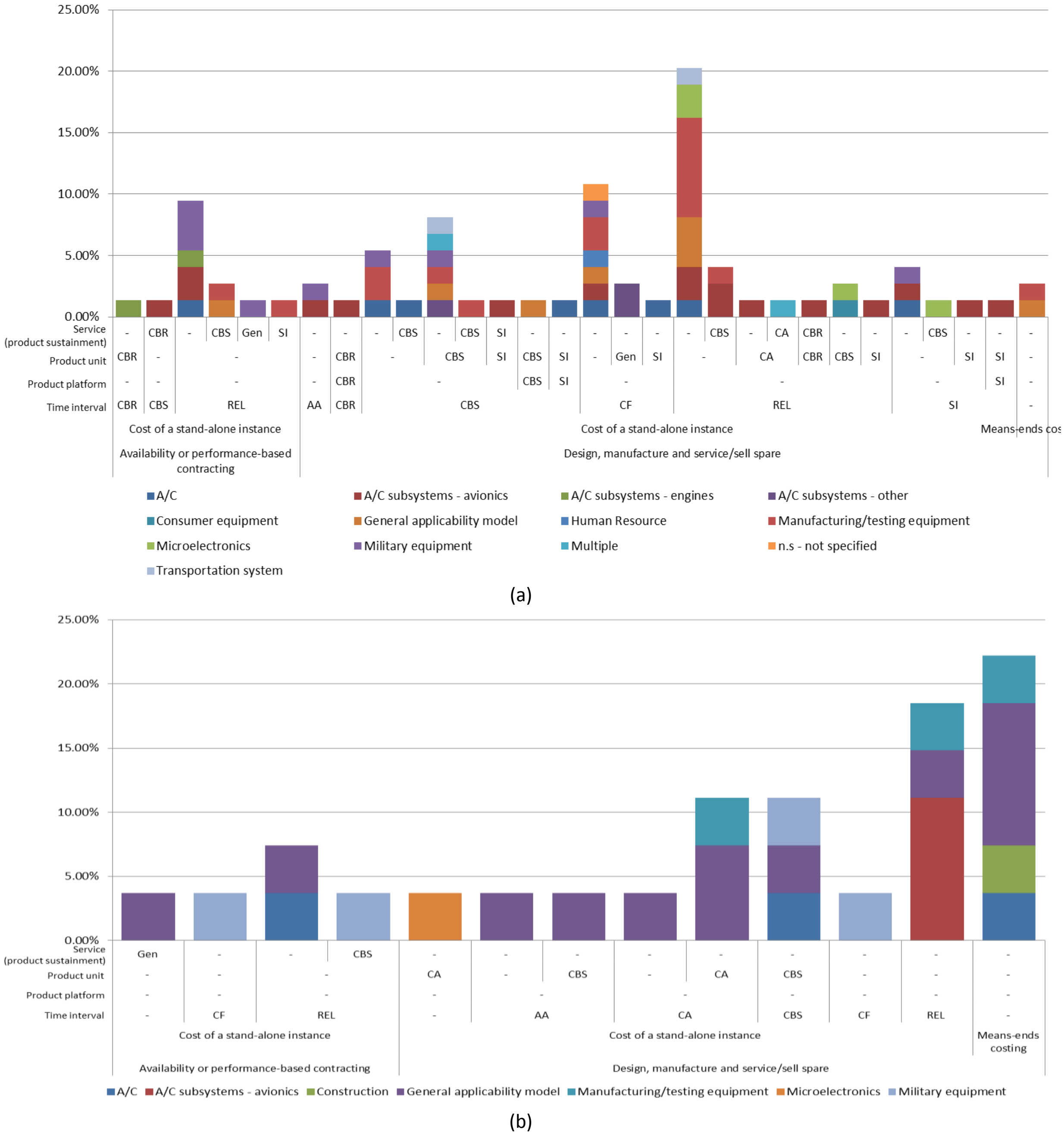


Figure 12 Combination of computational approaches in TLC: (a) Quantitative research; (b) Conceptual research. Abbreviations: see Table 4

A variety of non-monetary metrics amongst those mentioned earlier in this section can be involved in a TLC study. Figure 13(a-c) shows the metrics used directly in cost computation. Process-related metrics are not shown since they are only used in two of the cases reviewed for the purposes of means-ends costing. Platform-level metrics, which include reliability and maintainability metrics, feature in 75.7% of the cases; time-related metrics feature in 85.1% of cases normally relate to support occurrence; unit-related metrics in 33.8%, 48% of which concern direct inputs per unit of product-sustaining service.

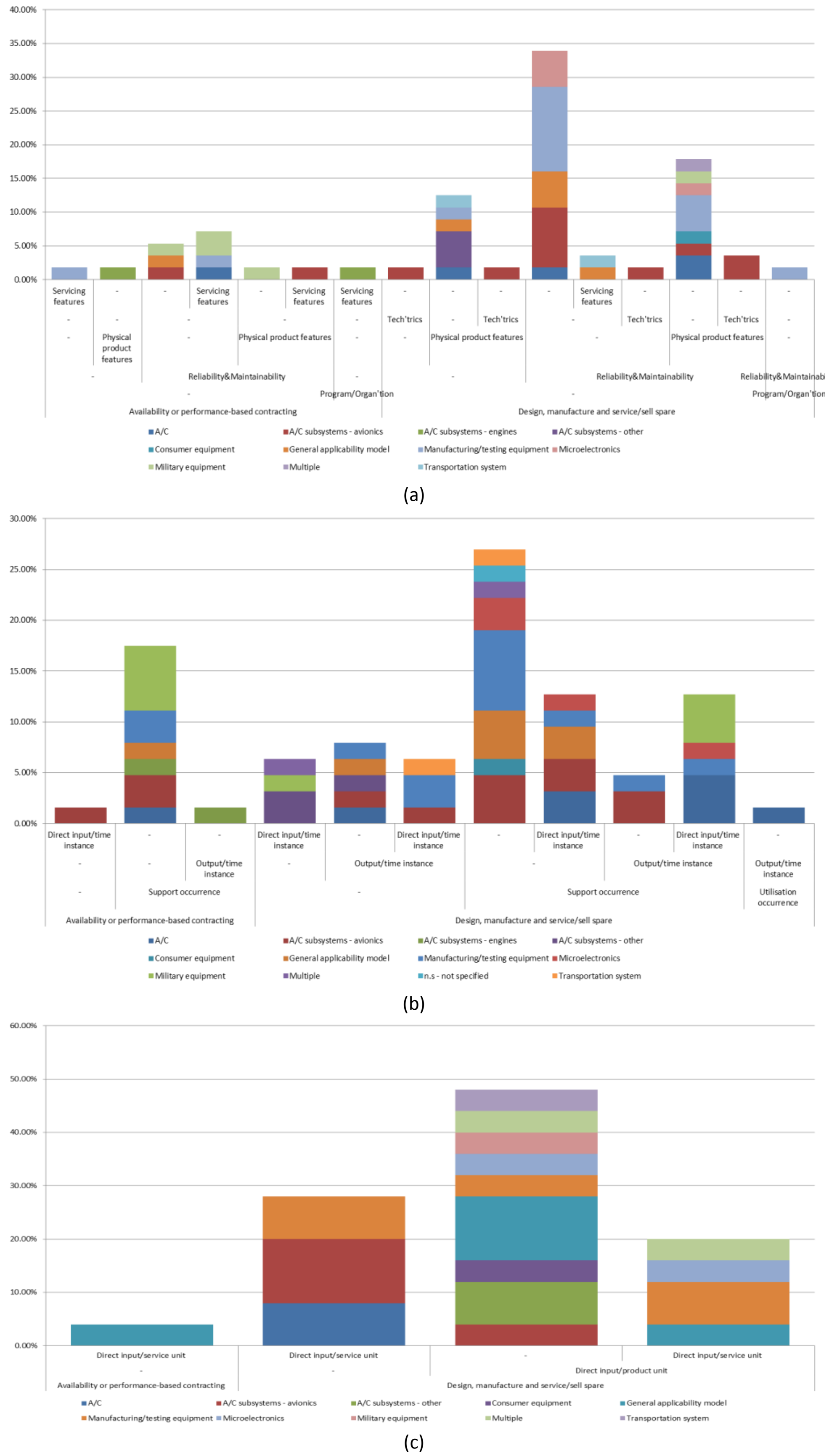


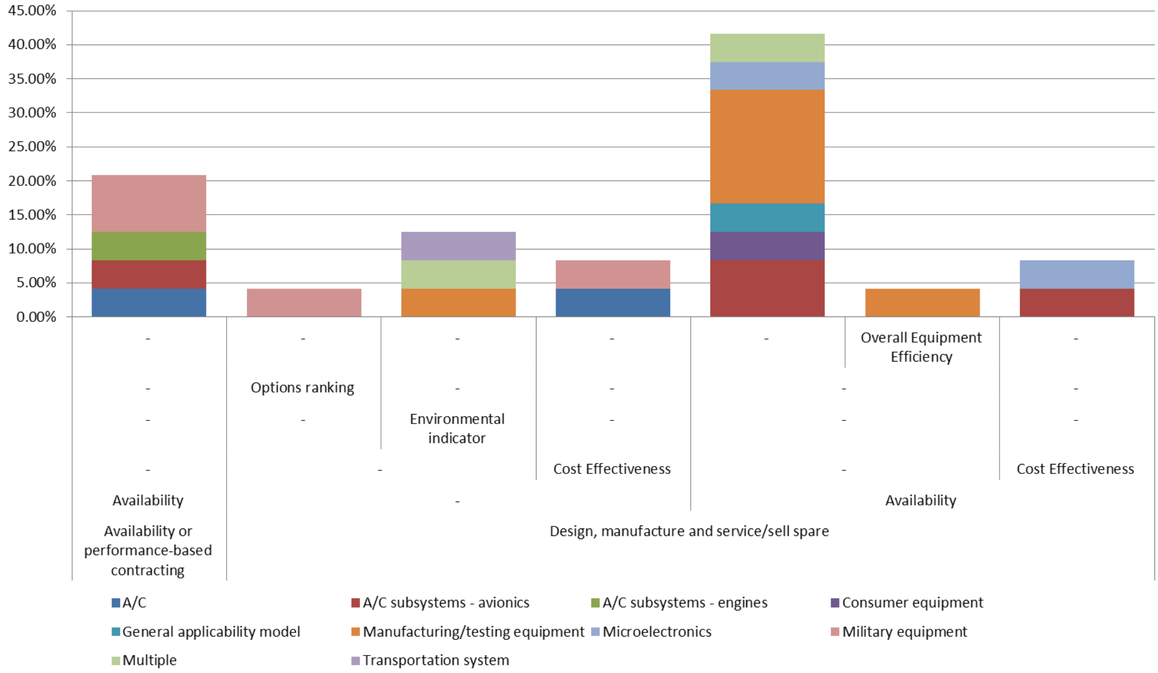
Figure 13 Non-monetary metrics used in TLC (except process-related metrics): (a) Platform-level metrics; (b) Time-related metrics; (c) Unit-level metrics;

Figure 14(a) shows complementary non-monetary metrics that may be derived from some of the primary metrics or obtained separately from TLC. For example, in Alonso et al. (2007) environmental performance metrics obtained through a Life Cycle Assessment are combined with TLC without otherwise overlapping. Similarly, *equipment efficiency* (Heilala et al., 2007) *cost effectiveness* (Blanchard, 1992), and *affordability* (Bankole et al., 2011) are obtained from the juxtaposition of separately determined cost and technical performance metrics related to an asset.

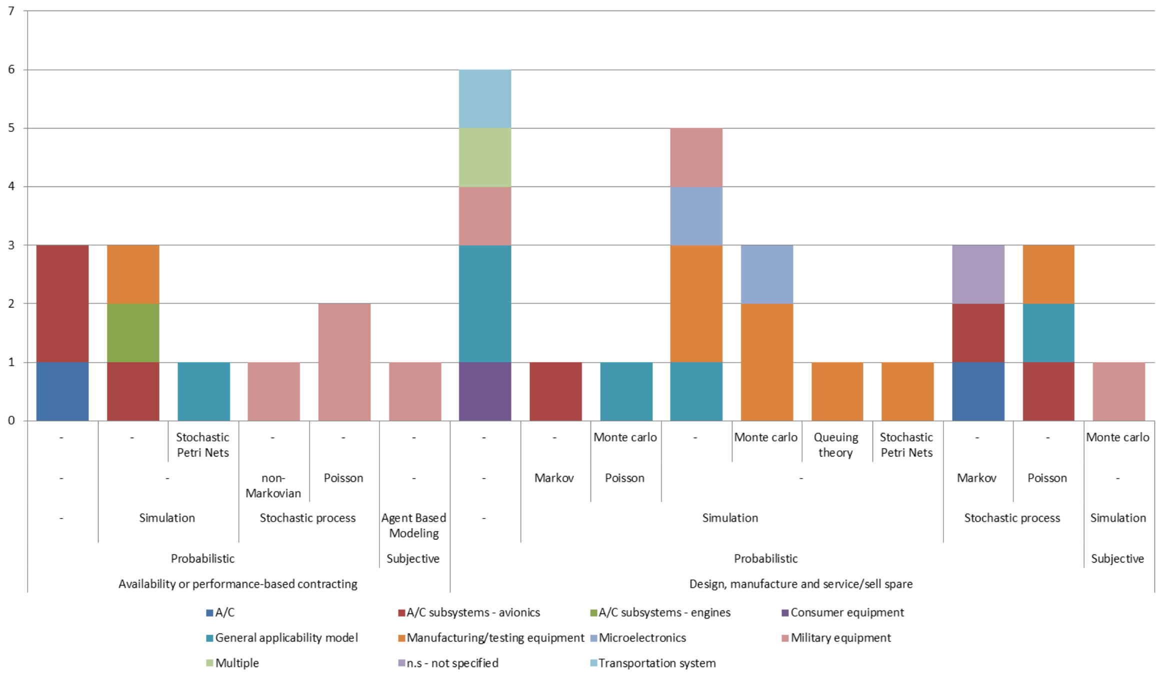
Availability features explicitly as a derived metric in 24% of cases. Availability is typically derived from design-related reliability (uptime) and maintainability (downtime) measures. These metrics are then used to solve optimization problems in parallel with TLC, such as: "given a specified level of asset availability, minimize the total cost of buying spare parts"; and "given a certain amount of money for buying spare parts, maximize the availability of the asset" (Ntuen and Moore, 1986). In 4% of cases, specific to the context of availability or performance-based contracts, availability concerns spare inventories and backorders, see for example Nowicki et al. (2008).

In the field of reliability engineering, a TLC model for an asset that operates and fails in unpredictable manner is also stochastic, the times to failure and to restore to operation being described by probability distributions that are known or knowable (Ntuen and Moore, 1986). Figure 14(b) shows that 47.3% of cases adopt a probabilistic approach to uncertainty; only two studies refer to subjective probability (Erkoyuncu et al., 2011a; Emblemsvåg and Tonning, 2003); the remaining cases are deterministic. None of the reviewed cases address epistemic uncertainties by means of imprecise probability as suggested by Goh et al. (2010). Random event generation, mainly product-sustaining events, features mostly stochastic processes (12.2%) and discrete event simulation (21.6%). Agent based modelling has also been suggested in the context of availability-based contracts (Roy and Erkoyuncu, 2011). However, the proposed model is not illustrated in detail, despite significant additional methodological complexities.

> ***Finding 3*** *Current approaches to TLC directly and immediately assign a measure of spending to an individual instance of product, service or time through non-monetary metrics expressing technical knowledge about the product. Uncertainty is addressed in terms of time distributions describing how an asset operates, fails and is restored to operation.*



(a)



(b)

Figure 14 (a) Derived metrics; (b) Approaches to uncertainty and random event generation

5 Discussion and TLC methodology outline

The challenges and findings from the previous section are summarised in Table 5 highlighting the potential gaps. The cost of providing an advanced service, for example availability, through a PSS is the cost of either doing something 'right' from the customer's point of view (hence delivering value 'in use' through an outcome), or dealing with the consequences of failing to do so. This requires a formulation of cost assessment as a problem of attributing the value of means to the economic activities carried out for the ends to be achieved. By contrast, current approaches to TLC do not deal explicitly with the attribution problem, rather, performance (for example, availability) and cost are properties designed into an asset. This promotes a partial view in which individual cost objects are stripped of their context, and the analysis is then carried out assuming all things being equal.

Rejecting a partial view requires a conceptualisation of TLC which assesses cost as an emergent property of the context within which multiple, potentially interacting products and services are designed and delivered simultaneously. From a modelling perspective, this requires a consistent and *transparent* representation of that context so that the interrelated consequences of changes in context can be translated into appropriate cost metrics (Field et al., 2007).

Few attempts have been made to question and substantially enrich the overall approach to TLC. Prasad (1999) discusses through-life performance metrics at a conceptual level, showing that the analysis should extend beyond the individual product item and also beyond the individual organisation's boundaries. Lindholm and Suomala (2007) recognise the importance of understanding maintenance and utilisation activities to improve "*cost consciousness*" i.e., awareness of the cost implications of the actions taken, after a purchase decisions is made. They advise using TLC in a continuous manner for cost monitoring. However, their focus is placed only on direct costs. Emblemsvåg (2003) provides an activity-based approach to TLC. By identifying key value creating activities within and across the organisational boundaries, the approach addresses interdependence and avoids focussing on isolated 'pockets' of performance (McNair, 1990). However, the aspects related to reliability engineering are not addressed in-depth. Another approach, Total Cost of Ownership (TCO), addresses all the costs of doing business *with* specific suppliers with the aim of removing inefficiencies while maintaining or enhancing effectiveness (Ellram, 1996). Mévellec and Perry (2006) suggest avoiding lack of transparency in TLC by highlighting the interrelations between the costs incurred within the network of partners involved in enabling the customer to use the services of a product. However, no computational counterpart is provided.

Table 5 Summary of challenges, findings and gaps

Challenges	Propositions about costing advanced services provided through a PSS	Findings about TLC methodological background	Potential gaps
Challenge 1: What is the appropriate cost object when costing an advanced service delivered by a PSS?	**Proposition-1**: There is no individual cost object. A PSS is a system potentially involving multiple, interconnected and interacting cost objects simultaneously.	**Finding 1**: TLC deals with one cost object at a time, be it an instance of product, service or time. The cost of a PSS tends to be identified with the expenditures accumulating over the time-span a stand-alone asset is in-service.	**Gap 1**: TLC is not methodologically equipped to deal with a system, specifically socio-technical systems.
Challenge 2: What is the purpose of costing an advanced service delivered by a PSS? What are the scope and boundaries of the analysis?	**Proposition 2**: The scope of a PSS is cross-organisational and inter-temporal. Its purpose is to exploit strategic alliances on a continuous basis.	**Finding 2**: TLC is a one-off, should-cost estimation exercise undertaken by the buying or the selling organisation independently. Its scope tends to be determined as the time-span a product exists, rather than the actions performed, their outcomes, relationships and occurrence.	**Gap 2**: TLC cannot support cost consciousness which requires continuous monitoring of how cost and performance evolve as a course of action is undertaken, within and across the relevant organisational boundaries.
Challenge 3: What are the computational aspects of costing an advanced service delivered through a PSS? What are the metrics involved?	**Proposition 3**: Costing an advanced service delivered through a PSS is a problem of attributing the value of means to the economic activities carried out for the ends to be achieved. A specific cost object's cost results from the interplay between monetary and non-monetary metrics, and uncertainties thereof.	**Finding 3**: Current approaches to TLC directly and immediately assign a measure of spending to an individual instance of product, service or time through non-monetary metrics expressing technical knowledge about the product. Uncertainty is addressed in terms of time distributions describing how an asset operates, fails and is restored to operation.	**Gap 3**: TLC per se does not allow answering the question which costs are to be attributed to which activity. Rather, the application of such models as availability-based TLC requires that the question has been already answered in such a way that the model can be entirely expressed in terms of technical knowledge about an individual product.

Although not working on cost assessment, Heijungs (2001) proposes a methodology to deal with the attribution problem based on a consistent analytical representation of an economic process as the building block, and rules to determine how processes are to be clustered into systems of economic activities. Settanni et al. (2010; 2011) outline an analogous approach to introduce a whole system view in the computational structure of TLC. Building on such an approach, a methodology of TLC for use in PSS can be conceptualised as four steps shown in Figure 15 and described below.

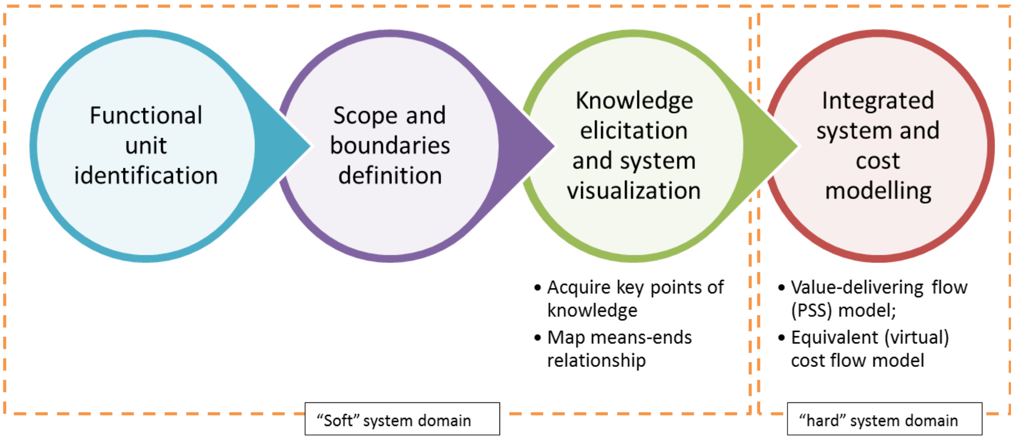


Figure 15 Proposed methodology of TLC for advanced services delivered through a PSS

5.1 Functional unit identification

PSS is an open system so the first step is to identify what constitutes the exogenously imposed demand for the system's deliverables. The delivery system's quantified performance in fulfilling its identified functions is called a *functional unit*. Originally developed in the field of Life Cycle Assessment (LCA), the term functional unit denotes the service which is expected to be rendered by a final consumption process (BS EN ISO, 2006). Analytically, a functional unit (e.g., passenger transportation for 1×10^3 km) must translate into one or more modes of realisation of the service-delivering flow (e.g., 1×10^3 km car-driving; 1×10^3 km train journey etc.).

Availability can be thought of in terms of providing a result of value to a final customer. For example, BAE System defines an available aircraft as one which is "…on the apron in a fit state for the men and women of Air Force to fly" (BAE Systems, 2009). However, formulating the appropriate functional unit is not straightforward, since availability – be it instantaneous, steady-state or mean availability (BS EN, 2009) – is typically thought of in terms of attributes designed into a product at the design phase, rather than in terms of a service-delivering flow. To overcome this, Settanni et al. (2013) suggest pooling individual top-level items (whole aircraft or LRU), or sub-items, as stocks of equivalent flyable hours (sorties, cycles etc.) through a common fictitious metric called 'capability units' so that the flows through the PSS to the exogenous demand can be thought of in terms of demand and supply of capability units, rather than individual items.

5.2 Scope and boundaries definition

The definition of boundaries and scope of the analysis draws a distinction between what is exogenous and what is endogenous to the system (width) and clarifies the level of granularity in examining what happens within those boundaries (depth). Phenomena taking place outside the defined boundaries are deemed exogenous to the system, hence uncontrollable and subject to forecasting rather than decision making (Makridakis et al., 1998).

Valerdi et al. (2009) discuss the use of boundaries to clearly define the enterprise as a 'system' which extends beyond traditional organizational or inter-departmental boundaries. The aim is to assist researchers in identifying the appropriate scope of their respective research and to assist practitioners in bounding problems and identifying critical issues.

Within the defined boundaries a system progresses through its life cycle as the result of actions, performed and managed by people in organizations; hence a system's life cycle stage can be modelled in terms of the processes involved, their outcomes, relationships and occurrence (BS ISO/IEC, 2002).

5.3 Knowledge elicitation and visualisation

Knowledge about an engineering system spans across multiple, interrelated domains (Bartolomei et al., 2012): functional (what the system does to achieve its objectives); process (current and perspective technological knowledge defined as detailed understanding of activities performed within or by the system); technical (architectural/physical entities needed to carry out the system functions or those used by the stakeholders); and social (human contribution and relationships between human elements of the system). Situations involving socio technical system, and hence human activity systems, are likely to be ill-defined, because complex and messy. In these situation emphasis is on building a defensible intellectual constructs to be used to represent such situation through a conceptual model, for example via Soft Systems Methodology (Wilson, 2001).

Qualitative methods are used for the elicitation of the necessary knowledge to formally represent a delivery system, in particular a PSS. Interviews are particularly suitable in applications concerning cost and performance estimation, where the key points of knowledge required involve not only what is done but also how and why (Naylor et al., 2001). Visualisation through pictures and diagrams then facilitates communication to achieve a shared understanding among a larger group about the same problem domain (Conklin, 2006). For example, an IDEF0 diagram produces a structured representation of the activities or processes within the modelled system or subject area, depicting how they interrelate and operate. This can be used to provide a common “baseline” for communication across individual organisational units (National Institute of Standards and Technology, 1993). The Functional Resonance Analysis Method (FRAM) is an approach developed for accident investigation and risk analysis, providing insight into why and how socio-technical systems normally succeed and occasionally fail (Hollnagel, 2012).

5.4 Integrated system and cost modelling

The application of qualitative methods provides an understanding of how the actions undertaken within the boundaries of the enterprise deliver advanced services, such as availability. The application of quantitative methods provides a mathematically treatable counterpart of the qualitative system representation, preserving the system structure in terms of dependencies and interdependencies. TLC is then conceptualised as a value representation of the system of interest. The necessary information has a dual nature (van der Merwe, 2007):

- A quantitative model of the flow of goods and services highlighting interlinked means, processes and ends within defined boundaries; and
- A corresponding value representation of these means-ends relationships, with monetary metrics serving as a meta-language to express the flow of goods and services.

One way of dealing analytically with this information is through Input-Output Analysis (IOA). IOA is a method originally developed for modelling the operation of an economic system in an integrated way. The building blocks can be as aggregated as whole industrial sectors within national economies, or as granular as individual processes within an enterprise. Applications of IOA outside macroeconomics include for example production-inventory systems modelling (Grubbstrom and Tang, 2000), costing (Boons, 1998) and life-cycle perspective (Settanni et al., 2011).

5.4.1 Basic input-output cost modelling

An input-output model is an operational-type model which enables a systematic understanding of the functioning or malfunctioning of the system being modelled. It is used for tracing the sources of trouble and deciding what action could be taken (Leontief, 1986). To establish a system blueprint each economic activity (process, sector etc.) within the system is represented by a vector describing in quantitative terms the relationship between the inputs absorbed and outputs produced. The interdependence among activities is then described by simultaneous equations expressing the balances between the total input and output of each commodity and service provided and used during a reference time interval.

For illustrative purposes, Figure 16 shows the relationships between two streamlined processes, both pictorially as orientated arcs and analytically as tables that can be treated mathematically as matrices or vectors. For example, proceeding from left to right in Figure 16(a): a 1×2 vector of exogenously acquired inputs $\mathbf{b} = [b_1 \quad b_2]$; a 2×2 matrix of inputs that are supplied by some process within the boundaries and employed by some process within the same boundaries $\mathbf{U} = \begin{bmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{bmatrix}$; a 2×2 matrix of the outputs delivered by each process operating within the boundaries $\mathbf{V} = \begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{bmatrix}$, having the activities' primary outputs as diagonal elements and their secondary outputs, if any, as off-diagonal elements; and a 2×1 vector of final exogenous demand $\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$. The elements of each matrix are recorded with respect to their quality (steel, energy, etc.) and quantity (kg, MJ, etc.). Analytically, these dimensions define the basis of a linear space. Also, the quantitative flows are expressed either in relation to a time span specified for the whole economic system (for example, one year) or in relation to the operating time of each economic activity individually considered (for example, one hour or any time a run takes). The latter case is known as 'activity level analysis' whereas the former as 'commodity flow accounting' (Heijungs, 2001).

Settanni et al. (2011) employ activity level analysis to formulate a TLC model with environmental extensions. Like basic IOA, the model involves two sets of simultaneous equations, respectively, in physical and monetary terms. The first set performs a 'demand-pull' analysis to determine, for each economic activity operating within the system, the activity levels that equate supply and demand – both intermediate and final – for all the goods and service flows. Using the matrix notation introduced earlier for illustrative purposes:

$$\mathbf{Vs} = \mathbf{Us} + \mathbf{y} \rightarrow (\mathbf{V} - \mathbf{U})\mathbf{s} = \mathbf{y} \rightarrow \mathbf{s} = (\mathbf{V} - \mathbf{U})^{-1}\mathbf{y} \qquad (1)$$

where $\mathbf{s} = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}$, if it exists, is a non-negative column vector of activity levels; $\mathbf{Vs}$ is the gross output; $\mathbf{Us}$ is the total intermediate input demand; $(\mathbf{V} - \mathbf{U})\mathbf{s}$ is the net output of the economic system; the superscript "-1" denotes matrix inversion. A final demand $\mathbf{y}$ is feasible if it does not exceed the net output for a feasible activity vector $\mathbf{s}$. Background on the computational aspects of IOA can be found in Raa (2005). An economic system in which each economic activity functions by absorbing output of other activities directly and indirectly will only be able to sustain itself whilst delivering to final demand if each subsystem contained in it is capable of doing so too: "…if even one of them cannot pass the test, it is bound to cause a leak that will destroy the sustainability of the entire system" (Leontief, 1986).

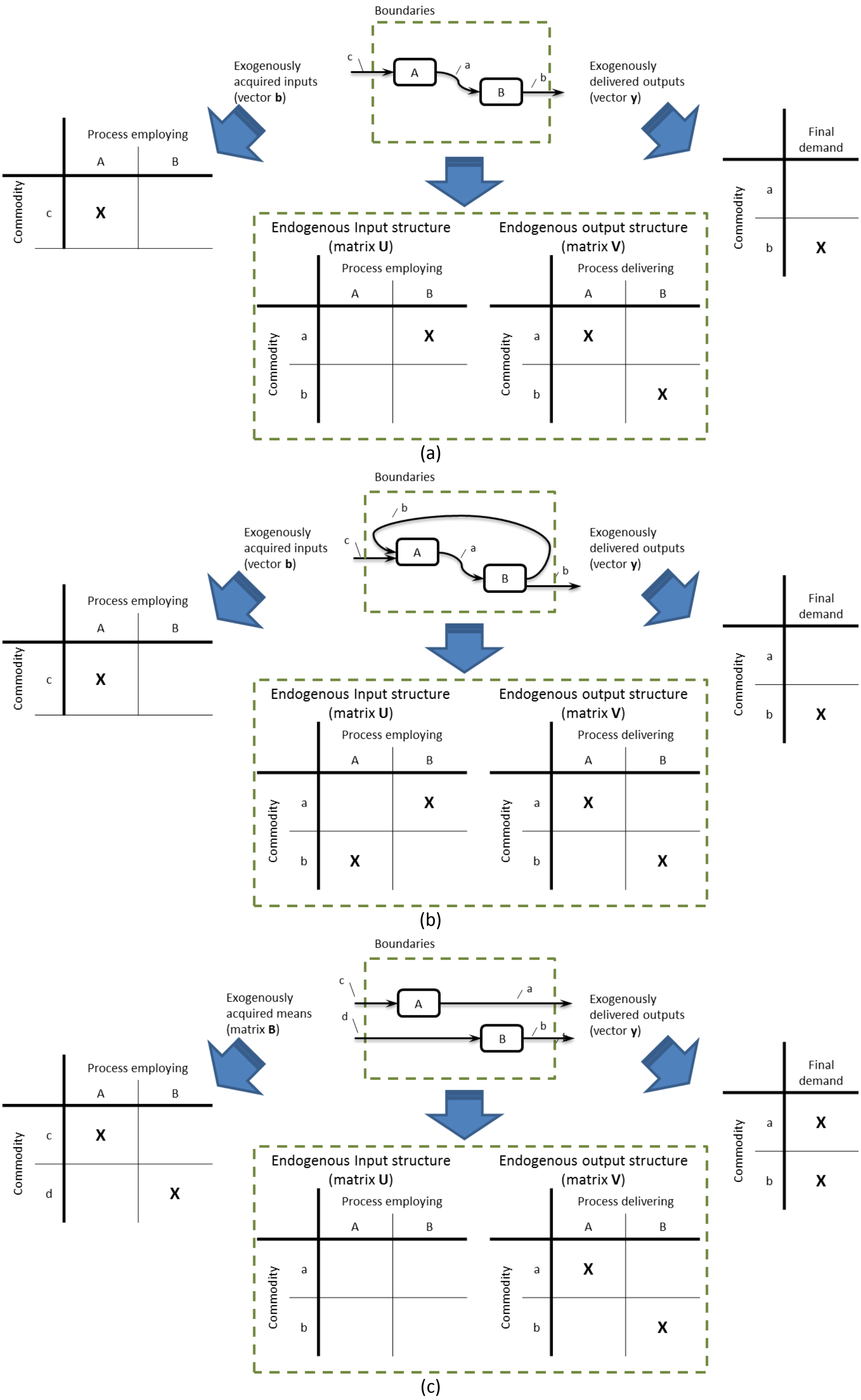


Figure 16 From diagrammatic to input-output representation of a system: (a) dependent processes; (b) interdependent processes; (c) independent processes. The term "commodity" indicates flows and funds of goods and services

Another set of simultaneous equations attributes monetary values to the quantitative flow of goods and services by equating the unit value of each activity's output and the total outlays incurred in the course of its delivery:

$$\mathbf{p}(\mathbf{V}\hat{\mathbf{s}}) = \mathbf{p}(\mathbf{U}\hat{\mathbf{s}}) + (\omega\mathbf{b}\hat{\mathbf{s}}) \rightarrow \mathbf{p} = \boldsymbol{\upsilon}(\mathbf{V}-\mathbf{U})^{-1} \tag{2}$$

where $\mathbf{p} = [p_1 \quad p_2]$, if it exists, is a non-negative row vector of monetary worth per unit of each activity's output; $\hat{\mathbf{s}}$ is a matrix having the elements vector $\mathbf{s}$ on the diagonal and zeros as off-diagonal elements; $\mathbf{p}(\mathbf{V}\hat{\mathbf{s}})$ is the monetary worth of the output flow through the system of interest corresponding to an activity level $\mathbf{s}$; $\mathbf{p}(\mathbf{U}\hat{\mathbf{s}})$ is the monetary worth of the corresponding input flows transferred-into each activity from other activities operating within the system; $\mathbf{b}\hat{\mathbf{s}}$ is the amount of exogenously acquired means; ω is the unit monetary worth of the externally purchased input (in the case of more such inputs, a matrix $\mathbf{B}$ rather than vector $\mathbf{b}$, and a row vector $\boldsymbol{\omega}$ rather than a scalar ω is used); $\boldsymbol{\upsilon} = \omega\mathbf{b}$ is often referred to as the 'value added' to the transactions occurring between activities within the system's boundaries.

5.4.2 Input-output representation of a traditional TLC

The two sets of equations discussed above provide a flexible conceptualisation of TLC, which arranges otherwise sparse computations in a concise way. Intricate systems of economic activities, as well as more traditional TLC models can be accommodated. For example, a simple cash flow analysis concerning an asset worth 10 k£, the utilisation and sustainment of which occurs over 40 years and involves only a recurring expenditure of 100£/year at a discount rate of 5% can be represented as two dependent activities (Figure 16(a)): "acquire asset" and "use/sustain asset". These are hollow processes, that is process specifications that add no information to the system, defined on the linear space $\begin{bmatrix} \text{Acquired asset (units)} \\ \text{Asset after 40 years existence (units)} \end{bmatrix}$ so that the relevant matrices read $\mathbf{U} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, $\mathbf{V} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, and $\mathbf{y} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$. Most of the information in this case concerns the external purchases recorded in matrix $\mathbf{B} = \begin{bmatrix} 1 & 0 \\ 0 & 100 \end{bmatrix}$, the columns of which are defined on the linear space $\begin{bmatrix} \text{Asset (units)} \\ \text{annual uniform payment (£)} \end{bmatrix}$, and the associated prices $\boldsymbol{\omega} = [1{,}000 \quad 17.1]$, where ω_2 is the present worth of an annually recurring uniform amount of 1£ over 40 years at 5%. This leads to $\mathbf{p} = [1000 \quad 2{,}715.9]$, the element p_2 being commonly referred to as the asset's through-life cost.

5.4.3 Dynamic input-output model of a PSS

The input-output economic system discussed above does not explicitly consider the temporal hierarchy of economic activity. The analytical treatment of timing aspects is critical since time lag in delivery is typically part of availability-based contracting. Settanni et al. (2013) suggest modelling a

PSS evolving over time analogously to an input-output production-inventory system to account for interdependencies (Grubbstrom and Tang, 2000). However, product items are seen as 'stocks' of potential capabilities to pursue a certain course of action. Hence, they are expressed in terms of a measure of the service that they are expected to render, as discussed in section 5.1. The analytical treatment of time is analogous to a dynamic input-output model with temporally distributed activities (Raa, 2005). This is described below through an example, and illustrated in Figure 17.

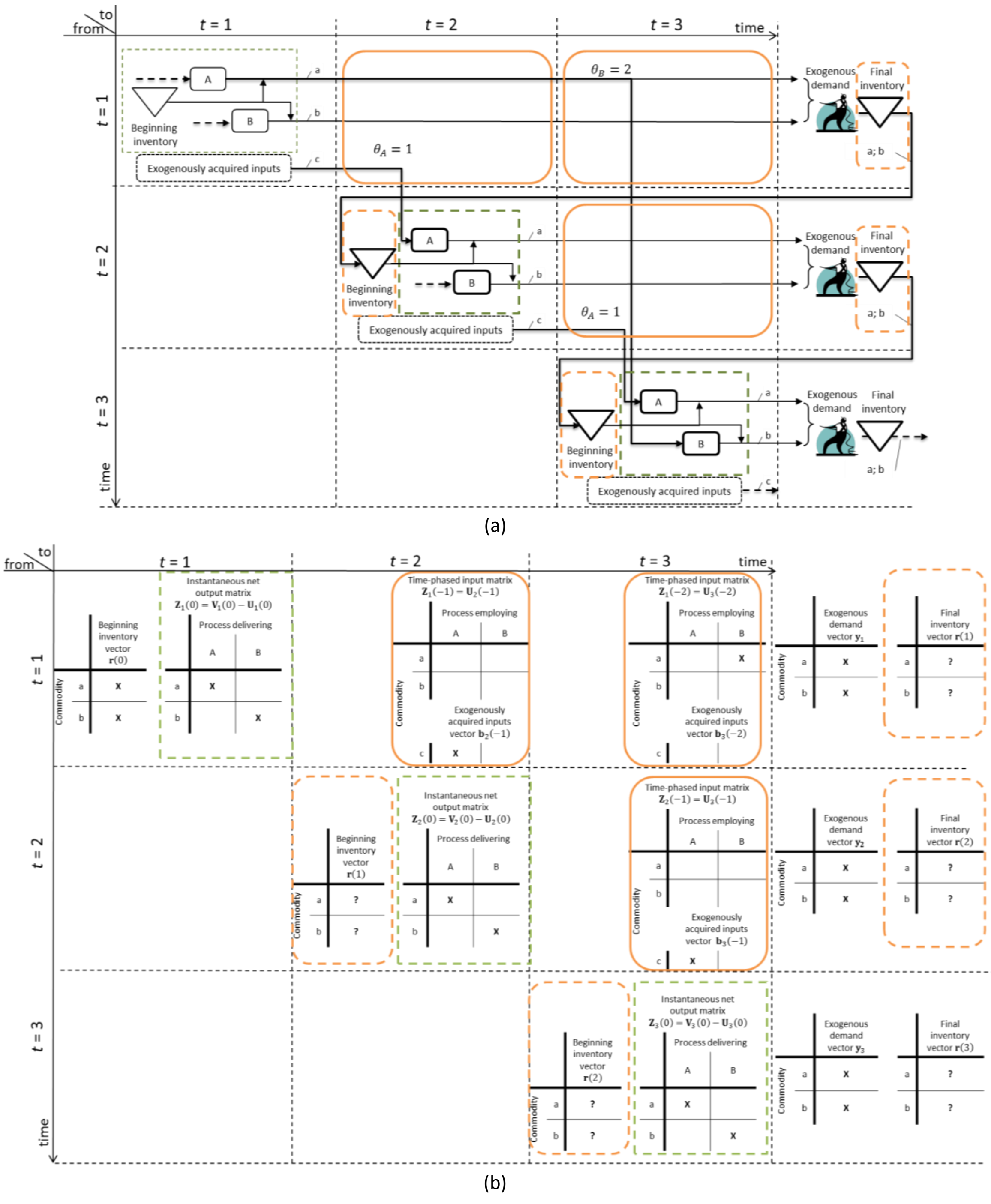


Figure 17 Example of two temporally distributed, dependent processes: (a) diagram; (b) tables

Consider two dependent processes, A and B, like those in Figure 16(a), over a discrete time horizon $t = 1, \cdots, 3$. The exogenous demand may trigger any process at any time. This is shown on the rightmost side of the diagram in Figure 17(a), from top down. Formally, this demand is denoted by non-negative vectors $\mathbf{y}_1 = \begin{bmatrix} y_1^A \\ y_1^B \end{bmatrix}$, $\mathbf{y}_2 = \begin{bmatrix} y_2^A \\ y_2^B \end{bmatrix}$, and $\mathbf{y}_3 = \begin{bmatrix} y_3^A \\ y_3^B \end{bmatrix}$ as shown in Figure 17(b). By assumption, the amount of output delivered by one run of each process is instantaneously usable at the time of delivery, and it is the same irrespective of when the processes are triggered. In Figure 17(a) this is shown by placing the process blocks along the main diagonal. In Figure 17(b) the output is expressed through the matrices $\mathbf{V}_1(0) = \mathbf{V}_2(0) = \mathbf{V}_3(0) = \mathbf{V} = \begin{bmatrix} v_{11} & v_{12} \\ v_{21} & v_{22} \end{bmatrix}$. The zero in brackets indicates that each process' output is immediately put to use. The time of delivery is indicated as a subscript. Matrix $\mathbf{V}$ is the same as in section 5.4.2. For illustrative purposes, lead times $\theta_A = 1$ and $\theta_B = 2$ are assumed. This means that one run of process *A* demands a certain amount of inputs one time unit prior to the delivery time, whilst one run of process *B* requires inputs to be present two time units in advance. This time lagging applies equally to the demand of inputs provided internally by *A* and *B*, and to the demand of inputs acquired exogenously. In the presence of positive lead times, the flow of goods and services between processes is distributed over the time horizon as shown in the upper-right part of the diagram in Figure 17(a). The corresponding temporally-distributed matrices are shown in Figure 17(b). Matrices $\mathbf{U}_2(-1) = \mathbf{U}_3(-1) = \mathbf{U}\boldsymbol{\delta}(-1) = \begin{bmatrix} u_{11} \times 1 & u_{12} \times 0 \\ u_{21} \times 1 & u_{22} \times 0 \end{bmatrix}$ represent the amount of internally supplied inputs that must be present 1 time unit prior to delivery at times 2 and 3. The lead time is indicated in brackets with a minus sign. The time of delivery is indicated as a subscript. Matrix $\mathbf{U}$ is the same as in section 5.4.2, and it is manipulated through vector $\boldsymbol{\delta}(-1) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ to ensure that $\mathbf{U}_2(-1)$ and $\mathbf{U}_3(-1)$ have zero elements except for process *A*, the lead time of which is equal to 1 time unit. Applying the same reasoning, the amount of internally supplied inputs that must be present 2 time units prior to delivery at time 3 is denoted by the non-negative matrix $\mathbf{U}_3(-2) = \mathbf{U}\boldsymbol{\delta}(-2) = \begin{bmatrix} u_{11} \times 0 & u_{12} \times 1 \\ u_{21} \times 0 & u_{22} \times 1 \end{bmatrix}$. In the same way, vectors $\mathbf{b}_2(-1) = \mathbf{b}_3(-1) = [b_1 \times 1 \quad b_2 \times 0]$ represent the demand of exogenously acquired inputs 1 time units prior to delivery at times 2 and 3, and vector $\mathbf{b}_3(-2) = [b_1 \times 0 \quad b_2 \times 1]$ represent the same demand 2 time units prior to delivery at time 3. Vector $\mathbf{b}$ is the same as in section 5.4.2.

Reading Figure 17 row-wise (left to right) one can see that at each time period 1) the available output consists of the sum of inventories that are present at the beginning of that period, plus the deliveries from the processes that are triggered in that time period; 2) the required input consists of the sum of the instantaneous internal demand (that enables deliveries at the current time), the time-lagged internal demand (that enables deliveries at future times), and the current exogenous demand. Each process must therefore operate at some non-negative activity level in order to align output to demand, considering that the excess output is carried over to the next time period. The inventory at the beginning of the planning period are represented by vector $\mathbf{r}(0) = \begin{bmatrix} r_1^0 \\ r_2^0 \end{bmatrix}$ and must be known, whilst the final inventories at the end of each time period, $\mathbf{r}(1) = \begin{bmatrix} r_1^1 \\ r_2^1 \end{bmatrix}$, $\mathbf{r}(2) = \begin{bmatrix} r_1^2 \\ r_2^2 \end{bmatrix}$ and $\mathbf{r}(3) = \begin{bmatrix} r_1^3 \\ r_2^3 \end{bmatrix}$, must be determined along with the activity levels.

Generalising to n activities, each with lead time θ_j $(j = 1 \ldots n)$, a temporally-distributed version of equation (1) is formulated as follows:

$$\mathbf{r}(t-1) + \mathbf{V}_t(0)\mathbf{s}(t) = \sum_{\tau=0}^{\max\{\theta_1 \cdots \theta_n\}} \mathbf{U}_{t+\tau}(-\tau)\mathbf{s}(t+\tau) + \mathbf{y}_t + \mathbf{r}(t) \tag{3}$$

where $t = 1,2,\cdots,T$; $\mathbf{U}_{t+\tau}(-\tau) = \mathbf{U}(t)\boldsymbol{\delta}(-\tau)$ is the temporally-distributed input structure matrix obtained by multiplying the generic element of the matrix $\mathbf{U}(t)$ by vector $\boldsymbol{\delta}(-\tau) = \begin{bmatrix} \delta_{\theta_1,\tau} \\ \vdots \\ \delta_{\theta_j,\tau} \\ \vdots \\ \delta_{\theta_n,\tau} \end{bmatrix}$; $\delta_{\theta_j,\tau}$ is the Kroneker symbol, taking values $\delta_{\theta_j,\tau} = 1$ if $\theta_j = \tau$ and 0 otherwise. In principle, the entries of $\mathbf{U}(t)$ can be different at each time t. Vectors $\mathbf{r}(t-1)$, $\mathbf{r}(t)$, $\mathbf{s}(t+\tau)$, $\mathbf{s}(t)$, and $\mathbf{y}_t$ denote, respectively, beginning inventory, final inventory, activity levels, future activity levels and exogenous demand at each time t. Developing equation (3) for $t = 1,2,\cdots,T$ one obtains:

$$\begin{bmatrix} \mathbf{Z}_1(0) & \mathbf{Z}_1(1) & \ldots & \mathbf{Z}_1(T-1) & -\boldsymbol{I} & & & \mathbf{0} & \\ & \mathbf{Z}_2(0) & & \mathbf{Z}_2(T-2) & \boldsymbol{I} & -\boldsymbol{I} & & & \\ & & \ddots & \vdots & & & \ddots & \ddots & \\ & \mathbf{0} & & \mathbf{Z}_T(0) & & \mathbf{0} & & \boldsymbol{I} & -\boldsymbol{I} \end{bmatrix} \begin{bmatrix} \mathbf{s}(1) \\ \mathbf{s}(2) \\ \vdots \\ \mathbf{s}(T) \\ \mathbf{r}(1) \\ \mathbf{r}(2) \\ \vdots \\ \mathbf{r}(T) \end{bmatrix} = \begin{bmatrix} \mathbf{y}_1 - \mathbf{r}(0) \\ \mathbf{y}_2 \\ \vdots \\ \mathbf{y}_T \end{bmatrix} \rightarrow$$

$$\rightarrow [\mathbf{Z} \quad \boldsymbol{\Phi}] \begin{bmatrix} \mathbf{s} \\ \mathbf{r} \end{bmatrix} = \mathbf{d} \tag{4}$$

where $\boldsymbol{I}$ is an identity matrix and $\mathbf{0}$ a null matrix of appropriate dimensions; $\mathbf{Z}_t(0) = [\mathbf{V}_t(0) - \mathbf{U}_t(0)]$ for $\tau = 0$ and $\mathbf{Z}_t(-p) = [-\mathbf{U}_{t+\tau}(-\tau)]$ for $0 > \tau \geq \max\{\theta_1 \cdots \theta_n\}$, as shown in the example in Figure 17. Given this temporally distributed representation of the system's operation, the problem is to find the lowest integer activity levels at each time satisfying the condition that the inventory levels carried over time are non-negative. This can be formulated as a multistage, mixed-integer linear programming problem:

$$\begin{aligned}
&\text{minimize } \boldsymbol{z} = \mathbf{1} \cdot \mathbf{s} + \mathbf{0} \cdot \mathbf{r} \\
&\text{subject to:} \\
&\begin{bmatrix} \mathbf{Z} & \boldsymbol{\Phi} \\ \mathbf{F} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{s} \\ \mathbf{r} \end{bmatrix} = \begin{bmatrix} \mathbf{d} \\ \mathbf{0} \end{bmatrix} \\
&\mathbf{s} = \text{integer} \\
&\mathbf{s} \geq \mathbf{0}; \mathbf{r} \geq \mathbf{0}
\end{aligned} \tag{5}$$

where $\mathbf{1}$ and $\mathbf{0}$ are, respectively, a unity vector and a null matrix of appropriate dimensions. Since a process cannot deliver its output unless there is time for doing, it is necessary to define for each time $1 \leq t \leq \max\{\theta_1 \cdots \theta_n\}$ a diagonal matrix $\mathbf{D}_{\mathrm{t}}$ having as its generic elements $d_{jj} = 1$ if $\theta_j \leq t$ and zero otherwise, and then post-multiply it with matrix $\mathbf{Z}_t(0)$. The result is used to define the matrix of constraints $\mathbf{F} = \begin{bmatrix} \mathbf{Z}_1(0)\mathbf{D}_1 & \cdots & \mathbf{0} & \\ \vdots & \ddots & \vdots & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{Z}_{\max\{\theta_1 \cdots \theta_n\}}(0)\mathbf{D}_{\max\{\theta_1 \cdots \theta_n\}} & \end{bmatrix}$.

Figure 18 shows an application for the same example in Figure 17 if $\mathrm{r}(0) = \begin{bmatrix} 920 \\ 170 \end{bmatrix}$; $\mathbf{y}_1 = \begin{bmatrix} 0 \\ 85 \end{bmatrix}$; $\mathbf{y}_2 = \begin{bmatrix} 0 \\ 80 \end{bmatrix}$; $\mathbf{y}_3 = \begin{bmatrix} 300 \\ 65 \end{bmatrix}$; $\mathbf{V} = \begin{bmatrix} 600 & 0 \\ 0 & 200 \end{bmatrix}$; $\mathbf{U} = \begin{bmatrix} 0 & 800 \\ 0 & 0 \end{bmatrix}$; $\mathbf{b} = [600 \quad 0]$. Multiple solutions could be obtained due to the inherent nature of the optimisation problem. Additional constraints may help refine the desired result.

From a conceptual viewpoint, the above mentioned approach can be seen as one possible way of realising integrated Maintenance Resource Planning aiming to effectively align the capacity of the sustainment process, also in terms of spares inventories, to the demand of sustainment tasks to be performed over time (Bruggeman and van Dierdonck, 1985). From a computational viewpoint alternative approaches, in particular the use of z-transforms (Grubbström and Ovrin, 1992), can be more effective for the mathematically literate, yet less practical to implement in a business context using, for example, spreadsheets.

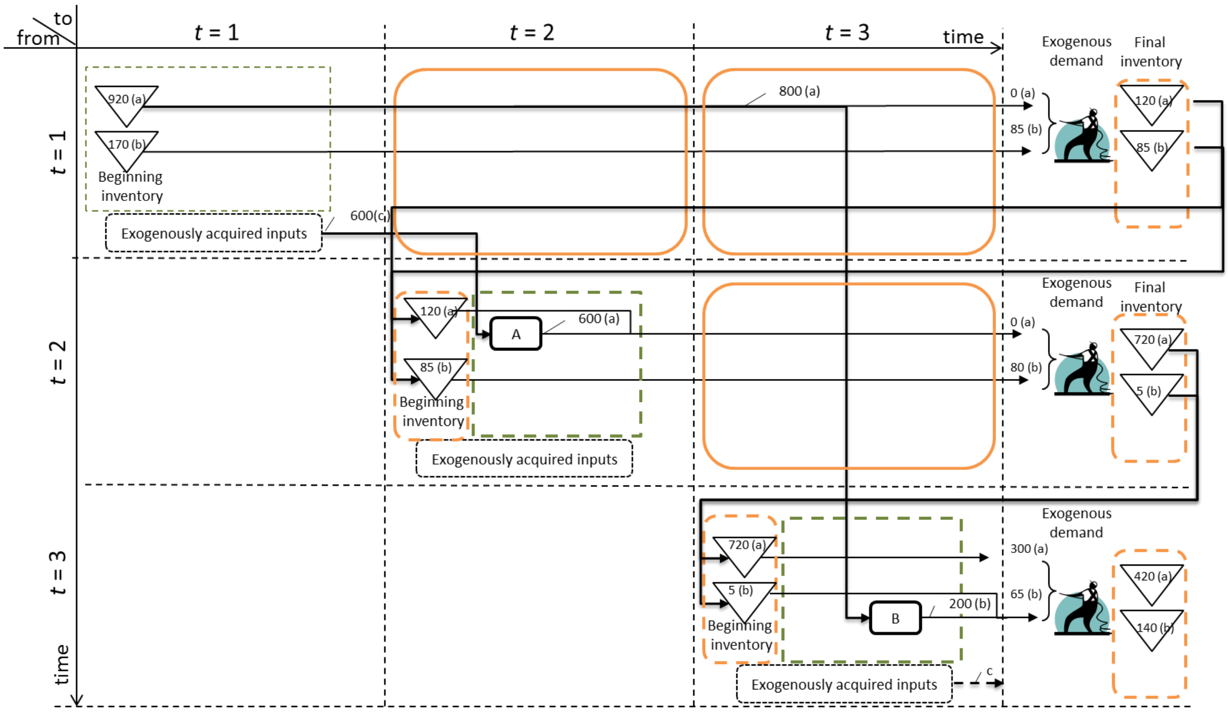


Figure 18 Numerical example with two temporally distributed, dependent processes

6 Conclusion

This paper has investigated the extent to which current approaches to TLC provide sufficient methodological foundations for estimating the cost of delivering advanced services such as availability through a product-service-system. The main motivation to undertake this research has been to provide a well-defined concept of TLC for use in contracting for availability. Too often, 'faith' that a candidate product technology alone will reduce cost is the result of a lack of descriptive and analytical power in the cost analysis (Davis et al., 2003). Avoiding such shortcomings is particularly important in the context of PSS, since what counts is neither the individual asset nor service, but the socio-technical system delivering results of value for the customer.

The methodological challenges for the prevailing approaches to TLC within a context where advanced services are offered through a PSS have been identified and assessed through a systemic review of the public domain literature. TLC is an enduring concept for which authors tend to assume is methodologically homogeneous across the literature. This assumption only becomes obvious when the literature is examined from multiple domains. Due to methodological heterogeneities and terminological ambiguities (e.g., for terms such as cost, cash flows, and expenses; cost drivers and CERs; 'system' and PSS; processes; and life cycle) the methods adopted in the reviewed literature on TLC provide very limited support for those engaged in through-life cost estimation for PSS. Current debates around the estimation of the through-life cost for providing a service centre on the adaptation of established product cost estimation techniques, with a restrictive interpretation of the concept of life cycle. As a consequence cost estimation for a PSS is reduced to estimating the cost of the in-service phase of a durable product, not the cost of a socio-technical system delivering results of value.

From the evidence in the literature a methodology of TLC for use in a PSS has been formulated which addresses the main challenges as follows:

- **Cost object (What):** *the proposed methodology is grounded on a representation of a PSS as a socio-technical 'system' delivering value in-use, and preserves its structure in order to handle multiple interacting cost objects simultaneously.*
- **Scope and purpose (Why?/To what extent?):** *the proposed methodology shifts emphasis from one-off should-cost estimating to through-life cost consciousness, enabling a systematic understanding of the functioning of the system being modelled as a basis to decide what action could be taken. It allows consistently expanding the boundaries of the analysis beyond the "four walls" of the individual firm to improve the visibility of end-to-end operations.*
- **Computations and metrics (How?):** *the proposed methodology formally and transparently addresses the interplay between monetary and non-monetary metrics. Reciprocal influences between multiple outcomes delivered by a system of purposeful activities are taken into account through a structure in which the relevant metrics and uncertainties thereof can be conveniently organised and simultaneously treated analytically.*

In particular, it is recognised that qualitative methods must be employed to provide an understanding of how the actions undertaken within the boundaries of the enterprise enable or prevent the delivery of advanced services through a PSS. Quantitative methods must offer a mathematically treatable counterpart of a qualitative PSS representation, preserving the system structure in terms of dependencies and interdependencies. The principles of IOA originally developed in macroeconomics provide a suitable foundation for dealing analytically with a system of interdependent economic activities expressed as both monetary and non-monetary information, without requiring a priori commitment to a specific modelling language or a specific Information System to be already in place.

The proposed methodology of TLC emphasises aspects that could be better exploited if the estimate of the cost of an advanced service delivered by such a system is integrated, from a computational perspective, with by a model of the operation of the delivery system itself – the PSS. However, some caveats are necessary:

- In the literature, ‘activities’ or ‘processes’ often serve as cost categories, whilst ignoring the logical relationships between them from an analytical viewpoint. Hence, invoking approaches such as Activity Based Costing in TLC is not sufficient per se to guarantee that the nature of PSS as a socio-technical system is adequately addressed.

- The proposed methodology best operates under contractual conditions that encourage transparency and clarity of mutual commitments. Nicolini et al. (2000) outline the limitations of implementing strategic-orientated approaches to cost in contexts where a lack of trust and transparency is deep-seated within the industry’s culture and practices. The move towards availability contracting should provide the cooperative environment which is necessary for approaches such as TLC to work (Goldbach, 2002).

- To achieve cost reductions beyond the possibilities of individual organisations within the enterprise, information asymmetry between the customer and the provider regarding the relationship between the specifications established by the former and the resulting costs at the latter, should be reduced (Cooper and Slagmulder, 2004b).

The research presented in this paper strengthens the concept of TLC as a cost engineering *and* management practice by addressing some of the ambiguities and inconsistencies of current approaches in terms of boundaries and scope, metrics and cost objects involved. This provides a foundation for future research on TLC that is capable of effectively directing the attention of the decision maker towards the enabling conditions for the successful provision of such an advanced service as availability through a PSS.

Appendix

Table A.1 Conceptual research on TLC - Availability/Performance-based business model. Abbreviations: see Table 4

References	Cost object						Viewpoint							Computations																				
		Stand-alone instance					Purpose		Scope						Stand-alone instance costing																			
									Inter-temporal			Activities			Time span							Product								Service Product-support				
																						Platform/ family			Unit									
	Delivery system (Enterprise)	Time interval	Product platform	Product unit	Service (product utilisation)	Service (product sustainment)	Strategic cost management	Should-cost estimate	Time with user	Duration of producer involvement	Time in the market	Value chain	Network	Means-ends costing	REL-CBS	CBS	AA	SI	CBR	CF	CA	SI	CBR	CBS	CBS	Gen	SI	CBR	CA	CBS	Gen	SI	CBR	CA
Aircraft																																		
(Buderath, 2011)		●						●	●						●																			
General applicability																																		
(Huang et al., 2012)						●		●	●																									●
(Roy and Erkoyuncu, 2011)		●				●		●	●						●																			
Military equipment																																		
(Bankole et al., 2011)		●						●	●											●														
(Datta and Roy, 2010)						●		●	●						●															●				

Table A.2 Conceptual research on TLC – "product and support" business model. Abbreviations: see Table 4

References	Cost object						Viewpoint							Computations																				
	Delivery system (Enterprise)	Stand-alone instance					Purpose		Scope					Means-ends costing	Stand-alone instance costing																			
									Inter-temporal			activities			Time span							Product								Service Product-support				
																						Platform/ family			Unit									
		Time interval	Product platform	Product unit	Service (product utilisation)	Service (product sustainment)	Strategic cost management	Should-cost estimate	Time with user	Duration of producer involvement	Time in the market	Value chain	Network		REL-CBS	CBS	AA	SI	CBR	CF	CA	SI	CBR	CBS	CBS	Gen	SI	CBR	CA	CBS	Gen	SI	CBR	CA
Aircraft																																		
(Mirghani, 1996)	●						●					●		●																				
(Pugh et al., 2010)		●		●				●		●						●									●									
Aircraft subsystems																																		
(Fiorello, 1973)		●						●	●						●																			
(Nalos and Schulz, 1965)		●						●	●						●																			
(Toohey and Calvo, 1980)		●						●	●						●																			
Military equipment																																		
(McGuire, 1971)		●						●	●											●														
(Smit, 2012)		●		●				●	●							●									●									
Manufacturing/test equip.																																		
(Lad and Kulkarni, 2008)		●						●	●						●																			
(Liu et al., 2008)		●		●				●		●											●								●					
(Shank and Govindarajan, 1992)	●						●					●		●																				
Microelectronics																																		
(Cooper and Slagmulder, 2004a)		●		●			●				●	●																	●					
Construction																																		
(Schulze et al., 2012)	●						●					●		●																				
General applicability																																		
(Clinton and Graves, 1999)		●					●				●	●					●																	
(Cople and Brick, 2010)		●						●	●						●																			
(Ellram, 1996)		●					●				●	●									●													
(Fixson, 2004)		●	●	●				●		●											●								●					
(Gutschelhofer and Roberts, 1997)		●					●				●	●					●								●									
(Mévellec and Perry, 2006)	●						●					●		●																				
(Newnes et al., 2008)		●		●				●	●												●								●					
(Prasad, 1999)	●						●					●		●																				
(Seuring and Goldbach, 2002)	●						●					●		●																				

Table A.3 Quantitative research in TLC - Availability/Performance-based business model. Abbreviations: see Table 4

References	Cost object						Viewpoint							Computations																				
	Delivery system (Enterprise)	Stand-alone instance					Purpose		Scope					Means-ends costing	Stand-alone instance costing																			
									Inter-temporal			activities			Time span							Product								Service Product-support				
																						Platform/ family			Unit									
		Time interval	Product platform	Product unit	Service (product utilisation)	Service (product sustainment)	Strategic cost management	Should-cost estimate	Time with user	Duration of producer involvement	Time in the market	Value chain	Network		REL-CBS	CBS	AA	SI	CBR	CF	CA	SI	CBR	CBS	CBS	Gen	SI	CBR	CA	CBS	Gen	SI	CBR	CA
Aircraft																																		
(Kim et al., 2007)	•						•	•						•																				
Aircraft subsystems																																		
(Jazouli and Sandborn, 2011)	•						•	•						•																				
(Newnes et al., 2011)		•						•	•						•																			
(Romero Rojo et al., 2012)		•				•		•			•					•																	•	
(Bowman and Schmee, 2001)		•						•			•				•																			
(Sandberg et al., 2005)	•		•				•	•										•									•							
General applicability																																		
(Löfstrand et al., 2012)		•				•		•	•						•															•				
Manufacturing/test equip.																																		
(Huang et al., 2011)						•		•	•						•																	•		
(Lanza and Ruhl, 2009)		•				•		•	•						•															•				
Military equipment																																		
(Early et al., 2012)		•				•		•	•						•																•			
(Erkoyuncu et al., 2011a)	•						•	•						•																				
(Kumar et al., 2007)		•						•	•						•																			
(Nowicki et al., 2008)		•						•	•						•																			

Table A.3 (continued) - Quantitative research in TLC - Availability/Performance-based business model

(Cont'ed)	Non-monetary metrics								Uncertainty				
	Primary					Derived					Random event generation		
	Program/ Organisation-level features	Platform-level features	Unit-level metrics		Time-related metrics	Availability	Cost Effectiveness	Other	Probabilistic	Subjective	Stochastic process	Simulation	Agent Based Modelling
			Product	Service									
Aircraft													
(Kim et al., 2007)		•			•	•			•				
Aircraft subsystems													
(Jazouli and Sandborn, 2011)		•			•	•			•			•	
(Newnes et al., 2011)					•				•				
(Romero Rojo et al., 2012)		•			•				•				
(Bowman and Schmee, 2001)	•	•			•	•			•			•	
(Sandberg et al., 2005)		•			•								
General applicability													
(Löfstrand et al., 2012)		•		•	•				•			•	
Manufacturing/test equip.													
(Huang et al., 2011)		•			•								
(Lanza and Ruhl, 2009)		•			•				•			•	
Military equipment													
(Early et al., 2012)		•			•				•		•		
(Erkoyuncu et al., 2011a)		•			•					•			•
(Kumar et al., 2007)		•			•	•			•		•		
(Nowicki et al., 2008)		•			•	•			•		•		

Table A.4 Quantitative research in TLC – "product and support" business model – aerospace applications. Abbreviations: see Table 4

References	Cost object						Viewpoint							Computations																				
	Delivery system (Enterprise)	Stand-alone instance					Purpose		Scope					Means-ends costing	Stand-alone instance costing																			
									Inter-temporal			activities			Time span							Product								Service Product-support				
																						Platform/ family			Unit									
		Time interval	Product platform	Product unit	Service (product utilisation)	Service (product sustainment)	Strategic cost management	Should-cost estimate	Time with user	Duration of producer involvement	Time in the market	Value chain	Network		REL-CBS	CBS	AA	SI	CBR	CF	CA	SI	CBR	CBS	CBS	Gen	SI	CBR	CA	CBS	Gen	SI	CBR	CA
Aircraft																																		
(Fielding, 1999)		●						●		●										●							●							
(Fiorello, 1975)		●						●		●										●														
(Khan and Houston, 2000)		●				●		●	●						●																			
(Marks and Massey, 1981)		●						●	●									●																
(Roskam, 1990)		●	●	●				●		●						●						●					●							
(Stump, 1988)		●						●	●							●																		
(Suwondo, 2007)		●				●		●	●							●														●				
Aircraft subsystems																																		
(Blackwell and Hausner, 1999)		●						●	●											●														
(Brode, 1975)		●				●		●	●						●															●				
(Cheung et al., 2009)		●		●				●		●					●														●					
(Curry, 1993)		●		●				●		●								●				●					●							
(Davis et al., 2003)		●	●	●				●		●									●				●					●						
(Debardelaben et al., 1997)		●		●				●		●								●									●							
(Feldman et al., 2009)		●						●	●						●																			
(Hitt, 1997)		●						●	●								●																	
(Kiang, 1979)		●						●	●						●																			
(Killingsworth and Jarvaise, 1990)				●		●		●		●						●											●					●		
(Kilpatrick and Jones, 1974)		●						●	●									●																
(Schor et al., 1989)		●				●		●		●					●															●				
(Seger, 1983)		●		●		●		●	●						●													●					●	
(Tuttle and Shwartz, 1979)		●		●		●		●		●					●												●							
(Curran et al., 2007)		●		●				●	●											●						●								
(Curran et al., 2004)		●		●				●		●						●									●									
(Xu et al., 2008)	●		●				●		●						●									●										

Table A.4 (continued) - Quantitative research in TLC – "product and support" business model – aerospace applications

(Cont'ed)	Non-monetary metrics								Uncertainty				
	Primary					Derived			Probabilistic	Subjective	Random event generation		
	Program/ Organisation-level features	Platform-level features	Unit-level metrics		Time-related metrics	Availability	Cost Effectiveness	Other			Stochastic process	Simulation	Agent Based Modelling
			Product	Service									
Aircraft													
(Fielding, 1999)		•			•								
(Fiorello, 1975)					•								
(Khan and Houston, 2000)					•								
(Marks and Massey, 1981)		•		•	•								
(Roskam, 1990)		•			•								
(Stump, 1988)					•				•		•		
(Suwondo, 2007)		•		•	•		•						
Aircraft subsystems													
(Blackwell and Hausner, 1999)					•								
(Brode, 1975)		•		•	•								
(Cheung et al., 2009)			•										
(Curry, 1993)		•											
Davis et al., 2003)		•											
(Debardelaben et al., 1997)		•											
(Feldman et al., 2009)		•			•	•			•			•	
(Hitt, 1997)					•								
(Kiang, 1979)		•			•	•			•		•		
(Killingsworth and Jarvaise, 1990)		•											
(Kilpatrick and Jones, 1974)		•			•								
(Schor et al., 1989)		•		•	•	•			•		•		
(Seger, 1983)		•			•								
(Tuttle and Shwartz, 1979)		•			•								
(Curran et al., 2007)		•	•		•								
Curran et al., 2004)		•	•		•								
(Xu et al., 2008)		•			•								

Table A.5 Quantitative research in TLC – "product and support" business model – non aerospace applications. Abbreviations: see Table 4

References	Cost object						Viewpoint							Computations																				
															Stand-alone instance costing																			
		Stand-alone instance					Purpose		Scope						Time span							Product								Service Product-support				
									Inter-temporal			activities										Platform/ family			Unit									
	Delivery system (Enterprise)	Time interval	Product platform	Product unit	Service (product utilisation)	Service (product sustainment)	Strategic cost management	Should-cost estimate	Time with user	Duration of producer involvement	Time in the market	Value chain	Network	Means-ends costing	REL-CBS	CBS	AA	SI	CBR	CF	CA	SI	CBR	CBS	CBS	Gen	SI	CBR	CA	CBS	Gen	SI	CBR	CA
Consumer products																																		
(Hatch and Badinelli, 1999)		•		•				•	•						•										•									
General applicability																																		
(BS EN, 2005)		•						•	•						•																			
(Emblemsvåg, 2003)	•						•						•	•																				
(Fabrycky and Blanchard, 1991)		•		•				•		•						•									•									
(Mueller, 2009)		•						•		•										•														
(Öner and van Houtum, 2010)		•						•		•					•																			
(Reimann and Huq, 1993)		•	•	•			•						•			•								•	•									
(Wu and Longhurst, 2011)		•						•	•						•																			
Human resource																																		
(Dahlén and Bolmsjö, 1996)		•						•	•											•														
Manufacturing/test equip.																																		
(Chen and Keys, 2009)		•		•				•		•						•									•					•				
(Degraeve et al., 2005)		•		•				•	•							•																		
(Folgado et al., 2010)		•		•				•		•						•									•									
(Gitzel and Herbort, 2008)		•						•	•							•																		
(Heilala et al., 2007)		•						•	•											•														
(Hwang, 2005)		•						•	•											•														
(Kayrbekova et al., 2011)		•				•		•	•						•															•				
(Kleyner and Sandborn, 2008)		•						•		•					•																			
(Lycette and Lowenstein, 2011)		•						•	•						•																			
(Ntuen, 1985)		•						•	•						•																			
(Rhee and Ishii, 2003)		•						•	•						•																			
(Sachdeva et al., 2008)		•						•	•						•																			
(Settanni and Emblemsvåg, 2010)	•						•						•	•																				
(Waghmode and Sahasrabudhe, 2011)		•						•	•						•																			

Table A.5 (continued) - Quantitative research in TLC – “product and support” business model – non aerospace applications

(Cont’ed)	Non-monetary metrics								Uncertainty				
	Primary					Derived					Random event generation		
			Unit-level metrics										
	Program/ Organisation-level features	Platform-level features	Product	Service	Time-related metrics	Availability	Cost Effectiveness	Other	Probabilistic	Subjective	Stochastic process	Simulation	Agent Based Modelling
Consumer products													
(Hatch and Badinelli, 1999)		•	•		•	•			•				
(BS EN, 2005)		•	•	•	•	•			•				
(Emblemsvåg, 2003)		•	•		•				•			•	
(Fabrycky and Blanchard, 1991)		•	•		•								
(Mueller, 2009)					•								
(Öner and van Houtum, 2010)		•			•				•		•		
(Reimann and Huq, 1993)			•						•			•	
(Wu and Longhurst, 2011)		•			•				•				
Human resource													
(Dahlén and Bolmsjö, 1996)													
Manufacturing/test equip.													
(Chen and Keys, 2009)		•	•	•	•								
(Degraeve et al., 2005)	•	•											
(Folgado et al., 2010)		•	•		•								
(Gitzel and Herbort, 2008)		•			•								
Heilala et al., 2007)		•			•			•					
(Hwang, 2005)		•			•			•	•			•	
(Kayrbekova et al., 2011)				•									
(Kleyner and Sandborn, 2008)		•			•				•			•	
(Lycette and Lowenstein, 2011)		•			•								
(Ntuen, 1985)		•			•	•			•			•	
(Rhee and Ishii, 2003)		•		•	•	•			•			•	
(Sachdeva et al., 2008)		•			•	•			•			•	
(Settanni and Emblemsvåg, 2010)								•	•			•	
(Waghmode and Sahasrabudhe, 2011)		•	•	•	•				•		•		

Table A.6 Quantitative research in TLC – "product and support" business model – military equipment and other applications. Abbreviations: see Table 4

References	Cost object						Viewpoint							Computations																				
		Stand-alone instance					Purpose		Scope						Stand-alone instance costing																			
									Inter-temporal			activities			Time span							Product								Service Product-support				
																						Platform/ family			Unit									
	Delivery system (Enterprise)	Time interval	Product platform	Product unit	Service (product utilisation)	Service (product sustainment)	Strategic cost management	Should-cost estimate	Time with user	Duration of producer involvement	Time in the market	Value chain	Network	Means-ends costing	REL-CBS	CBS	AA	SI	CBR	CF	CA	SI	CBR	CBS	CBS	Gen	SI	CBR	CA	CBS	Gen	SI	CBR	CA
Microelectronics																																		
(Park and Seo, 2004)		•				•		•	•									•												•				
(Prabhakar and Sandborn, 2012)		•						•	•						•																			
(Sandborn, 2013)		•		•				•	•						•										•									
(Skwirzynski, 1983)		•						•	•						•																			
Military equipment																																		
(Blanchard, 1992)	•		•				•		•						•									•										
(Burridge and Coyle, 2003)		•						•	•							•																		
(Emblemsvåg and Tonning, 2003)		•				•		•	•											•														
(Lindholm and Suomala, 2007)		•					•				•	•					•																	
(Ryan et al., 2013)		•						•	•									•																
Multiple																																		
(Dhillon, 2010)		•	•	•				•	•						•														•					•
(Hunkeler et al., 2008)		•		•			•					•				•									•									
Not specified																																		
(Marais and Saleh, 2009)		•						•	•											•														
Transport																																		
(Alonso et al., 2007)		•		•				•		•						•									•									
(Jambulingam and Jardine, 1986)		•						•	•						•																			

Table A.6 (continued) - Quantitative research in TLC – “product and support” business model – military equipment and other applications

(Cont’ed)	Non-monetary metrics								Uncertainty				
	Primary					Derived					Random event generation		
			Unit-level metrics										
	Program/ Organisation-level features	Platform-level features	Product	Service	Time-related metrics	Availability	Cost Effectiveness	Other	Probabilistic	Subjective	Stochastic process	Simulation	Agent Based Modelling
Microelectronics													
Park and Seo, 2004)		•			•								
(Prabhakar and Sandborn, 2012)		•	•		•								
(Sandborn, 2013)		•	•	•	•	•			•			•	
(Skwirzynski, 1983)		•			•	•	•		•			•	
Military equipment													
(Blanchard, 1992)		•	•		•		•		•				
(Burridge and Coyle, 2003)					•								
(Emblemsvåg and Tonning, 2003)								•		•		•	
Lindholm and Suomala, 2007)					•				•			•	
(Ryan et al., 2013)	•				•								
Multiple applications													
(Dhillon, 2010)		•	•	•	•	•			•				
(Hunkeler et al., 2008)			•		•			•					
Not specified													
Marais and Saleh, 2009)					•				•		•		
Transport													
(Alonso et al., 2007)		•	•		•			•					
(Jambulingam and Jardine, 1986)		•			•				•				

References

Aguilar-Saven, R.S., 2004. Business process modelling: Review and framework. International Journal of Production Economics 90 (2), 129–149.

Alonso, J.C., Dose, J., Fleischer, G., Geraghty, K., Greif, A., Rodrigo, J., Schmidt, W.-P., 2007. Electrical and electronic components in the automotive sector: Economic and environmental assessment. International Journal of Life Cycle Assessment 12 (5), 328–335.

Anagboso, M., Spence, A., 2009. Measuring Defence. Economic & Labour Market Review 3 (1), 44–52.

Asiedu, Y., Gu, P., 1998. Product life cycle cost analysis: State of the art review. International Journal of Production Research 36 (4), 883–908.

Assaf, S.A., Al-Hammad, A., Jannadi, O.A., Abu Saad, S., 2002. Assessment of the Problems of Application of Life Cycle Costing in Construction Projects. Cost Engineering 44 (2), 17–22.

BAE Systems, 2009. Availability contracting: MAS procurement handbook. BAE Systems Plc.

Baines, T., Lightfoot, H., 2013. Made to serve. Wiley, Hoboken, NJ.

Bankole, O.O., Roy, R., Shehab, E., Cheruvu, K., Johns, T., 2011. Product–service system affordability in defence and aerospace industries: state-of-the-art and current industrial practice. International Journal of Computer Integrated Manufacturing 25 (4-5), 398–416.

Bartolomei, J.E., Hastings, D.E., Neufville, R. de, Rhodes, D.H., 2012. Engineering Systems Multiple-Domain Matrix: An organizing framework for modeling large-scale complex systems. Systems Engineering 15 (1), 41–61.

Batista, L., Smart, A., Maull, R., 2008. The systemic perspective of service processes: underlying theory, architecture and approach. Production Planning & Control 19 (5), 535–544.

Blackwell, P., Hausner, E., 1999. The redefinition of supportability and its role as a systems engineering tool. Naval Engineers Journal 111 (3), 269–277.

Blanchard, B.S., 1992. Logistics engineering and management, 4th ed. Prentice-Hall, Englewood Cliffs, N.Y.

Bohn, R.E., 1994. Measuring and Managing Technological Knowledge. Sloan Management Review 36 (1), 61–73.

Boons, A.N.A.M., 1998. Product costing for complex manufacturing systems. International Journal of Production Economics 55 (3), 241–255.

Bowman, R.A., Schmee, J., 2001. Pricing and managing a maintenance contract for a fleet of aircraft engines. Simulation 76 (2), 69–77.

Brode, H., 1975. Cost of Ownership – An overview. Life Cycle Costs: evaluation of avionic system reliability improvements, In: Proceedings of the Annual Reliability and Maintainability Symposium. Washington, D.C., 28-30 January 1975, 212–216.

Bruggeman, W., van Dierdonck, R., 1985. Maintenance resource planning an integrative approach. International Journal of Production Economics 9 (1-3), 147–154.

BS EN, 2005. 60300-3-3:2004 Dependability management. Part 3-3: Application guide — Life cycle costing. BSI.

BS EN, 2009. 60300-3-4:2008 Dependability management. Application guide. Guide to the specification of dependability requirements. BSI.

BS EN IEC, 2009. 60300-3-16:2008 Dependability management. Application guide. Guidelines for specification of maintenance support services. BSI.

BS EN ISO, 2006. 14040:2006 Environmental management. Life cycle assessment. Principles and framework. BSI.

BS ISO/IEC, 2002. 15288:2002 Systems engineering. System life cycle processes. BSI.

Buderath, M., 2011. The management of reliability and maintainability and the choice of maintenance concept to optimize aircraft availability and life cycle cost, in: RTO (Ed.). Enhanced aircraft platform availability through advanced maintenance concepts and technologies. Neuilly-sur-Seine CEDEX, France: NATO, Research and Technology Organisation, 9.1-9.24.

Burridge, J., Coyle, J., 2003. OSCAM – simulating Operation and Support Costs using system dynamics, in: Cost Structure and Life Cycle Cost (LCC) for Military Systems. NATO, Research and Technology Organisation, 9.1-9.10.

Caldwell, N.D., Settle, V., 2011. Incentives and contracting for availability: procuring complex performance, in: Ng, I.C.L., Parry, G.C., Wild, P., McFarlane, D., Tasker, P. (Eds.). Complex engineering service systems. Concepts and research. Berlin: Springer, 147–160.

Chen, S., Keys, L.K., 2009. A cost analysis model for heavy equipment. Computers & Industrial Engineering 56 (4), 1276–1288.

Cheung, W.M., Marsh, R., Newnes, L.B., Mileham, A.R., Lanham, J.D., 2009. Standards and inference of design information in through-life costing of innovative defence electronic products. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 223 (2), 169–181.

Christensen, P.N., Sparks, G.A., Kostuk, K.J., 2005. A method-based survey of life cycle costing literature pertinent to infrastructure design and renewal. Canadian Journal of Civil Engineering 32 (1), 250–259.

Cinquini, L., Tenucci, A., 2010. Strategic management accounting and business strategy: a loose coupling? Journal of Accounting & Organizational Change 6 (2), 228–259.

Clinton, B.D., Graves, A.H., 1999. Product value analysis: Strategic analysis over the entire product life cycle. Journal of Cost Management (May/June), 22–29.

Coccia, M., 2005. Technometrics: Origins, historical evolution and new directions. Technological Forecasting and Social Change 72 (8), 944–979.

Conklin, E.J., 2006. Dialogue mapping: Building shared understanding of wicked problems. Wiley, Hoboken, NJ.

Cooper, R., 1990. Explicating the logic of ABC. Management Accounting 68 (10), 58–60.

Cooper, R., Slagmulder, R., 2004a. Achieving full-cycle cost management. Sloan Management Review 46 (1), 45–52.

Cooper, R., Slagmulder, R., 2004b. Interorganizational cost management and relational context. Accounting Organizations and Society 29 (1), 1–26.

Cople, D.G., Brick, E.S., 2010. A simulation framework for technical systems life cycle cost analysis. Simulation Modelling Practice and Theory 18 (1), 9–34.

Curran, R., Gomis, G., Castagne, S., Butterfield, J., Edgar, T., Higgins, C., McKeever, C., 2007. Integrated digital design for manufacture for reduced life cycle cost. International Journal of Production Economics 109 (1-2), 27–40.

Curran, R., Raghunathan, S., Price, M., 2004. Review of aerospace engineering cost modelling: The genetic causal approach. Progress in Aerospace Sciences 40 (8), 487–534.

Curry, E.E., 1993. FALCCM-H: Functional Avionics Life Cycle Cost Model for Hardware, in: Proceedings of the IEEE National Aerospace and Electronics Conference, Dayton, OH , USA. 24-28 May 1993, 950–953.

Dahlén, P., Bolmsjö, G.S., 1996. Life-cycle cost analysis of the labor factor. International Journal of Production Economics 46-47, 459–467.

Datta, P.P., Roy, R., 2010. Cost modelling techniques for availability type service support contracts: A literature review and empirical study. CIRP Journal of Manufacturing Science and Technology 3 (2), 142–157.

Davis, N., Jones, J., Warrington, L., 2003. A framework for documenting and analyzing life-cycle costs using a simple network based representation, in: Proceedings of the Annual Reliability and Maintainability Symposium, Tampa, FL, January 27-30, 2003, 232–236.

Dean, E.B., 1993. Why Does It Cost How Much? in: Proceedings of the AIAA Aircraft Design, Systems, and Operations Meeting, Monterey, CA, 11-13 August 1993. doi: 10.2514/6.1993-3966

Debardelaben, J.A., Madisetti, V.K., Gadient, A.J., 1997. Incorporating cost modeling in embedded-system design. IEEE Design & Test of Computers 14 (3), 24–35.

Degraeve, Z., Roodhooft, F., Doveren, B. van, 2005. The Use of Total Cost of Ownership for Strategic Procurement: A Company-Wide Management Information System. The Journal of the Operational Research Society 56 (1), 51–59.

Dhillon, B.S., 1981. Life cycle cost: A survey. Microelectronics Reliability 21 (4), 495–511.

Dhillon, B.S., 2010. Life cycle costing for engineers. Taylor & Francis, Boca Raton, FL.

Doost, R.K., 1996. Input, output, outcome: simply a change in orientation. Managerial Auditing Journal 11 (7), 12–15.

Dunk, A., 2004. Product life cycle cost analysis: the impact of customer profiling, competitive advantage, and quality of IS information. Management Accounting Research 15 (4), 401–414.

Durairaj, S.K., Ong, S.K., Nee, A.Y.C., Tan, R.B.H., 2002. Evaluation of Life Cycle Cost Analysis Methodologies. Corporate Environmental Strategy 9 (1), 30–39.

Early, J.M., Price, M.A., Curran, R., Raghunathan, S., 2012. Whole-Life Costing for Capability. Journal of Aircraft 49 (3), 712–723.

Edwards, J.B. (Ed.), 1999. Cost management for service industries. Warren, Gorham & Lamont, NY.

Elford, D.G., 2011. The Evolution of Aircraft Support Concepts Within the UK MoD's Defence Logistics Transformation Programme, in: RTO (Ed.). Enhanced aircraft platform availability through advanced maintenance concepts and technologies. NATO, Research and Technology Organisation, 6.1-6.14.

Ellram, L.M., 1995. Total cost of ownership: an analysis approach for purchasing. International Journal of Physical Distribution & Logistics Management 25 (8), 4–23.

Ellram, L.M., 1996. A Structured Method for Applying Purchasing cost Management Tools. International Journal of Purchasing & Materials Management 32 (1), 11–19.

Emblemsvåg, J., 2003. Life-cycle costing: Using activity-based costing and Monte Carlo methods to manage future costs and risks. Wiley, Hoboken, N.J.

Emblemsvåg, J., 2011. Augmenting the Risk Management Process, in: Nota, G. (Ed.). Risk Management Trends. Rijeka, Croatia: InTech, 1–26.

Emblemsvåg, J., Tonning, L., 2003. Decision support in selecting maintenance organization. Journal of Quality in Maintenance Engineering 9 (1), 11–24.

Erkoyuncu, J.A., Roy, R., Datta, P.P., Wardle, P., Murphy, F., 2011a. Service uncertainty and cost for product service systems, in: Ng, I.C.L., Parry, G.C., Wild, P., McFarlane, D., Tasker, P. (Eds.). Complex engineering service systems. Concepts and research. Berlin: Springer, 129–146.

Erkoyuncu, J.A., Roy, R., Shehab, E., Cheruvu, K., 2011b. Understanding service uncertainties in industrial product–service system cost estimation. The International Journal of Advanced Manufacturing Technology 52 (9-12), 1223–1238.

Fabrycky, W.J., Blanchard, B.S., 1991. Life-cycle cost and economic analysis. Prentice Hall, Englewood Cliffs, N.J.

Feldman, K., Jazouli, T., Sandborn, P.A., 2009. A Methodology for Determining the Return on Investment Associated With Prognostics and Health Management. IEEE Transactions on Reliability 58 (2), 305–316.

Ferrin, B.G., Plank, R.E., 2002. Total Cost of Ownership Models: An Exploratory Study. Journal of Supply Chain Management 38 (3), 18–29.

Field, F., Kirchain, R., Roth, R., 2007. Process cost modeling: Strategic engineering and economic evaluation of materials technologies. JOM Journal of the Minerals, Metals and Materials Society 59 (10), 21–32.

Fielding, J.P., 1999. Introduction to aircraft design. Cambridge University Press, Cambridge.

Fiorello, M.R., 1973. Problems in avionics life-cycle analysis. RAND Corporation, Santa Monica, CA.

Fiorello, M.R., 1975. Estimating Life-Cycle Costs: a case study of the A-7D. RAND Corporation, Santa Monica, CA.

Fixson, S.K., 2004. Assessing product architecture costing: product life cycles, allocation rules and cost models, in: Proceedings of ASME 2004 Design Engineering Technical Conference, Salt Lake City, Utah. 28 September - 2 October 2004.

Folgado, R., Peças, P., Henriques, E., 2010. Life cycle cost for technology selection: A Case study in the manufacturing of injection moulds. International Journal of Production Economics 128 (1), 368–378.

Galloway, I., 1996. Design for support and support the design: integrated logistic support – the business case. Logistics Information Management 9 (1), 24–31.

Geissdörfer, K., Gleich, R., Wald, A., 2009. Standardisierungspotentiale lebenszyklusbasierter Modelle des strategischen Kostenmanagements. Zeitschrift für Betriebswirtschaft 79 (6), 693–715.

Gitzel, R., Herbort, M., 2008. Optimizing life cycle cost using genetic algorithms. Cost Management 22 (6), 34–47.

Goh, Y.M., Newnes, L.B., Mileham, A.R., McMahon, C.A., Saravi, M.E., 2010. Uncertainty in Through-Life Costing - Review and Perspectives. IEEE Transactions on Engineering Management 57 (4), 689–701.

Goldbach, M., 2002. Organisational settings in supply chain costing, in: Seuring, S.A., Goldbach, M. (Eds.). Cost management in supply chains. Physica-Verlag, Heidelberg, 89–108.

Grubbstrom, R.W., Tang, O., 2000. An Overview of Input-Output Analysis Applied to Production-Inventory Systems. Economic Systems Research 12 (1), 3–25.

Grubbström, R.W., Ovrin, P., 1992. Intertemporal generalization of the relationship between material requirements planning and input-output analysis. International Journal of Production Economics 26 (1-3), 311–318.

Gupta, Y., Chow, W.S., 1985. Twenty-Five Years of Life Cycle Costing — Theory and Applications: A Survey. International Journal of Quality & Reliability Management 2 (3), 51–76.

Gutschelhofer, A., Roberts, H., 1997. Anglo-Saxon and German life-cycle costing. The International Journal of Accounting 32 (1), 23–44.

Hansen, D.R., Mowen, M.M., 2003. Cost management: Accounting and control, 4th ed. Thomson/South-Western, Mason, OH.

Hatch, M., Badinelli, R.D., 1999. A concurrent optimization methodology for concurrent engineering. IEEE Transactions on Engineering Management 46 (1), 72–86.

Heijungs, R., 2001. A Theory of the environment and economic systems. Edward Elgar, Cheltenham.

Heilala, J., Montonen, J., Helin, K., 2007. Selecting the right system - assembly system comparison with total cost of ownership methodology. Assembly Automation 27 (1), 44–54.

Hitt, E.F., 1997. Avionics cost of ownership. IEEE Aerospace and Electronic Systems Magazine 12 (11), 3–7.

Hollnagel, E., 2012. FRAM, the functional resonance analysis method: Modelling complex socio-technical systems. Ashgate, Farnham.

Hoyle, C., 2013. UK reveals expenditure on delayed Watchkeeper programme. Flightglobal. http://www.flightglobal.com/news/articles/uk-reveals-expenditure-on-delayed-watchkeeper-programme-380779/ [Accessed 8 January 2013].

Huang, X., Newnes, L.B., Parry, G.C., 2011. An analysis of industrial practice for estimating the in-service costs of a product service system, in: Proceedings of the ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Washington, DC. August 28-31, 2011.

Huang, X.X., Newnes, L.B., Parry, G.C., 2012. The adaptation of product cost estimation techniques to estimate the cost of service. International Journal of Computer Integrated Manufacturing 25 (4-5), 417–431.

Hunkeler, D., Lichtenvort, K., Rebitzer, G. (Eds.), 2008. Environmental life cycle costing. SETAC/CRC Press, Pensacola, FL.

Hwang, H.-S., 2005. Costing RAM design and test analysis model for production facility. International Journal of Production Economics 98 (2), 143–149.

Hypko, P., Tilebein, M., Gleich, R., 2010. Clarifying the concept of performance-based contracting in manufacturing industries: A research synthesis. Journal of Service Management 21 (5), 625–655.

Jackson, D.W., Ostrom, L.L., 1980. Life Cycle Costing in industrial purchasing. Journal of Purchasing and Materials Management 16 (4), 8–12.

Jambulingam, N., Jardine, A.K.S., 1986. Life Cycle Costing considerations in reliability centered maintenance: an application to maritime equipment. Reliability Engineering 15 (4), 307–317.

James, K.L., 2003. Environmental life cycle costs in the Australian food packaging supply chain. PhD thesis. Victoria University of Technology, School of Accounting and Finance, Victoria University, Melbourne, Australia.

Jazouli, T., Sandborn, P., 2011. Using PHM to meet availability-based contracting requirements, in: Proceedings of the Annual Conference of the Prognostics and Health Management Society, Montreal, Canada. September 25-29, 2011.

Kaenzig, J., Wüstenhagen, R., 2010. The Effect of Life Cycle Cost Information on Consumer Investment Decisions Regarding Eco-Innovation. Journal of Industrial Ecology 14 (1), 121–136.

Kayrbekova, D., Markeset, T., Ghodrati, B., 2011. Activity-based life cycle cost analysis as an alternative to conventional LCC in engineering design. International Journal of System Assurance Engineering and Management 2 (3), 218–225.
Keller, S., Collopy, P., Componation, P., 2014. What is wrong with space system cost models? A survey and assessment of cost estimating approaches. Acta Astronautica 93 (0), 345–351.
Khan, K.A., Houston, G.D., 2000. Design optimization using Life Cycle Cost Analysis for low operating costs, in: Design for Low Cost Operation and Support. NATO, Research and Technology Organisation, 8.1-8.8.
Kiang, T., 1979. The development and implementation of Life Cycle Cost methodology, in: . Methodology for control of Life Cycle Costs for avionic systems. AGARD/NATO, Neuilly-sur-Seine CEDEX, France: 3.1-3.25.
Killingsworth, P., Jarvaise, J., 1990. VHSIC electronics and the cost of Air Force avionics in the 1990s. RAND Corporation, Santa Monica, CA.
Kilpatrick, P.S., Jones, A.L., 1974. Life Cycle Costs comparisons of avionic system design alternatives, in: Proceedings of the IEEE National Aerospace and Electronics Conference, Dayton OH, May 13-15, 1974, 514–520.
Kim, S.-H., Cohen, M.A., Netessine, S., 2007. Performance Contracting in After-Sales Service Supply Chains. Management Science 53 (12), 1843–1858.
Kim, Y.S., Lee, S.W., Koh, D.C., 2011. Representing product-service systems with product and service elements, in: Proceedings of the 18th International Conference on Engineering Design, Copenhagen, Denmark. 15-18 August 2011.
Kimita, K., Hara, T., Shimomura, Y., Arai, T., 2009. Cost evaluation method for service design based on Activity Based Costing, in: Proceedings of the 7th International Conference on Manufacturing Research, University of Warwick, UK, September 8-10, 2009.
Kleyner, A., Sandborn, P., 2008. Minimizing life cycle cost by managing product reliability via validation plan and warranty return cost. International Journal of Production Economics 112 (2), 796–807.
Korpi, E., Ala-Risku, T., 2008. Life cycle costing: a review of published case studies. Managerial Auditing Journal 23 (3), 240–261.
Kumar, D.U., Nowicki, D., Ramirez-Marquez, J., Verma, D., 2007. A goal programming model for optimizing reliability, maintainability and supportability under performance based logistics. International Journal of Reliability, Quality and Safety Engineering 14 (3), 251–261.
Lad, B.K., Kulkarni, M.S., 2008. Integrated reliability and optimal maintenance schedule design: a Life Cycle Cost based approach. International Journal of Product Lifecycle Management 3 (1), 78–90.
Lanza, G., Ruhl, J., 2009. Simulation of service costs throughout the life cycle of production facilities. CIRP Journal of Manufacturing Science and Technology 1 (4), 247–253.
Leontief, W., 1986. Input-output economics, 2nd ed. Oxford University Press, NY.
Lindholm, A., Suomala, P., 2002. Present and Future of Life Cycle Costing: Reflections from Finnish Companies. Liiketaloudellinen aikakauskirja: The Finnish Journal of Business Economics 54 (2), 282–292.
Lindholm, A., Suomala, P., 2007. Learning by costing: Sharpening cost image through life cycle costing? International Journal of Productivity and Performance Management 56 (8), 651–672.

Liu, H., Gopalkrishnan, V., Ng, W.K., Song, B., Li, X., 2008. An intelligent system for estimating full product Life Cycle Cost at the early design stage. International Journal of Product Lifecycle Management 3 (2/3), 96–113.

Löfstrand, M., Andrews, J., Karlberg. Magnus, Karlsson, L., 2012. Modelling and simulation of functional product system availability and support costs. International Journal of Product Development 16 (3/4), 304–326.

Lycette, B., Lowenstein, D., 2011. The real "Total Cost of Ownership" of your test equipment. IEEE Aerospace and Electronic Systems Magazine 26 (1), 40–44.

Makridakis, S.G., Wheelwright, S.C., Hyndman, R.J., 1998. Forecasting: Methods and applications, 3rd ed. John Wiley & Sons, New York, xiv, 642.

Marais, K.B., Saleh, J.H., 2009. Beyond its cost, the value of maintenance: An analytical framework for capturing its net present value. Reliability Engineering & System Safety 94 (2), 644–657.

Marks, K.E., Massey, H.G., 1981. A new approach for modeling the cost of ownership for aircraft systems: A project Air Force report. R-2601-AF. RAND, Santa Monica, CA, xiii, 139.

McGuire, G.G., 1971. The Defense Department's use of discounting in the procurement of equipment by the Life Cycle Costing concept. Journal of Purchasing and Materials Management 7 (3), 41–55.

McNair, C.J., 1990. Interdependence and control: traditional vs. Activity-Based responsibility accounting. Journal of Cost Management 4 (2), 15–24.

Meier, H., Roy, R., Seliger, G., 2010. Industrial Product-Service Systems—IPS2. CIRP Annals - Manufacturing Technology 59 (2), 607–627.

Mévellec, P., Perry, N., 2006. Whole life-cycle costs: a new approach. International Journal of Product Lifecycle Management 1 (4), 400–414.

Mirghani, M.A., 1996. Aircraft maintenance budgetary and costing systems at the Saudi Arabian Airlines: An integrated business approach. Journal of Quality in Maintenance Engineering 2 (4), 32–47.

Möller, A., 2010. Material and Energy Flow-Based Cost Accounting. Chemical Engineering & Technology 33 (4), 567–572.

Mueller, D., 2009. Modelling trade-offs in design-accompanying life cycle cost calculation. International Journal of Product Lifecycle Management 4 (1-3), 290–310.

Nalos, E.J., Schulz, R.B., 1965. Reliability and Cost of Avionics: IEEE Transactions on Reliability 14 (2), 120–130.

NIST, 1993. Integration definition for function modeling (IDEF0). National Institute of Standards and Technology, Draft Federal Information Processing Standards Publication 183.

Naylor, J.B., Griffiths, J., Naim, M.M., 2001. Knowledge-based system for estimating steel plant performance. International Journal of Operations & Production Management 21 (7), 1000–1019.

Neely, A., Gregory, M., Platts, K., 2005. Performance measurement system design: A literature review and research agenda. International Journal of Operations & Production Management 25 (12), 1228–1263.

Newnes, L.B., Mileham, A.R., Cheung, W.M., Marsh, R., Lanham, J.D., Saravi, M.E., Bradbery, R.W., 2008. Predicting the whole-life cost of a product at the conceptual design stage. Journal of Engineering Design 19 (2), 99–112.

Newnes, L.B., Mileham, A.R., Rees, G., Green, P., 2011. Costing for Avionic Through-Life Availability, in: Hesselbach, J., Herrmann, C. (Eds.), Glocalized Solutions for Sustainability in Manufacturing. Springer-Verlag, Berlin, 675–680.

Ng, I.C.L., Parry, G.C., Wild, P., McFarlane, D., Tasker, P. (Eds.), 2011. Complex engineering service systems: Concepts and research. Springer, Berlin, p.

Nicolini, D., Tomkins, C., Holti, R., Oldman, A., Smalley, M., 2000. Can Target Costing and Whole Life Costing be Applied in the Construction Industry?: Evidence from Two Case Studies. British Journal of Management 11 (4), 303–324.

Nowicki, D., Kumar, D.U., Steudel, H., Verma, D., 2008. Spares provisioning under performance-based logistics contract: profit-centric approach. Journal of the Operational Research Society 59 (3), 342–352.

Ntuen, C.A., 1985. Availability-based life cycle cost model: A simulation approach. Microelectronics Reliability 25 (2), 331–342.

Ntuen, C.A., Moore, L., 1986. Approaches to life cycle cost analysis with system availability constraints - A review. Microelectronics Reliability 26 (2), 341–354.

Olubodun, F., Kangwa, J., Oladapo, A., Thompson, J., 2010. An appraisal of the level of application of life cycle costing within the construction industry in the UK. Structural Survey 28 (4), 254–265.

Öner, K.B.K.G.P., van Houtum, G.J., 2010. Optimization of component reliability in the design phase of capital goods. European Journal of Operational Research 205 (3), 615–624.

Park, J.-H., Seo, K.-K., 2004. Incorporating life-cycle cost into early product development. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 218 (9), 1059–1066.

Perrigo, W., Easterday, L.J., 1974. Avionic equipment reliability and low life cycle cost, in: Proceedings of the IEEE National Aerospace and Electronics Conference, Dayton OH, May 13-15, 1974, 521–531.

Prabhakar, V.J., Sandborn, P., 2012. A part total cost of ownership model for long life cycle electronic systems. International Journal of Computer Integrated Manufacturing 25 (4-5).

Prasad, B., 1999. A model for optimizing performance based on reliability, life-cycle costs and other measurements. Production Planning & Control 10 (3), 286–300.

Pugh, P.G., Faddy, D., Curran, R., 2010. Project Management: Cost Analysis, in: Blockley, R., Shyy, W. (Eds.). Encyclopedia of Aerospace Engineering: John Wiley & Sons, Ltd.

Purchase, V., Parry, G.C., Valerdi, R., Nightingale, D., Mills, J., 2011. Enterprise Transformation: Why Are We Interested, What Is It, and What Are the Challenges? Journal of Enterprise Transformation 1 (1), 14–33.

Raa, T. ten, 2005. The economics of input-output analysis. Cambridge University Press, Cambridge.

Reimann, M.D., Huq, F., 1993. Using activity based costing to define a quantitative product life cycle cost model for concurrent engineering, in: Proceedings of the third international conference on Flexible Automation and Information Management, Limerick, Ireland.

Rhee, S.J., Ishii, K., 2003. Using cost based FMEA to enhance reliability and serviceability. Advanced Engineering Informatics 17 (3-4), 179–188.

Romero Rojo, F.J., Roy, R., Shehab, E., Cheruvu, K., Mason, P., 2012. A cost estimating framework for electronic, electrical and electromechanical (EEE) components obsolescence within the use-oriented product–service systems contracts. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 226 (1), 154–166.

Roskam, J., 1990. Airplane Design: Part VIII (Part 8): Airplane Cost Estimation: Design, Development, manufacturing, and Operating. The University of Kansas, Lawrence, Kansas, USA.

Roy, R., 2003. Cost engineering: why, what and how? Decision Engineering Report Series. Cranfield University.

Roy, R., Erkoyuncu, J.A., 2011. Service cost estimation challenges in Industrial Product-Service Systems, in: Hesselbach, J., Herrmann, C. (Eds.). Functional thinking for value creation: Heidelberg, Springer-Verlag, 1–10.

Ryan, E.T., Schubert Kabban, Christine M., Jacques, D.R., Ritschel, J.D., 2013. A Macro-Stochastic Model for Improving the Accuracy of Department of Defense Life Cycle Cost Estimates. Journal of Cost Analysis and Parametrics 6 (1), 43–74.

Sachdeva, A., Kumar, D., Kumar, P., 2008. Planning and optimizing the maintenance of paper production systems in a paper plant. Computers & Industrial Engineering 55 (4), 817–829.

Sampson, S.E., 2012. Visualizing Service Operations. Journal of Service Research 15 (2), 182–198.

Sandberg, M., Boart, P., Larsson, T., 2005. Functional Product Life-cycle Simulation Model for Cost Estimation in Conceptual Design of Jet Engine Components. Concurrent Engineering 13 (4), 331–342.

Sandborn, P., 2013. Cost Analysis of Electronic Systems. World Scientific Publishing Co. Pte. Ltd., Singapore.

Schor, A.L., Leong, F.J., Babcock, P.S., 1989. Impact of fault-tolerant avionics on life-cycle costs, in: Proceedings of the IEEE National Aerospace and Electronics Conference, Dayton, OH , USA. 22-26 May 1989, 1893–1899.

Schulze, M., Seuring, S., Ewering, C., 2012. Applying activity-based costing in a supply chain environment. International Journal of Production Economics 135 (2), 716–725.

Seddon, J., O'Donovan, B., Zokaei, K., 2011. Rethinking Lean Service, in: Macintyre, M., Parry, G.C., Angelis, J. (Eds.). Service Design and Delivery. New York: Springer, 41–60.

Seger, J.K., 1983. Reliability Investment and Life-Cycle Cost. IEEE Transactions on Reliability R-32 (3), 259–263.

Settanni, E., 2008. The need for a computational structure of LCC. International Journal of Life Cycle Assessment 13 (7), 526–531.

Settanni, E., Emblemsvåg, J., 2010. Applying a non-deterministic conceptual life cycle costing model to manufacturing processes. Journal of Modelling in Management 5 (3), 220–262.

Settanni, E., Tassielli, G., Notarnicola, B., 2011. An Input–Output technological model of Life Cycle Costing: computational aspects and implementation issues in a generalised supply chain perspective, in: Burritt, R., Schaltegger, S., Bennett, M., Pohjola, T., Csutora, M. (Eds.). Environmental management accounting and supply chain management. Springer, Dordrecht, 55–109.

Settanni, E., Thenent, N.E., Newnes, L.B., 2013. System modeling: a foundation for costing through-life availability provision, in: Proceedings of the 10th International Conference on Product Lifecycle Management. PLM13, Nantes. France. 6-10 July 2013.

Seuring, S.A., Goldbach, M. (Eds.), 2002. Cost management in supply chains. Physica-Verlag, Heidelberg.

Shank, J.K., Govindarajan, V., 1992. Strategic Cost Management and the value chain. Journal of Cost Management 5 (4), 5–21.

Sharma, D., Cui, Q., 2012. Design of Concession and Annual Payments for Availability Payment Public Private Partnership (PPP) Projects, in: Proceedings of the Construction Research Congress, West Lafayette, IN. May 22-23, 2012.

Sherif, Y.S., Kheir, N.A., 1982. Weapons systems analysis, part I: System effectiveness. Microelectronics Reliability 22 (3), 531–567.

Sherif, Y.S., Kolarik, W.J., 1981. Life cycle costing: Concept and practice. Omega 9 (3), 287–296.

Shields, M.D., Young, M.S., 1991. Managing product Life Cycle Costs: An organizational model. Journal of Cost Management 5 (3), 39–51.

Simões, J.M., Gomes, C.F., Yasin, M.M., 2011. A literature review of maintenance performance measurement: A conceptual framework and directions for future research. Journal of Quality in Maintenance Engineering 17 (2), 116–137.

Skwirzynski, J.K. (Ed.), 1983. Electronic Systems Effectiveness and Life Cycle Costing. Springer, Berlin.

Smit, M.C., 2012. A North Atlantic Treaty Organisation framework for Life Cycle Costing: IInternational Journal of Computer Integrated Manufacturing 25 (4-5), 444–456.

Smith, R., Mobley, R.K., 2007. Rules of Thumb for Maintenance and Reliability Engineers. Elsevier.

Stump, E.J., 1988. An application of Markov chains to life-cycle cost analysis. International Journal of Production Economics 14 (2), 151–156.

Stump, E.J., 1989. “Cost Driver” Confusion. Journal of Parametrics 9 (3), 11–12.

Suwondo, E., 2007. LCC-OPS: Life cycle cost application in aircraft operations. ITB Press, Bandung.

The Economist, Jul 30th 2011. A tale of two industries: The contrast between two adjacent factories in an East Midlands town suggests how British manufacturing might prosper.

Thenent, N.E., Settanni, E., Newnes, L.B., 2012. Know what you need to know: The role of technological knowledge in product service systems. in: Proceedings of the 11th ASME Biennial Conference on Engineering Systems Design and Analysis. Nantes, France. 2-5 July 2013.

Toohey, E., Calvo, A., 1980. Cost analyses for avionics acquisition, in: Proceedings of the Annual Reliability and Maintainability Symposium, San Francisco CA. January 22-24, 85–90.

Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. British Journal of Management 14 (3), 207–222.

Tukker, A., Tischner, U., 2006. Product-services as a research field: past, present and future. Reflections from a decade of research. Journal of Cleaner Production 14 (17), 1552–1556.

Tuttle, D.E., Shwartz, M.N., 1979. Lower avionic temperature lower life cycle cost, in: Proceedings of the Annual Reliability and Maintainability Symposium, Washington, D.C., January 23-25, 1979, 332–337.

Tysseland, B.E., 2008. Life cycle cost based procurement decisions. International Journal of Project Management 26 (4), 366–375.

Valerdi, R., Nightingale, D., Blackburn, C., 2009. Enterprises as systems: Context, boundaries, and practical implications. Information Knowledge Systems Management 7 (4), 377–399.

van der Merwe, A., 2007. Management accounting philosophy II: The cornerstones of restoration. Cost Management 21 (5), 26–33.

Veldman, J., Klingenberg, W., Wortmann, H., 2011. Managing condition-based maintenance technology: A multiple case study in the process industry. Journal of Quality in Maintenance Engineering 17 (1), 40–62.

Wacker, J.G., 2004. A theory of formal conceptual definitions: developing theory-building measurement instruments. Journal of Operations Management 22 (6), 629–650.

Waghmode, L., Sahasrabudhe, A., 2011. Modelling maintenance and repair costs using stochastic point processes for life cycle costing of repairable systems. International Journal of Computer Integrated Manufacturing 25 (4-5), 353–367.

Wang, J., Wang H. F., Zhang, W.J., Ip W.H., Furuta, K., 2013. On a Unified Definition of the Service System: What is its Identity? IEEE Systems Journal (in press).

Webster, J., Watson, R.T., 2002. Analyzing the Past to Prepare for the Future: Writing a Literature Review. MIS Quarterly 26 (2), xiii.

Wilson, B., 2001. Soft systems methodology: Conceptual model building and its contribution. Wiley, Chichester, New York.

Wu, S., Longhurst, P., 2011. Optimising age-replacement and extended non-renewing warranty policies in lifecycle costing. International Journal of Production Economics 130 (2), 262–267.

Xu, Y., Elgh, F., Erkoyuncu, J.A., Bankole, O., Goh, Y.M., Cheung, W.M., Baguley, P., Wang, Q., Arundachawat, P., Shehab, E., Newnes, L.B., Roy, R., 2012. Cost Engineering for manufacturing: Current and future research. International Journal of Computer Integrated Manufacturing 25 (4-5), 300–314.

Xu, Y., Wang, J., Tan, X., Curran, R., Raghunathan, S., Doherty, J., Gore, D., 2008. A generic Life Cycle Cost modeling approach for aircraft system, in: Curran, R., Chou, S.-Y., Trappey, A. (Eds.). Collaborative Product and Service Life Cycle Management for a Sustainable World. Springer, London, 251–258.