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Development of a Product Life-Cycle Cost Estimation Model to Support Engineering Decision-Making in a Multi-Generational Product Development Environment

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The research under product development domain identifies and implements new concepts in design, planning, manufacturing, testing, and service sectors to keep up with the market demands. Many product developments are multi-generational in nature and may require redesigning the product at each generation because an optimized strategy for a single generation may not be the best option in the multi-generation scenarios. With this regard, this article proposes a novel product life-cycle cost estimation model to support engineering decision-making in a multi-generational product development environment. This cost estimation model develops a mathematical formulation which has three major cost constituents: development cost, service cost, and associated risks cost. The risks cost further includes three components coming from technical risk, market risk, and operation risk. The developed mathematical formulation measures the on-going multi-generational product development's status, addresses its basic needs such as design for future reuse. It also serves as a strategic decision-making tool for successful project management. For the purpose of validating the proposed cost model, an empirical case study of a manufacturing-based product (gas turbine) is illustrated by considering three candidate concepts. This cost estimation is very handy to those design engineers who have a little idea of cost analysis when they design a product. It assists design teams by accurately forecasting and strategically planning a project and by making decisions which are compatible with future generations at a relatively cheaper cost. Thus, this article aims to provide a new direction and approach to maximize the business profit earned from multi-generational products.

Introduction

Traditionally, product development (PD) is defined as a set of activities which begin with the identification of a business opportunity, passes through conception, design, and manufacturing stages, and finally ends with the product delivery to the end consumer (Tyagi, Yang, Tyagi, & Dwivedi, 2011). As per recent market trends (Cai, Tyagi, & Yang, 2011; Huang & Tzeng, 2008; Kim, Bridges, & Srivastava, 1999; Lin & Kremer, 2014), PD is not confined to just implementing innovative technologies and realizing the benefits from the single generation of a product. But many products, such as phones, vehicles, and so forth are naturally developed generation after generation to take advantage of the opportunities arising from customer's continuously increasing requirements (Tyagi, Yang, Tyagi, & Verma, 2012). The success of such multi-generational products explicitly rely on the project

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cost accrued from different life-cycle phases (i.e., design, development, marketing, service) and associated risks until the product is disposed. The researchers have also realized that almost 80% of the total product cost is committed to the early stage of the life-cycle (Rapp, 2000), thereby; preliminary design decisions and actions significantly affect overall cost the most (Stewart, 1991; Tyagi, Ghorpade, Karunakaran, & Tiwari, 2007). Additionally, an optimized strategy for a single generation may not be the best option in the case of the multi-generation (Lin & Okudan, 2013). Hence, they raise the impetus to compare various initial designs to make the final product cost effective and competitive (Aulds, Kozman, Lee, & Tyagi, 2009). In such scenario, an accurate, fast, and robust cost estimation technique can offer a competitive advantage to an organization.

Keeping aforesaid facts in mind, the motivation of this research is to provide the engineers a tool that is intuitive and can exploit cost-saving potentials from the multi-generational perspective at the concept development stage of PD. Direct benefit of having a reasonably accurate cost estimate includes identification of major cost drivers and critical activities for economic success of a product (Ma & Yang, 2012; Stewart, Wyskidsa, & Johannes, 1995; Verma, Shukla, Tyagi, & Mishra, 2014). On the basis of this estimated cost and anticipated profits, along with project planning, a product can be priced and economic feasibility and survival can be tested in a suggested market model. Additionally, cost benefit analysis provides a fundamental platform to explore the best possible alternative of goods or services in cost effective ways within the given constraints. Most of the literature targets cost estimation from general perspectives of a single generation and basically lacks multi-generational aspects of the products (Brierley, Cowton, & Drury, 2006; Jiao, 2012; Mikaelian, Nightingale, Rhodes, & Hastings, 2011; Newnes et al., 2008; Tyagi, Yang, & Verma, 2013). The current article presents a novel mathematical formulation to estimate product life-cycle cost in order to support decision-making specifically suited for a multi-generational product development (MGPD) environment. In the mathematical formulation, three major factors: development cost, service cost, and associated risks cost are considered. Furthermore, the risks cost includes three factors: technical risk, market risk, and operation risk. The model will assist design teams by accurately forecasting and strategically planning a project in a relatively small time window and by making decisions which are compatible with future generations at a relatively cheaper cost. This cost estimation model also addresses the crucial relationships among quality, time, resources, and cost in a PD project by considering the future alterations of the product design.

This article focuses on a product with generic characteristics such as a complex module structure, a long development cycle time, a long lead-time, and a high parts cost. This research primarily considers a manufacturing-based product where activities are used to: (a) determine if a new product is required to serve some needs, (b) conceive a concept for the product based on those needs of customers, (c) develop all the technical specifications, and (d) validate both design and production (Yang, 2007; Tyagi, Choudhary, Cai, & Yang, 2014). The rest of this article is organized as follows. The Literature Review section reviews the relevant literature related to cost estimation methods. The Life-Cycle Cost Estimation Model For MGPD section offers the mathematical formulation of the objective function, comprising of development cost, service cost, and associated risks cost. The Illustrative Example section provides an illustrative example and reports computational results and their discussions. The Conclusions section summarizes the entire article and offers future research topics.

Literature Review

Various cost estimation practices have evolved over time, all having the fundamental aim of estimating cost in a more accurate and effective manner. Such accuracy largely depends on the legitimacy and appropriateness of data. No "one right way" of performing cost estimation task in the best way has been found in an exhaustive literature search. Traditionally, the "*direct*" or parametric approach (Mileham, Currie, Miles, & Bradford, 1993) and the "*detail*" or industrial engineering approach (Layer, Brinke, Houten, Kals, & Haasis, 2002) are the two well-known practices of cost estimation. Principally, a similar but slightly different approach based on the effective use of "analogy" between various processes or products and known standard processes or products is also found in the literature (Auer, Trendowicz, Graser, Haunschmid, & Biffl, 2006). This "analogy" approach can be used effectively for cost estimation of relatively new but certain processes only.

History of Cost in Manufacturing

Taylor (1906) is the originator of the "Time Study analysis," which was implemented to establish standard times for conducting certain tasks and determining wage incentives. Gilbreth (1911), the proponent of "Motion Study analysis," carefully studied motions of workers and suggested the elimination of unwanted motions. When applied together, Motion and Time Study formed a great tool for improving productivity. Although these two methods originated for different purposes, Lowry, Maynard, and Stegemerten, (1940) and Carrol (1943) advocated their use for cost control and proposed methodologies for planning, budgeting, standardizing costs, and comparing them to actual accrued costs to come up with the profit-loss statements. Ostwald (1974) employed metal cutting equations and predetermined motion/time study standards to estimate the direct labor and materials cost. Traditional cost accounting allocates overhead on volume-based measures such as labor hours, machine hours, or material cost (see Figure 1). As these allocations are

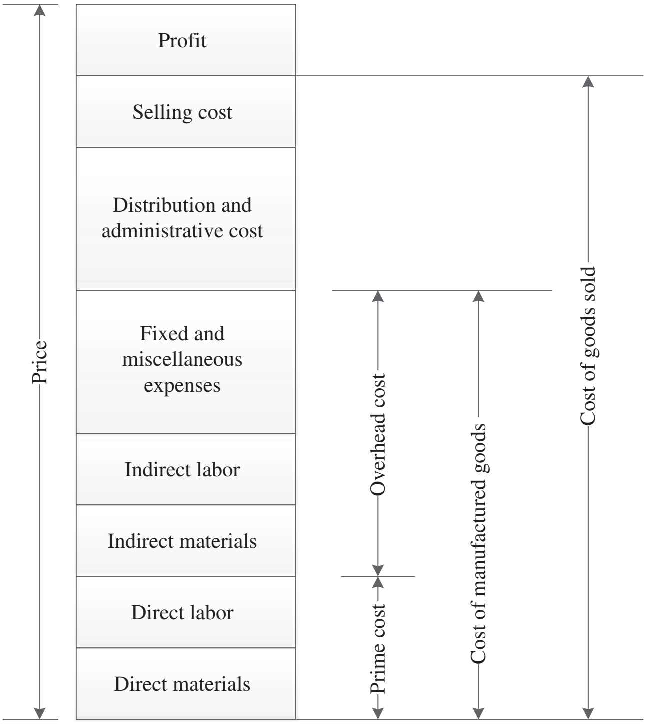

FIGURE 1 Cost and price structure in traditional cost accounting.

aggregate-based, they tend to distort the final cost information. The approach suggested by Samid (1981) is based on cost knowledge and is termed as "Top-Down" approach. In principle using this approach to estimate the cost of entity "*X*," one needs to analyze a set of entities "*Sx*" of which "*X*" is a member. The problem, according to the author (Samid, 1981), is to identify which element of "*Sx*" is close to, or same, as "*X*." Mills and Redford (1983) focused more on material specifications of designs, thereby putting more emphasis on the machinability index of materials in estimating the manufacturing cost. Boothroyd, Dewhurst, and Knight (1994) presented a philosophy only of product design for manufacturing and assembly, along with its implementation framework in a real world. Next, Huang (1996) presented a broad spectrum of other considerations like maintainability, modularity, reliability, environmental friendliness, quality, and life cycle, also referred as the "Design for X" philosophy. Mathematical analysis of tolerancing and its effect on manufacturing cost was presented by Creveling (1997).

A fundamental shift in thinking about product cost came from a relatively new philosophy called "Design to Cost" or "Target Costing" (Cooper, 1997; Geiger & Dilts, 1996; Michaels, 1989). According to this philosophy, cost is an input to the designer rather than an output from his actions and is driven by the market forces and competitors. Thurston and Essington (1993) suggested integrating cost in design decision-making. They report the use of their system as a means to formulate the multi-criteria design optimization problems to compare alternatives. Furthermore, Veeramani and Joshi (1997) identified the need for a rapid response to quotation requests and discussed how today's cost estimating techniques fail to address this issue. Nevertheless, the framework suggested is geared to fast quotation generation, it may be less significant because of inefficient quote generation in systems. Weustink, Brinke, Streppel, and Kals (2000) and Tyagi et al. (2013) proposed a generic framework pertaining to different elements of design objects described in completeness along with their cost attributes. This information framework is one way of organizing cost information, but it does not address how the basic cost of features is calculated. Furthermore, a resource-based estimation framework was proposed by Esawi and Ashby (2003), where they assessed material, capital, time, and space information of product for cost estimation.

Cost Estimating Models

These models are more specific and detailed implementation of methodologies. As early cost estimation has become more and more important, researchers have attempted to resolve this problem from various perspectives. Their endeavors include the implementation of techniques well known to other areas of engineering, science, and mathematics for this purpose. In this regard, Boothroyd and Reynolds (1989) proposed an approximate method for cost estimation of typical turned components and made it simple for designers. The model helps in analyzing cost against material specifications, surface area generation, and material volume removal. However, such a model is not enough, as it does not address design requirements like surface finish, tolerance, and so forth, and tool life equation constants are not readily available for all specific materials. Badiru (1992) suggested a multivariate approach to learning curve implementation. The learning curve can be used to extrapolate average cost of design if manufactured in multiples (i.e., cost of "i^{th}" unit of production can be estimated from cost of initial units). Learning curve implies that when a process is performed in a similar way for a number of times, the efficiency of the execution of process improves. French and Widden (1993) suggested that a number of commonly used components show a close relationship between quantified functions and cost. They also explained the construct of a costing method and how it is beneficial in early costing of mechatronics or similar systems that have a large number of components bought from outside.

A basic problem in cost estimation is that there is no complete theoretical model. Gutowski (1994) made an attempt to explain the theoretical significance of power law coefficients that underlie cost estimating relationships (CERs) for composite manufacturing and addressed the issue of how they change with part complexity. Their model agrees favorably with experiments and other detail estimating methods, at the same time enhancing understanding of the basics of CERs in composite manufacturing. An interesting analogy used by researchers is information theory (IT), used by Suh, Bell, and Gossard, (1978) and Singh, Rathore, and Kaur. (2013). They showed that IT used in communications technology could be applied to highlight manufacturing complexity. Hoult and Meador (1997) used a similar complexity theory approach for manufacturing cost estimation. They conclude that manufacturing time could be estimated fairly accurate for manual lathe and milling operations based on availability of dimensional information, and they suggest that similar estimates could be made for other operations. Ting (1999) proposed to include fuzzy cost variables to formulate a fuzzy multi-attribute utility theory (MAUT) framework that was a very pragmatic formulation incorporating incomplete or uncertain information. They also claimed that their method is more efficient than traditional cost estimation, as it does not require collection of a great deal of historic data. However, it is important to note that expert's opinions are required initially to generate utility values of specific cost drivers considered as well defined, but in reality, they are not. Kirchain and Field (2000), Nikolaos and Lefteris (2013), and Zhai, Jiang, and Pedrycz (2013) suggested the need for looking at cost and/or process/material substitution not only at the individual part but also the whole system level. They called this the "Extrapolative Method" or "Total System Model" for evaluating cost effects.

Disadvantages of Current Cost Estimation Models

Presently available cost estimation approaches (e.g., parametric, detail, analogy estimation, etc.) often fail to address some of the important requirements. First, none of these approaches completely encompass the product life-cycle. This means, in the early design stage (where there are not many details available) only parametric estimation can be used, and later, process-model-based estimates and pre-determined motion-time-study (PMTS) estimates can be used when complete details are available. Moreover, since most of these approaches use statistical data as their basis for estimation, they inherit associated drawbacks. The estimates are valid only under the conditions for which the data is valid, and their accuracy depends on the accuracy of the base data. Many software packages based on existing techniques are available for cost estimation, but none of them is fully integrated with CAD and product optimization tools. Moreover, their integration in current form may be very difficult due to the fact that the details required by cost estimation software are not directly available within CAD systems alone (Kumari & Pushkar, 2013; Verma, Tyagi, & Yang, 2014). For example, in the case of a PMTS-based estimate, one has to generate process plans from part design, and then a detailed activity chart should be prepared. Only then can a detailed estimate be made. In addition to this, most of these methods use historic data to come up with critical factors like coefficients and rates, and are easily affected by cost accounting methods within the company. Under such conditions, the same processes consuming the same resources will have different costs under two different cost accounting setups. In order to overcome the aforesaid weaknesses in cost estimation, this article presents a mathematical model to accurately estimate the life-cycle cost for a multi-generational product development. The details of this model are provided in the Life-Cycle Cost Estimation Model For MGPD section.

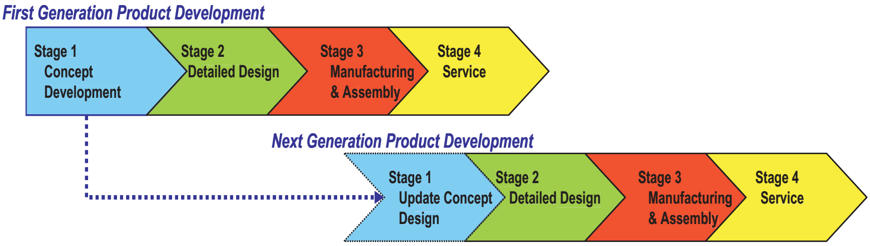

FIGURE 2 Multi-generational product development process model.

Multi-Generational Product Development (MGPD)

This section reviews literature of PD process and examines its overview, needs, and current challenges. This review can be generically applied across the industry, but is more focused at PD for single generational product. By comparing the differences between single generational and multi-generational product, the natures of MGPD are studied from different aspects. The next sub-section focuses on extended PD process. The basic process steps required to develop a multi-generational product are similar to that of a single generation product. The objective of MGPD is to optimize the overall resource planning and to maximize the profits over multiple generations. The starting point of the development of a next-generation product includes updating or continuously designing the first generation design as shown in Figure 2. Therefore, more efforts should be involved in the development of a first generation concept design. However, in the real world, the development of a next generation product sometimes starts while the previous generation is still progressing. Moreover, connections among four stages of MGPD are typically parallel instead of sequential.

Figure 3 shows a sample of the occurrences between several MGPD processes in 3D according to a timeline. In this figure, *Gi*, *Gj*, *Gk* represent the starting point (concept design stage) of three generations of a product in different colors. There is an information flow among different stages within the development processes of two generations. For

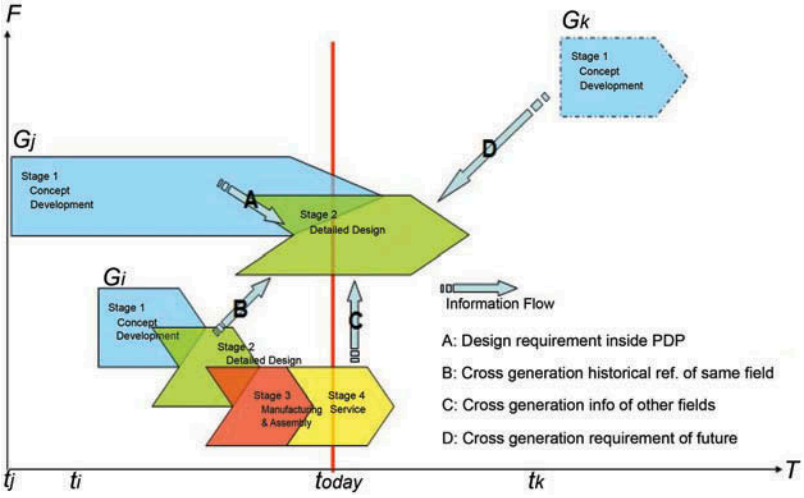

FIGURE 3 Sample of MGPD process—3D: information flows.

example, during SGPD stage 2 “detailed design” of product generation *Gj*, there are four identical information streams. These four information flows are 1) design requirements from stage 1 within the same SGDP, 2) historical reference data from the same stages of another generation, 3) historical reference information from the different stages of another generation, and 4) potential design requirements need for the development of other future generation product. All these information flows are important for an efficient development process in a MGPD scenario.

Life-Cycle Cost Estimation Model For MGPD

The life-cycle cost takes into account the total cost of product or service from its concept development to its disposal. The proposed cost estimation mathematical model is intended to study and introduce a measurement for the deployment of MGPD and to provide a tool for multi-generational project management. As mentioned earlier, this study of cost-related aspects a product is driven by the fact that success of PD is directly related to total cost. This total cost includes different aspects of product life-cycle, such as development, marketing, operations, service, and also the associated risks with them. Thus, the total cost (C^{PT}) includes development cost (C^{PD}), product service cost ($C^{service}$), marketing risk transformed cost (C^{MR}), technical risk transformed cost (C^{TR}), and operation risk transformed cost (C^{SR}) as shown in Equation (1).

$$C^{PT} = C^{PD} + C^{Service} + (C^{MR} + C^{TR} + C^{SR}) \tag{1}$$

Development Cost

Development cost (C^{PD}) is considered to be the combination of material cost (C^{Matl}) from product manufacturing, processing cost (C^{Mfg}) from manufacturing and assembly, and labor cost (C^{Hr}) from product design and production. Cost of materials is considered as a deterministic factor and has been studied during the MGPD Stage 1. C^{Matl} is an “interface” of the proposed model, which implies that the value of material cost should come from the output of any applicable cost estimation methods or commercial software. The processing cost from manufacturing and assembly is also considered as a deterministic factor for each concept, which is the result of the preliminary manufacturing capacity study during the MGPD Stage 1. Labor cost is the summation of all manpower required in the MGPD Stages 1 to 3. The manpower related expenditure is also considered as a part of service cost during MGPD Stage 4.

$$C^{PD} = C^{Matl} + \left(C^{Hr} + C^{Mfg}\right) \times R \tag{2}$$

During MGPD, design for future reuse could significantly reduce development cost. In the proposed model, design for future reuse has been represented as Reusable Index (R). To simplify the problem, the scope of design for future reuse is considered only between current generation and next generation. When a module or part meets requirements from two generations, then a certain portion of the labor and processing-related costs can be considered to be amortized into the next generation. To calculate this, the number of total recognized design requirements is assumed as n, and m represents the number of design requirements that target both generations. k is the number of design requirements that have been fulfilled during each of the candidate concepts.

$$R = \left(1 - \frac{k}{n}\right) + \frac{k}{2n} = 1 - \frac{k}{2n} \text{ where, } (0 \le k \le m) \le n \tag{3}$$

If no cross-generational design requirements have been adopted, then $R_{\max} = 1 - \frac{0}{2n} = 1$, which means no cost can be amortized into the next generation. On the other hand, if all the possible cross generational design requirements have been adopted, then the percentage of current cost can be reduced by a factor $R_{\min} = 1 - \frac{m}{2n}$. Therefore, for each candidate concept, $R_i = 1 - \frac{k_i}{2n}$ and $C_i^{PD} = C_i^{Matl} + \left(C_i^{Hr} + C_i^{Mfg}\right) \times R_i$.

Service Cost

All the costs and expenses occurring during Stage 4 are considered as the service cost ($C^{Service}$). To generalize and simplify, $C^{Service}$ is considered to be the combination of material, hardware-related costs of the adopted design concept. $T^{Warranty}$ represents the duration of the warranty contract, which is pre-determined based on the company policy and T^{Life} indicates the average lifetime of the product. These values serve as the key design parameters and can be estimated at the end of MGPD Stage 1. Assuming $\left(T^{Warranty} / T^{Life}\right)$ indicates the number of times of material/hardware replacement, $C^{Service}$ for each candidate concept can be estimated using Equation 4.

$$C^{Service} = C^{Matl} \times \left(T^{Warranty} / T^{Life}\right) \tag{4}$$

Associated Risk Cost

Technical Risk Coefficient. Technical-related risk occurs when the product has been introduced to the market too early and the techniques adopted in the concept have not been studied and tested adequately. Logically, this type of risk increases when the concept development time is reduced. In this study, C^{TR} is represented as a certain portion of development cost (C^{PD}). Thus,

$$C^{TR} = C^{PD} \times \mu\left(t_\alpha\right), \text{ for each candidate concept } C_i^{TR} = C_i^{PD} \times \mu\left(i, t_\alpha\right) \tag{5}$$

$\mu(t_\alpha)$ is defined as the technical risk transforming index. Let t_α represent the duration of MGPD Stage 1, which is the length of concept development, and t_β represents the duration of MGPD Stages 1, 2, and 3, which is the length of traditional PD. As mentioned, $T^{Warranty}$ represents the duration of the warranty contract, which is just the duration of MGPD Stage 4. Thus we have $t^{wt} = t_\beta + T^{Warranty}$ covering the duration of MGPD. Therefore, technical risk transforming index is defined as:

$$\mu\left(i, t_\alpha\right) = \begin{cases} 0 & t_\alpha = t^{wt} \\ \mu_i^s & t_\alpha = t^s \\ +\infty & t_\alpha = 0 \end{cases} \tag{6}$$

t^s and μ_i^s are pre-determined values. t^{wt} represents the best case for introducing a product to the market, and t^s represents the average time that a company needs to introduce a product to the market (see Figure 4). These values could be an input from an expert system or historical data, which is also an "interface" of the proposed cost estimation model. Based on the nature of $\mu(t_\alpha)$, and the study of logarithm functions, the technical risk transforming index is defined as:

$$\mu\left(i, t_\alpha\right) = -\frac{\ln t_\alpha}{\ln \sqrt[\mu_i^s]{t^{wt} / t^s}} + \frac{\ln t^{wt}}{\ln \sqrt[\mu_i^s]{t^{wt} / t^s}} \text{ and derivative is } \frac{d\mu\left(i, t_\alpha\right)}{dt_\alpha} = -\frac{1}{\ln \sqrt[\mu_i^s]{t^{wt} / t^s}} \times \frac{1}{t_\alpha} \tag{7}$$

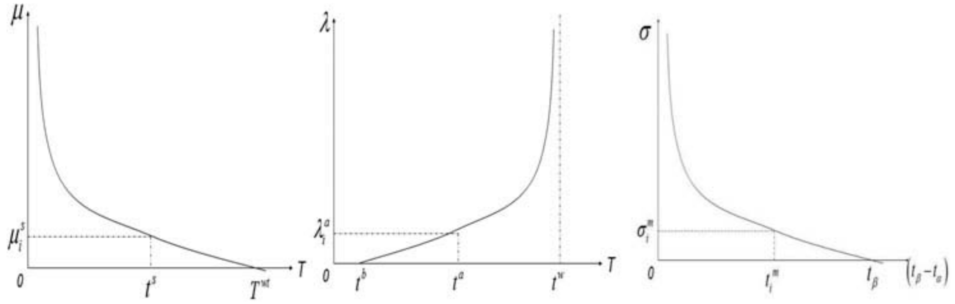

FIGURE 4 Technical risk, market risk, operation risk transform indexes, respectively.

Market Risk Coefficient. Market-related risk occurs when the product has been introduced to the market too late, and the potential market share has been taken by a competitors' product. Logically, this type of risk increases when the design time and manufacturing time increase. In this study, C^{MR} is represented as a certain portion of development cost (C^{PD}). Thus,

$$C^{MR} = C^{PD} \times \lambda\left(t_\beta\right), \text{ for each candidate concept } C_i^{MR} = C_i^{PD} \times \lambda\left(i, t_\beta\right) \tag{8}$$

$\lambda(t_\beta)$ is defined as the technical risk transforming index. t^b represents the best case for marketing, which is the earliest time of product market introduction, and t^w represents the worst case for marketing, which is the longest time of a similar product being established in the market (see Figure 4). And t^a represents the average time that a company needs to introduce its product. Obviously, $t^b \leq t^a \leq t^w$, the technical risk transforming index is defined as:

$$\lambda\left(i, t_\beta\right) = \begin{cases} 0 & t_\beta = t^b \\ \lambda_i^a & t_\beta = t^a \\ +\infty & t_\beta = t^w \end{cases} \tag{9}$$

t^b, t^a, t^w, λ_t^a are pre-determined values. They could be inputs from an expert system or historical data. Based on the nature of $\lambda(t_\beta)$, and the study of logarithm functions, the technical risk transforming index is defined as:

$$\lambda\left(i, t_\beta\right) = -\frac{\ln\left(t^w - t_\beta\right)}{\ln \sqrt[\lambda_i^a]{\frac{t^w - t^b}{t^w - t^a}}} + \frac{\ln\left(t^w - t^b\right)}{\ln \sqrt[\lambda_i^a]{\frac{t^w - t^b}{t^w - t^a}}} \text{ and its derivative is}$$

$$\frac{d\lambda\left(i, t_\beta\right)}{dt_\beta} = \frac{1}{\ln \sqrt[\lambda_i^a]{\frac{t^w - t^b}{t^w - t^a}}} \times \frac{1}{\left(t^w - t_\beta\right)} \tag{10}$$

Operation Risk Coefficient. Operation-related risk refers to the risk and uncertainty during project management, especially schedule risk. Logically, under the assumption that the resources of a project are limited, this type of risk becomes serious when detailed design and manufacturing/assembly time is reduced. During this study, operation-related risk is also represented as a certain portion of C^{PD}.

$$C^{SR} = C^{PD} \times \sigma\left(t_\beta - t_\alpha\right), \text{ for each candidate concept } C_i^{SR} = C_i^{PD} \times \sigma\left[i, \left(t_\beta - t_\alpha\right)\right] \tag{11}$$

$\sigma(t_{\beta\text{-}}\ t_\alpha)$ is defined as the technical operation transforming index (see Figure 4). The operation risk transforming index is defined as:

$$\sigma\left[i, \left(t_\beta - t_\alpha\right)\right] = \begin{cases} 0 & t_\beta - t_\alpha = t_\beta \\ \sigma_i^m & t_\beta - t_\alpha = t_i{}^m \\ +\infty & t_\beta - t_\alpha = 0 \end{cases} \tag{12}$$

$t_i{}^m$, σ_i^m are pre-determined. They could be inputs from an expert system or historical data, which is also an "interface" of the integrated cost model. Based on the nature of $\sigma(t_{\beta\text{-}}\ t_\alpha)$, and the study of Logarithm functions, the technical risk transforming index is defined as:

$$\begin{gathered} \sigma\left[i, \left(t_\beta - t_\alpha\right)\right] = -\frac{\ln\left(t_\beta - t_\alpha\right)}{\ln \sqrt[\sigma_i^m]{t_\beta / t_i{}^m}} + \frac{\ln t_\beta}{\ln \sqrt[\sigma_i^m]{t_\beta / t_i{}^m}} \text{ and its derivative is} \\ \frac{\sigma\left[i, \left(t_\beta - t_\alpha\right)\right]}{d\left(t_\beta - t_\alpha\right)} = -\frac{1}{\ln \sqrt[\sigma_i^m]{t_\beta / t_i{}^m}} \times \frac{1}{\left(t_\beta - t_\alpha\right)} \end{gathered} \tag{13}$$

Integrated Life-Cycle Cost Model

Therefore, for each candidate concept, cost model with consideration of technical risk, market risk, and operation risk, as well as development cost and service cost could be defined as:

$$C_i^{PT} = C_i^{PD} + C_i^{Service} + C_i^{MR} + C_i^{TR} + C_i^{SR} \tag{14}$$

$$C_i^{PT} = C_i^{PD} + C_i^{Service} + C_i^{PD} \times \mu\left(i, t_\alpha\right) + C_i^{PD} \times \lambda\left(i, t_\beta\right) + C_i^{PD} \times \sigma\left[i, \left(t_\beta - t_\alpha\right)\right] \tag{15}$$

$$C_i^{PT} = C_i^{PD} \times \left\{1 + \mu\left(i, t_\alpha\right) + \lambda\left(i, t_\beta\right) + \sigma\left[i, \left(t_\beta - t_\alpha\right)\right]\right\} + C_i^{Service} \tag{16}$$

$$\begin{aligned} C_i^{PT} = & \left[C_i^{Matl} + \left(C_i^{Hr} + C_i^{Mfg}\right) \times R_i\right] \\ & \times \left\{1 + \mu\left(i, t_\alpha\right) + \lambda\left(i, t_\beta\right) + \sigma\left[i, \left(t_\beta - t_\alpha\right)\right]\right\} + C_i^{Service} \end{aligned} \tag{17}$$

Finally, total project cost for each candidate concept can be estimated as follows:

$$\begin{aligned} C_i^{PT} = & \left[C_i^{Mail} + (C_i^{Hr} + C_i^{Mfg}) \times \left(1 - \frac{k_i}{2_n}\right)\right] \\ & \times \left[1 - \frac{\mathrm{1n}\, t_\alpha}{\mathrm{1n} \sqrt[\mu_i^s]{t^{wt} / t^s}} + \frac{\mathrm{1n}\, \mathrm{t}^{wt}}{\mathrm{1n} \sqrt[\mu_i^s]{t^{wt} / t^s}} - \frac{\mathrm{1n}\, (\mathrm{t}^w - t_\beta)}{\mathrm{1n} \sqrt[\lambda_i^a]{\frac{t^w - t^b}{t^w - t^a}}} + \frac{\mathrm{1n}\left(t^w - t^b\right)}{\mathrm{1n} \sqrt[\lambda_i^a]{\frac{t^w - t^b}{t^w - t^a}}} \right. \end{aligned}$$

$$- \frac{1\text{n}\,(\text{t}_\beta \;-\; t_\alpha)}{1\text{n}\,\sqrt[\sigma_i^m]{t_\beta / t_i^m}} + \frac{1\text{n}\,t_\beta}{1\text{n}\;\sqrt[\sigma_i^m]{t_\beta / t_i^m}} \Bigg] + C_i^{Matl} \times \left(\frac{T^{Warranty}}{T_i^{Life}} \right)$$

Illustrative Example

Two problems are predominantly present in making a trade-off between different designs. First, today's design engineers have a little idea of cost analysis when they design a product. The proposed cost estimation model will be very handy to those engineers. They will be able to see the cost as a design characteristic, similar to other characteristics like weight. The outcome of the proposed cost model has included all perspectives, which increases the accuracy and confidence of forecasting. Another problem in coming up with accurate cost estimation is that it largely depends on the experience of the working team related to different interfaces. The data for "interface" cost elements in this cost model could be automatically retrieved from existing software package used in other functional groups. It will result in less interaction with the user during the estimation process. Another benefit of using "interface" cost elements is the possibility of adopting multiple cost estimating methods in a model (Kumar, Tripathi, Tyagi, Shukla, & Tiwari, 2007). For example, when estimating material/hardware cost, it is hard to determine among the existing approaches which one is the best solution for all the components.

In this section, a case study has been developed to demonstrate and validate the efficacy of the proposed life-cycle cost estimation model. This analysis is based on the input data summarized from an industrial project. It is quite difficult (or to some extent impossible) to conduct a new case to demonstrate the MGPD theory from the ground level for products with complex module structure, long lead-time in production, long product life-cycle time, high cost in parts. The approach adopted in this research simulates PD environment using historical data. First, two already present mature product generations are selected since they have sufficient and accurate project data such as part cost, project schedule, product module structure, and so forth, to support the simulation. The second step is to select a target project, which is conducted on multiple concepts at the concept development stage. Moreover, the most important criterion is that the final selected concept must be used for following generation. Hence, a similar PD environment is created to demonstrate cost model, as well as the MGPD theory.

Unfortunately, the original data cannot be directly used due to the sensitivity and security of the information. In this case, the original figures have been transformed via certain rules, but the interrelationships still remain identical to the original. Thus, the transformed data can still be used to illustrate how to the proposed cost estimation model can act as a tool for concept selection, as well as project management. In this case, three candidate concepts have been identified and developed during the MGPD Stage 1. At the end of Stage 1, the design engineers have to select one of these concepts to pursue a further detailed design. This cost model can generate a figure, which provides a summarized overview from all aspects of PD to determine the concept with the lowest cost ($min\ C_i^{PT}\ for\ i = 1, 2, 3$). Based on the input data provided in Table 1 and Table 2, the detailed project costs for each concept are calculated, with different configurations of t_α and t_β. A portion of this calculation is presented in Table 3 for select values of t_α and t_β. In this table, the cells marked with green color indicate the best concept selected under specific configurations of t_α and t_β. In Table 1, n is the number of total recognized design requirements, m is the number of design requirements that target both generations and k is the number of design requirements that have been fulfilled during each of the candidate concept.

Here, concept-I (CPT-I) represents the existing mature design with less reusability. It has low material cost, low labor cost, short concept development time, short development

TABLE 1 Input data 1 for all the three concepts

Concept	C^{Matl}	$T^{\mathrm{wt/M}}$	$T^{\mathrm{life/M}}$	C^{Hr}	C^{Mfg}	n	m	K
CPT-I	$1,000,000.00	360	96	$900,000.00	$150,000.00	100	80	30
CPT-II	$1,150,000.00	360	120	$1,000,000.00	$160,000.00	100	80	80
CPT-III	$1,100,000.00	360	108	$ 950,000.00	$150,000.00	100	80	50

TABLE 2 Input data 2 for all the three concepts

Concept	t^{s}	t^{b}	t^{a}	t^{w}	t^{m}
CPT-I	8	24	30	36	6
CPT-II	20	24	30	36	12
CPT-III	12	24	30	36	10

TABLE 3 A portion of project costs for each concept with different configurations of t_α and t_β

t_α	t_β	CPT-I	CPT-II	CPT-III
1	13	$5,890,183.57	$5,703,087.53	$5,619,077.51
2	13	$5,843,197.00	$5,816,293.88	$5,605,267.67
3	13	$5,826,582.08	$5,984,940.86	$5,629,774.93
4	13	$5,824,030.28	$6,191,629.17	$5,674,851.12
5	13	$5,830,876.95	$6,435,110.98	$5,736,271.94
6	13	$5,845,599.77	$6,720,063.89	$5,813,820.68
7	13	$5,868,144.67	$7,056,125.18	$5,909,653.96
8	13	$5,899,616.08	$7,459,757.94	$6,028,466.49
9	13	$5,942,630.72	$7,959,524.42	$6,178,994.87
10	13	$6,002,665.92	$8,609,701.61	$6,378,267.65
11	13	$6,092,520.40	$9,532,786.36	$6,665,085.25
12	13	$6,253,606.98	$11,120,390.49	$7,163,908.53
1	14	$5,911,275.12	$5,630,771.79	$5,627,220.74
2	14	$5,860,916.85	$5,639,239.99	$5,595,423.43
3	14	$5,840,435.74	$5,692,321.56	$5,599,816.06
4	14	$5,833,403.29	$5,770,190.14	$5,622,141.15
5	14	$5,834,969.10	$5,868,230.69	$5,657,440.58
6	14	$5,843,328.26	$5,986,294.01	$5,704,416.70
7	14	$5,857,978.19	$6,126,767.98	$5,763,556.10
8	14	$5,879,263.44	$6,294,533.63	$5,836,800.17
9	14	$5,908,391.19	$6,498,020.13	$5,927,924.01
10	14	$5,947,859.75	$6,751,958.30	$6,043,793.21
11	14	$6,002,732.84	$7,084,450.31	$6,197,710.75
12	14	$6,084,730.58	$7,559,037.22	$6,419,942.40
13	14	$6,231,670.18	$8,379,010.46	$6,807,540.66

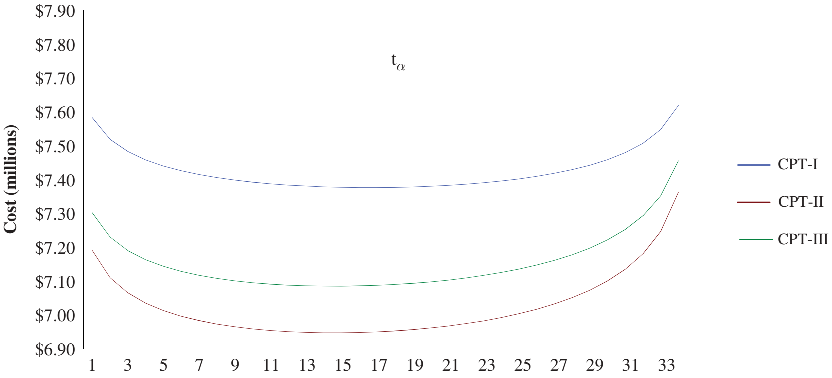

FIGURE 5 Comparison of total cost for all three concepts for $t_\beta = 35$.

lead-time, and short product life time. Concept-II (CPT-II) represents the new design targeting future generations. It has high-level future reuse, and also scores high in various other costs. The concept-III (CPT-III) is considered a "compromise" option. In the real world, however, one of the concepts could be pre-selected by management to favor a new technology, customer requirements, or for some other reasons. In that case, the project team has to figure out the detailed project plan which minimizes the risk and cost. One of the important decisions that have to be made is the duration of the concept development, or how much time the design engineers have to develop a mature concept. This could result in fewer engineering changes during the later manufacturing and assembly stage, as well as meet most of the requirements and have a lower overall cost.

Figure 5 shows the sensitivity graph for the total cost when t_β is kept constant and the value of t_α is changed from 1 to 33 for all the three concepts. For this figure, it is evident that Concept-I is the cheapest option when (t_β) has a constant value of 35. The total cost value continuously is reduced for all three concepts up to t_α value reaches to 19 months, but it starts to go up again. Project costs for concept-II for different values of (t_α) for the constant value of (t_β) ranging from 13–35 months are shown in Figure 6. Here, t_α ranges from 0 months to 34 months. This is also the boundary of best and worst cases identified for the target project. This figure represents the dynamic changes in the cost when values of both t_α and t_β are changed in a range. For example, the total cost ranges between 55 million to 56 million when t_α and t_β are kept in between 13–19 months. Such ranges provide an organization a view to estimate the durations when focusing on the total cost of the product.

Figure 7 shows the change of total project cost by each t_α for any determined t_β. The result directly indicates the best t_α values on each t_β curve. This curve provides the sensitivity analysis of total cost when one value is kept fixed and other one is changed. The results in Table 3 suggest that CPT-II is the obvious best choice, when the project has sufficient resources. Concept-I would only be considered when the project is under high pressure to introduce the new product as fast as possible. As discussed, t_β represents the total time of MGPD Stages 1, 2, and 3, which is also considered as the representation of project resources. Based on a determined t_β, we can choose the candidate concept that has the lowest project cost.

Conclusions

The research conducted in this article primarily targets those multi-generational products, which have higher costs in parts and relatively longer development time. The fundamental

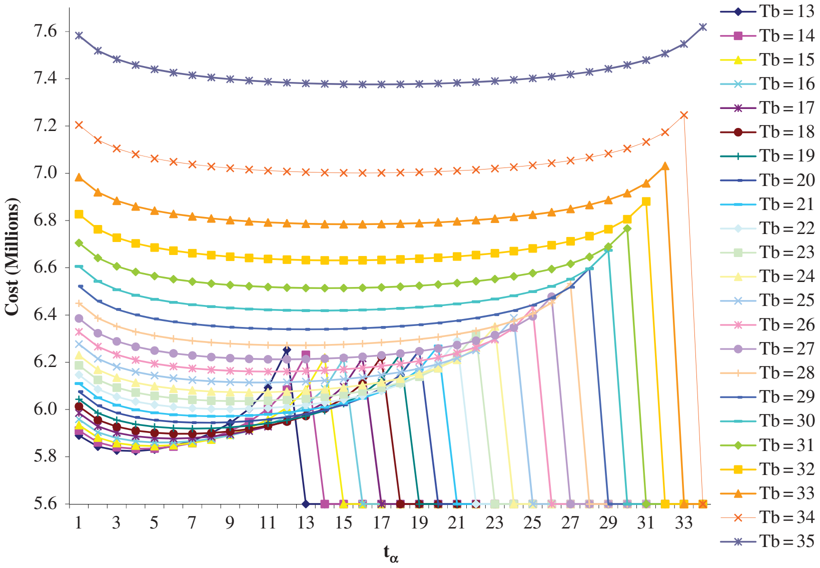

FIGURE 6 Project cost of concept-II for t_β's.

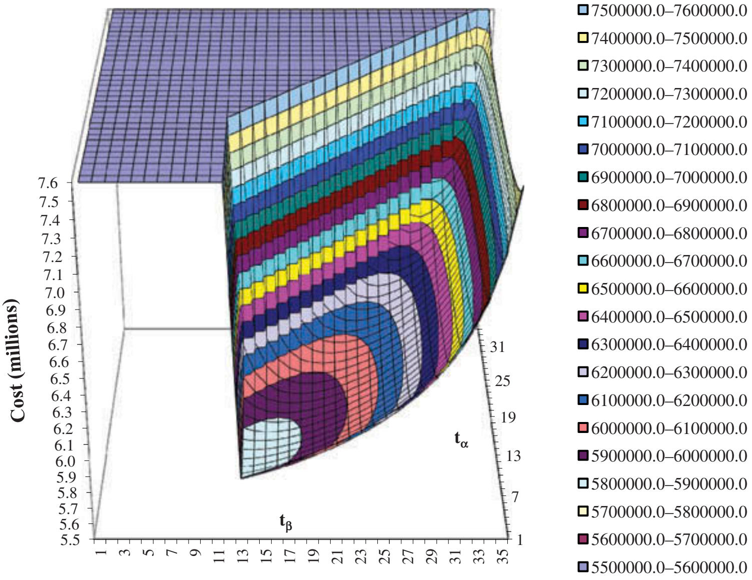

FIGURE 7 Project cost of concept-II.

purpose of this study is to achieve the maximum profits considering the product scope for a certain future time duration. For this purpose, a product life-cycle cost estimation model has been specially introduced that serves as the ultimate decision-making tool. This cost estimation model addresses the needs and incorporates the different aspects of MGPD into mathematical analysis. The three types of risks have been quantified and incorporated in the overall development while calculating the total cost of a project. Additionally, total cost includes product cost and service cost. Estimates of total project cost also serves a comparison basis for selecting the best alternative in multiple scenarios. A case study has been presented to illustrate and validate the performance of the proposed cost estimation model. During analysis, it is found that concept-II which has a new design to target future generations is the best alternative. This is due to the fact that concept-II has a high potential for future reuse of design, thus, it scores high in minimizing various other costs and ultimately the total cost from MGPD perspectives. However, many detailed studies have to be continued from each perspective to build up the entire MGPD theory. Because all the conclusions achieved are either from comparative analysis or historical data, there is more work to be done. The future research includes the implementation of lean product development, Design for Six-Sigma (DFSS) techniques and tool refinement, incorporation of the multi-generational requirements measurement of modularity and reusability, and further refinement of the cost estimation model.

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