Initial proposal for a general systems engineering methodology to early design phase cost/value estimation

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Abstract We propose that a systems engineering methodology may be applied in an effective interactive design environment for lifecycle cost estimation and value optimization in the context of a manufacturing enterprise. In order to optimize a product design for value, engineering and manufacturing businesses need to be able to estimate accurately product lifecycle costs during the early design phases of its development, because this is when the majority of these costs are determined. Systems engineering defines realizing value as meeting stakeholder requirements and emphasizes formalizing these in order to link coherently the individual estimated costs of a design to the needs it fulfils. Furthermore, formalized requirement and design parameters are suitable for modelling and simulation, and we envision a systems model implemented within existing knowledge-based engineering tools embedded in a design environment. The results of this model may support design decisions, as well as reinforce systems engineering analyses in evaluating processes for value chain simulations.

Keywords: Design-to-cost, Design-to-value, Systems Engineering, Knowledge Based Engineering, Design decision-making, Early design phase.

1 Introduction

Businesses whose revenues derive from sales of engineered products of their own design and manufacture often suffer from a lack of means to accurately estimate and allocate the costs of product development during the initial design phases of its lifecycle. It is during these early conceptual design phases that decisions are made that dictate the majority (at least 70% [1]) of overall costs of the product. These costs are only fully revealed several phases later however, when they are incurred to put the product into production. This is summarised in a graph shown in Figure 1, which illustrates how the cost incursion of a product lags the cost commitment across its lifecycle phases [2]. During later lifecycle phases, a business has fewer opportunities to revise the product design and optimise for cost. The result is that the final products may generate sub-optimal values to the business, its customers and other stakeholders.

Despite the apparent importance of the design phase for controlling value, it is most commonly only at later lifecycle phases, once the product has entered production, where product value is closely scrutinised and metered by means of statistical process control paradigms for quality management such as Taguchi methods, Six Sigma, and Lean Manufacturing [3]. These focus on increasing value and reducing costs by reducing manufacturing defects and non-value-added expenditures, rather than optimizing the product design itself.

Industry standards on Value Engineering [4] [5], provide methods to formally take account of cost to evaluate designs during design phases, however they do not provide guidance on cost estimation. Value Engineering considers a technical definition of value derived from the general relationship value = function/cost. It insists that value is relative and *"viewed differently by different parties in differing situations"* [4]. The task of optimizing value is therefore achieved by balancing the extent to which needs are satisfied against resource expenditure [4]. Systems engineering, the theory and practice of realising and modelling systems—be they products, services, or organisations—to fulfil a particular purpose, can apply to this task because it is centred on a multidisciplinary interpretation of value as meeting needs, namely 'stakeholder requirements' [3], and that cost may be understood as a member or subcategory of such needs. We therefore propose to investigate how to apply systems engineering to a methodology of concept evaluation and cost estimation. This proposal accordingly identifies three challenges to meet:

1. Implementing a means to estimate product cost and value from design concepts.
2. Integrating a means to display estimate results within the concept design workflow in an interactive environment that responds to evolving product concept data, and which can simulate alternative scenarios.
3. Integrating cost estimate information into design decision and concept selection processes.

The following sections are dedicated to explaining the challenges as well as the approaches, methods and tools that can be used in the first instance to address these issues. Finally, the paper ends with a conclusion and some perspectives to explain how this work will continue.

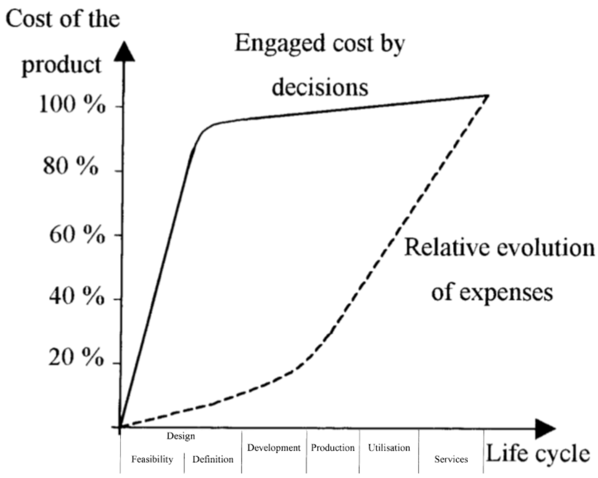

Fig. 1. Evolution of committed (engaged) and incurred costs (expenses) [2].

2 Cost estimation—a Systems Engineering approach

While a study from Saravi et al. [6] indicates that Taguchi methods can apply to cost estimation in the concept design phases, the literature discusses several dedicated cost estimation techniques for product and service designs. Elmakkaoui [7], and Datta and Roy [8] review and classify these techniques in detail, while Farineau et al. [2] outline a more concise classification summarised by Table 1 with Figure 2, comparing the approaches of the techniques and indicating to which lifecycle phases they are suited.

Table 1. Fundamental cost estimation techniques.

Name	*Description*	*Analysis methods*
Analogical	Estimation by comparison with similar previously completed projects and existing systems.	Case based reasoning
Analytic	Estimation by the classification of a system's lifecycle into evaluable constituent processes.	Business process modelling. Value stream mapping of similar systems.
Parametric	Estimation by the classification of a system into evaluable components, features or functions which are used to build a cost model supported by statistically derived scaling formulae.	Bill of Materials (BOM) analysis. Functional analysis. Regression.

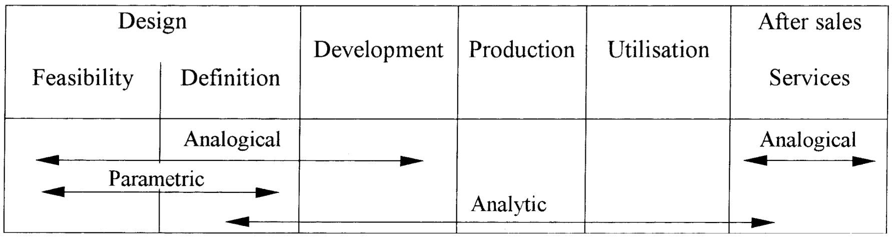

Fig. 2. Recommended lifecycle phases for performing cost estimation techniques [2].

Two characteristics of cost estimation imply that it is well suited to a systems engineering approach to value optimization:

1. Cost estimation techniques take account of all product lifecycle phases so the domain of design engineering cannot solve the problem of cost estimation alone. This is because manufacturing enterprises integrate multiple operations centres of various disciplines, not just engineering but also project management, production, planning, supply chain, marketing, finance, customer services etc., which each have different degrees of responsibility over different lifecycle phases. They have complex interrelationships and the decisions and actions of one are liable to affect any of the others. Systems engineering is the domain of engineering theory and practice that analyses these relationships. Fundamentally it does not consider an engineered product and its lifecycle to be the central object of value, but rather the system of interactions between the product, its components, and the various organisational apparatus constructed for its development (thus acknowledging that the latter is itself 'engineered' concurrently with the former) [3]. Precisely, systems engineering is defined by the International Council of Systems Engineering as *"A transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods."* [3].
2. In order to optimize for value, estimated costs must be representative of the costs of meeting needs. Systems Engineering is advantageous because it focuses on realizing value as opposed to "value proxies" such as technical performance or efficiency, which it achieves when stakeholder requirements are met. Systems engineering therefore emphasizes formally integrating these requirements into the specification of a product system design, in order to link them coherently to its estimated costs [3] [9].

Applied studies of systems-focused cost estimation are described in the literature [10] [11] [12], of these, COSYSMO [12] is a parametric model deriving from cost modelling theory applied to both product development and software projects. This model evaluates a system by calculating the person-months required to develop it from 'size drivers' and 'cost drivers', coefficients that estimate the complexity of the system. This model also features in the commercial systems engineering cost estimation tools SEER-H and SEER-SYS from Galorath Inc. [13], assimilating with aforementioned product and service cost models. A blind validation study comparing the former with a competing tool found it had an average error of 23% estimating the cost of twelve NASA science missions, comprising the project management, systems engineering, safety and mission assurance, payload, spacecraft bus, and systems integration and test components [14].

3 Cost estimation in the interactive design environment workflow—knowledge-based engineering

Systems engineering methods are deployable in most engineering and manufacturing organisations because of the availability of substantial volumes of enterprise records and data. These may be processed and classified to model the product and enterprise systems and simulate alternative scenarios. This is possible thanks to the ubiquity of IT systems in engineering enterprises, which can augment their computing resources as needed by scalable cloud services.

Knowledge-based engineering (KBE) software tools, reviewed by La Rocca et al. [15] and Verhagen et al. [17] are a proven technology to organise, process, and generate systems data for aiding the rapid generation of new designs. In some implementations, these are embedded tools in computer-aided design (CAD) software environments and thus directly integrate into a design workflow. Such tools may be used to structure and classify costs data (among others) for an arbitrary set of system entities and processes, as well as costs calculation rules for use in making estimations for new designs. Verhagen et al. [18] and Zhao et al. [19] both present KBE implementations for cost estimations of aerospace designs. These implementations demonstrate how a product cost model may be constructed and executed. They may be extended and adapted to a systems model, accommodating information flows from multiple functional units (operation centres within the manufacturing business), and generating results for multiple measures of value. Such a KBE implementation may have multiple interfaces embedded within the workflows of the functional units as, for example, modular extensions to existing CAD and enterprise resources planning (ERP) tools.

4 Cost considerations in design decisions

Estimating cost during design phases allows it to be a factor in design decisions. The literature describes several concept selection and design decision tools from the mature Pugh concept selection [20] to more recent advances on multi-criteria decision aiding methods [21], and joint probability distribution techniques [22]. These methods compare alternative product concepts over a number of selection phases by scoring them on arbitrary sets of criteria relating to customer/stakeholder requirements. The methods also provide guidance on the selection of criteria, how their relative values are weighted and interact in scoring, and the rules of competition. Such models may consider estimated cost as a single criterion. For the systems engineering view, Bosch-Mauchand et al. [23] present value-based decision support tools for manufacturing processes.

5 Conclusion

We propose that an effective methodology for cost and value estimation in the early design of phases of engineered products should follow a systems engineering approach. Systems engineering emphasizes formally defining stakeholder requirements before providing a value analysis of product components and functionality, while considering the costs of its supporting development, manufacturing and servicing apparatus to determine overall generated value. Individual dedicated models exist for product, service and system cost/value estimation techniques. Integrating these may provide an extensive, holistic, and more accurate, methodology or model of cost/value estimation.

A product design workflow may implement such a model via established knowledge-based engineering tools. These tools may query product and process cost and value data to compute evaluations for new designs, and generate results to support design decisions in concept selection by including costs and values as determining criteria. These results may feedback and reinforce systems engineering analyses in evaluating processes for value chain simulations.

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