Product Cost Estimation: Technique Classification and Methodology Review

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This paper provides a detailed review of the state of the art in product cost estimation covering various techniques and methodologies developed over the years. The overall work is categorized into qualitative and quantitative techniques. The qualitative techniques are further subdivided into intuitive and analogical techniques, and the quantitative ones into parametric and analytical techniques. Each of the techniques is then described and discussed, in detail, with further subdivisions. The paper also signifies the importance of cost estimation in the early phases of the design cycle and, as such, briefly discusses the current trends and future directions in the area. Research work carried out in the field with reference to specific applications is also reviewed. The paper provides a comprehensive literature review in the field and should be useful to researchers and practitioners interested in this field. [DOI: 10.1115/1.2137750]

Keywords: cost estimation, technique classification, methodology review, cost estimation applications

1 Introduction

Good cost estimation has a direct bearing on the performance and effectiveness of a business enterprise because overestimation can result in loss of business and goodwill in the market, whereas underestimation may lead toward financial losses to the enterprise. Because of this sensitive and crucial role in an organization, cost estimation has been a focal point for design and operational strategies and a key agenda for managerial policies and business decisions. As a result, a substantial research effort has been expanded in exploring design implications, new techniques, and methods for producing accurate and consistent cost estimates not only to generate optimum design solutions but also to achieve the maximum customer satisfaction in terms of low-cost, high-quality, and in-time product delivery.

The published literature on product cost estimation (PCE) covers a wide variety of issues ranging from manufacturing cost estimation of standard mechanical components to cost analysis of highly customized assembled products, from process cost optimization techniques to specific methods for overhead costing, from unique approaches for estimation at the conceptual design stage to general costing rules designed for use at a later stage in the design cycle, and also from classical costing methods to highly novel cost estimation techniques. Several textbooks [1–3] can be found on some of the subjects. A number of researchers have attempted to categorize the PCE techniques using certain criteria. Zhang et al. [4] categorized some techniques into traditional detailed-breakdown, simplified-breakdown, group-technology-based, regression-based, and activity-based cost estimation techniques. Ben-Arieh and Qian [5] classified cost estimation methods into intuitive, analogical, parametric, and analytical methods. Shehab and Abdalla [6] mentioned intuitive, parametric, variant-based, and generative cost estimating approaches without defining them clearly. The same authors [7] later classified cost modeling approaches at the design stage into knowledge-, feature-, function-, and operations-based approaches. Cavalieri et al. [8] identified three approaches for cost estimation: analogy-based, parametric, and engineering approaches. However, a comprehensive hierarchical classification of the estimation techniques has not been exploited.

This paper presents an extensive hierarchical classification of these techniques. The classification is based on grouping the techniques with similar features into various categories. The methodologies for cost estimation discussed in different categories are distinct and reflect the nature of that category. Each group or category is discussed in detail, with reference to published work. Meanwhile, mathematical models are presented on occasions with particular references in order to better understand the nature of a given category. This paper categorizes the PCE techniques into *qualitative* and *quantitative*. Qualitative techniques are discussed in detail in Secs. 2 and 3, and Secs. 4 and 5 present a comprehensive discussion about quantitative techniques.

Qualitative cost estimation techniques are primarily based on a comparison analysis of a new product with the products that have been manufactured previously in order to identify the similarities in the new one. The identified similarities help to incorporate the past data into the new product so that the need to obtain the cost estimate from scratch is greatly reduced. In that sense, the past design and manufacturing data or previous experience of an estimator can provide useful help to generate reliable cost estimates for a new product that is similar to a past design case. Sometimes, this can be achieved by making use of the past design and manufacturing knowledge encapsulated in a system based on rules, decision trees, etc. Historical design and manufacturing data for products with known costs may also be used systematically to obtain cost estimates for new products. For example, regression analysis models and neural-network approaches could provide an efficient way to predict costs for new products by using historical cost data. In general, qualitative techniques help obtain rough estimates during the design conceptualization. These techniques can further be categorised into *intuitive* and *analogical techniques*, which are discussed, in detail, in Secs. 2 and 3, respectively.

Quantitative techniques, on the other hand, are based on a detailed analysis of a product design, its features, and corresponding manufacturing processes instead of simply relying on the past data or knowledge of an estimator. Costs are, therefore, either calculated using an analytical function of certain variables representing different product parameters or as the sum of elementary units

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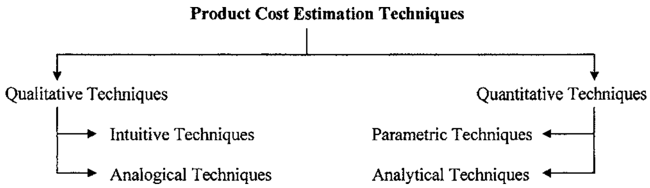

Fig. 1 Initial classification of the PCE techniques

representing different resources consumed during a whole production cycle of a given product. Although these techniques are known to provide more accurate results, their use is normally restricted to the final phases in the design cycle due to the requirement of a detailed product design. Quantitative techniques can be further categorized into *parametric* and *analytical techniques*, which are discussed, in detail, in Secs. 4 and 5, respectively.

These techniques categorised as qualitative and quantitative can be illustrated in a tree diagram in Fig. 1. The importance of making cost estimates in the early stages of the design cycle is discussed in Sec. 6 with reference to relevant published literature. Section 7 deals with the review of the cost estimation for specific applications. Finally, Sec. 8 provides an overview of the present study with a brief discussion on the current trends and future directions in the field.

2 Intuitive Cost Estimation Techniques

The intuitive cost estimation techniques are based on using the past experience. A domain expert's knowledge is systematically used to generate cost estimates for parts and assemblies. The knowledge may be stored in the form of rules, decision trees, judgments, etc., at a specific location, e.g., a database to help the end user improve the decision-making process and prepare cost estimates for new products based on certain input information. The present study identified three subcategories under intuitive techniques.

2.1 Case-Based Methodology. This approach also known as case-based reasoning (CBR) attempts to make use of the information contained in previous design cases by adapting a past design from a database that closely matches the attributes of a new design. This often requires making necessary changes to parts and assemblies of previous design cases and incorporating missing details to it. Figure 2 shows a flow diagram of the case-based approach with the dotted lines representing the cost interfaces to the system. The process starts by outlining a new product's design specifications followed by retrieving a closest design match from a design database. The system then attempts to find the changed assemblies and, subsequently, changed parts in the assemblies. Changes are incorporated into the design either by retrieving similar parts and/or similar assemblies from the design database or by designing the new ones altogether. All the necessary changes are incorporated in a similar way until the new design conforms to the outlined design specifications. The new design is later stored in the design database. This technique allows the cost estimation for a new product by combining the past results with those for the newly designed components and assemblies, thereby greatly reducing the need to design from scratch. The approach is, therefore, helpful in making good estimates at the conceptual design stage, since the use of the past cost data to generate new estimates greatly minimizes the estimation time. However, the methodology is applicable only when similar past designs are available to incorporate the relevant cost data during cost estimation for new products.

A typical example can be seen in the methodology presented by Rehman and Guenov [9] in which an attempt is made to predict design features from incomplete design descriptions based on past designs and production knowledge. In their work, a system allows the retrieval of past design cases that match the new problem description. The cost modeler detects necessary modifications in the retrieved designs, and the cost data is updated accordingly using the adaptation rules stored within the design models. The method, thus, allows the cost estimation and evaluation for innovative designs. The method applied by Li-hua and Yun-feng [10] evaluated costs for new products by implementing the functions of CBR. These functions included organizing case bank, indexing case, initializing case, seeking and searching case, and adapting case. The method was useful for rapid costing to satisfy customers' demands on pricing. Ficko et al. [11] conceived a CBR system for predicting total cost of the tool manufacture. The system is based on extracting geometrical features from computer-aided design (CAD) models stored in a database and calculating the similarities with the problem description of a new product's features.

Although the developed system is only limited to tools for manufacture of sheet metal products by stamping, it provides good-quality predictions based on enough similar cases. Balarman and Vattam [12] analyzed other applications of CBR in the domains of help desks, diagnosis, cost estimation, and design based on its functions (such as representations, indexing, matching, adaptation, and process of problem solving). Their work is an effort toward building a general-purpose case-based problem solver.

2.2 Decision Support Systems (DSS). These systems are helpful in evaluating design alternatives. The main purpose of these systems is to assist estimators in making better judgments and decisions at different levels of the estimation process by making use of the stored knowledge of experts in the field. This is illustrated in Fig. 3. One such system incorporating expert rules has been developed by Kingsman and De Souza [13] for cost estimation and price setting in versatile manufacturing companies dealing with make-to-order (MTO) systems. The developed system not only focused on different factors that influence the decision-making process in handling a customer enquiry, but discussed the rules that cost estimators apply when making decisions about these factors.

To incorporate experts' experience, the artificial intelligence (AI) philosophy is used to represent and utilize a domain expert's knowledge in a way that is oriented toward problem solving and serves as a decision-aid tool. In the particular context of the PCE, for example, it may constitute a segment of the system containing information about machining processes, manufacturability analysis and constraints, product characteristics with design functions, and relationships with each other set out in logical statements. It may also incorporate rules about the actions to be taken or more conventional mathematical formulas. It can point outside to external programs and databases that can be associated with it including some that can cope with uncertain or conflicting judgments.

Shehab and Abdalla [14] developed knowledge-based cost models for the PCE in early design stages, whereas Luong and Spedding [15] developed a knowledge-based system by integrating process planning into cost estimation. Another approach adopted by Gayretli and Abdalla [16] focused on developing a prototype system for manufacturing process optimization. The system assisted designers to create real-time cost estimates and feasible process plans by retrieving manufacturing form features and parameters from the feature database.

One of the most common ways to represent DSS is based on storing design, manufacturing, or other constraints as a set of *rules*. Since many practical situations deal with uncertainty and nonavailability of heuristic data, *fuzzy logic* techniques are used to some extent to overcome such problems. Another nonconventional approach makes use of *expert systems* (ES) or *expert support systems* in the domain of DSS.

2.2.1 Rule-Based Systems. These systems are based on process time and cost calculation of feasible processes from a set of available ones for the manufacture of a part based on design and/or manufacturing constraints. Such a system reflects these

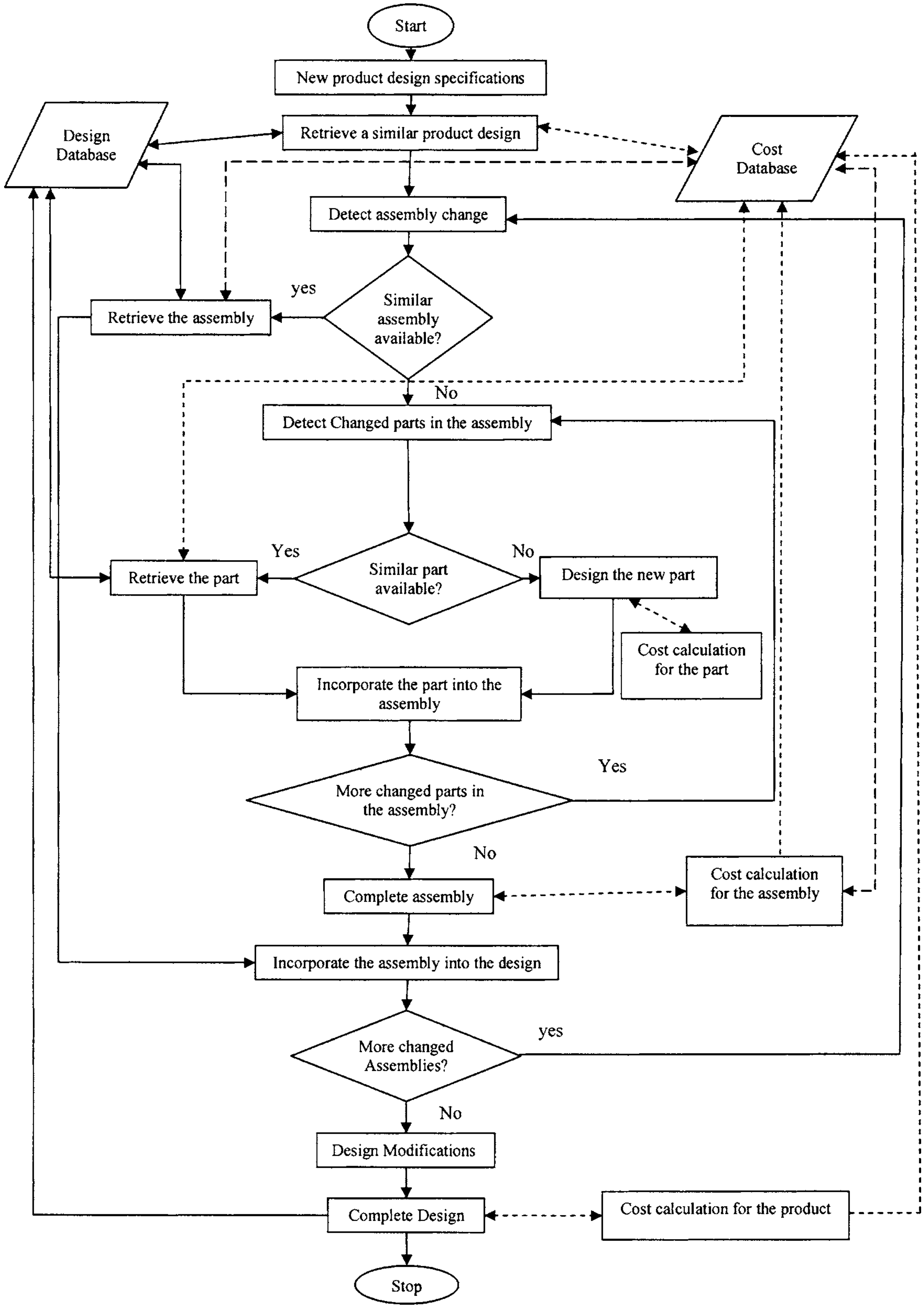

Fig. 2 Flow diagram of the case-based approach for cost estimation

constraints in a respective rule class with the information encapsulated in it by an expert in the area. A rule-based algorithm is an example of one such approach that helps to establish design and manufacturing constraints. This approach is shown diagrammatically in Fig. 4. Based on a set of user constraints, manufacturing processes are selected that are then used to calculate the product cost. The set of constraints may need to be changed to obtain a different set of manufacturing processes to obtain an acceptable product cost estimate. This methodology is helpful for cost optimization based on process evaluation criteria. However, obtaining the optimized results can be very time consuming, especially when there are a large number of processes to be evaluated.

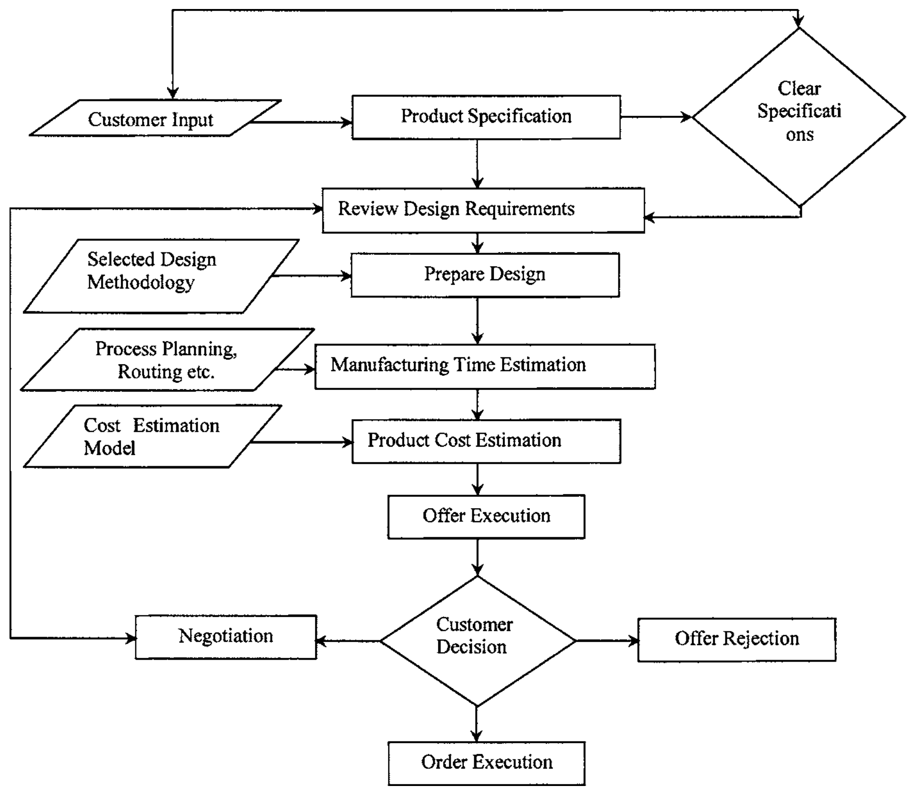

Fig. 3 Decision-support-system approach to cost estimation

Gayretli and Abdalla [17] developed a rule-based algorithm for the selection and optimization of feasible processes to estimate process time and cost based on parts features. A detailed description of part features with possible processes and constraints was given. Process times were calculated using a standard formula as

$$\text{Process Time} = \frac{\text{Form Feature Volume}}{\text{Material Removal Rate}} \tag{1}$$

The process time is then used to calculate *lot time*, which is based on a form feature quantity. The total process cost is subsequently calculated as follows:

$$\text{Total Process Cost} = \text{Lot Time} \times \text{PHC} \tag{2}$$

where PHC is the *productive hour cost* given by a cost estimation database [18]. The total cost is then calculated as follows:

$$\text{Total Cost} = \text{Material Cost} + \Sigma[(\text{Lot Time} \times \text{PHC}) + \text{Tool Cost} + \text{Setup Cost}] \tag{3}$$

The proposed system allowed the selection of a combination of feasible processes from the possible ones, and hence, the calculation of process time and cost based on the user input constraints (e.g., maximum allowable cost and process time for a particular

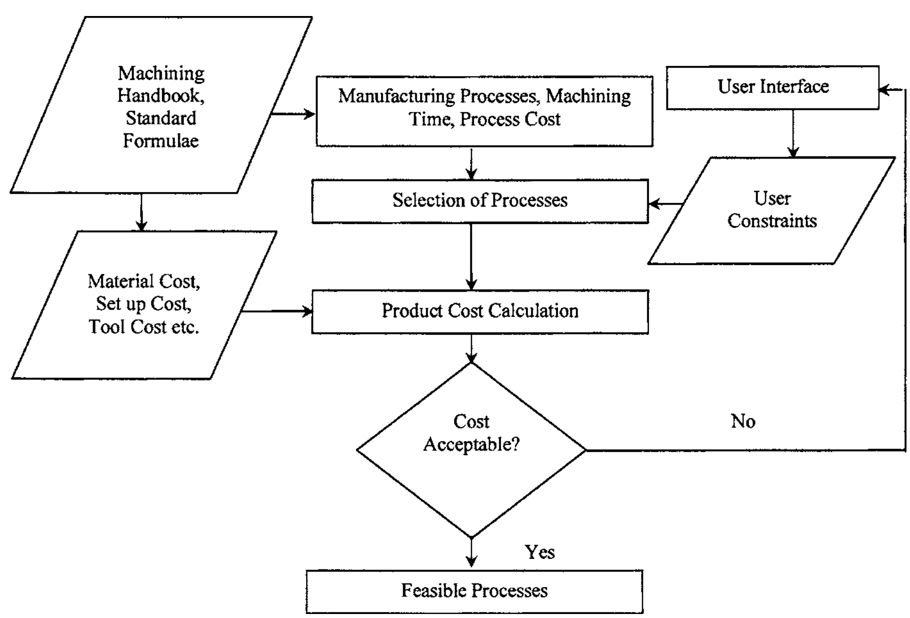

Fig. 4 Cost estimation process model based on user constraints

feature). A criterion of feasibility was judged against the level of satisfaction for input constraints. The process allowed flexibility based on user constraints. Another example of this category can be found in [9] where manufacturing and assembly rules were used to update cost data in the proposed system; whereas, an object-oriented and rule-based system can also be found in [7] for product cost modeling and estimation.

2.2.2 Fuzzy-Logic Approach. This approach to cost estimation is particularly helpful in handling uncertainty. Fuzzy rules, such as those for design and production, are applied to such problems to get more reliable estimates. However, estimating the costs of objects with complex features using this approach is quite tedious and requires further research in the area. Shehab and Abdalla [6] used fuzzy rules with linguistic expressions and assigned truth values to them. They used several steps to develop a fuzzy-logic model. These steps were fuzzification of input variables followed by fuzzy inference based on a set of rules, and finally defuzzification of the inferred fuzzy values. A fuzzy technique, consisting of a decision table providing a means for system rules and indicating the relationships between the input and output variables of the fuzzy logic system, is used to handle the uncertain knowledge on cost estimation. The construction of a set of rules from the decision table enables the estimation of the machining time T_i for a given feature, which is multiplied by the unit time cost R_i to get the machining cost C_m for that feature, i.e.,

$$C_m = R_i T_i \tag{4}$$

The developed fuzzy-logic-based system was capable of estimating the total product cost apart from enabling the material selection and estimating the assembly cost. The same investigators [7] carried out a similar but more comprehensive study by considering other essential costs, such as nonproductive and setup costs.

2.2.3 Expert Systems. This approach is based on storing the knowledge in a database and manipulating it on demand to infer quicker, more consistent, and more accurate results based on an attempt to mimic the human expert thought process with the help of an automated logical reasoning approach, normally achieved by rule-based programing. Within the specific context of cost estimation, the expert-system approach refers to a model and associated procedure exhibiting a degree of expertise comparable to that of a human expert in generating or to help in generating reliable cost estimates. Expert systems applied to the PCE have mainly focused on formalizing the theoretical techniques largely from textbooks, etc., rather than encapsulating the practical knowledge (e.g., the expert conceptual estimator developed by Musgrove [19]). Further research in the area considering the human contemplating process of an estimator has a better potential to exploit the typical characteristic. Cost estimation methods for various applications using expert systems or expert support systems can be found in [20,21].

3 Analogical Cost Estimation Techniques

These techniques employ similarity criteria based on historical cost data for products with known cost, such as regression analysis models or back propagation methods. Sections 3.1 and 3.2 describe these methods in detail.

3.1 Regression Analysis Models. These models make use of the historical cost data to establish a linear relationship between the product costs for the past design cases and the values of certain selected variables so that the relationship can be used to forecast the cost of a new product. The regression analysis approach based on the similarity principle was adopted by Hundal [22] and Poli et al. [23] to use a basic cost value and consider the effects of variable cost factors by assuming linear relationships between the final product cost and the cost factors. Lewis [24] further used existing designs to provide cost estimates for similar new designs, whereas Pahl and Beitz [25] provided more general costing approaches based on similarity.

3.2 Back-Propagation Neural-Network (BPNN) Models. These models use a neural network (NN) that can be trained to store knowledge to infer the answers to questions that even may not have been seen by them before. This means that such models are particularly useful in uncertain conditions and are adaptable to deal with nonlinearity issues as well. The back-propagation neural network (BPNN) is the most common of all network types and also suits better the nature of the PCE. The application of neural network in cost engineering is discussed in [26].

Shtub and Zimerman [27] compared the cost results obtained with the regression model and the BPNN model and observed the superiority of the latter in many ways. In another study [4], a feature-based methodology was proposed using BPNN to estimate the cost of packaging products. Cost-related features of packaging products were used in conjunction with historical cost data to obtain a relationship between cost and cost-related features based on BPNN. The proposed method overcame the limitations of regression analysis models, such as the assumption of nonlinear relationships between product cost and its variables, as well as those of traditional breakdown approaches, e.g., the requirement of detailed cost information, such as process planning cost. Zhang and Fuh [28] proposed a similar approach for early cost estimation, whereas Chen and Chen [29] proposed a BPNN model for a strip-steel coiler. Furthermore, a back-propagation algorithm [8] was used with momentum and a flat spot elimination term for a multilayer perceptron (MLP) neural network, in which neurons are organized in several layers, including an *input* layer, a number of *hidden* layers, and an *output* layer.

4 Parametric Cost Estimation Techniques

Parametric models are derived by applying the statistical methodologies and by expressing cost as a function of its constituent variables. These techniques could be effective in those situations where the parameters, sometimes known as cost drivers, could be easily identified. Parametric models are generally used to quantify the unit cost of a given product. Cavalieri et al. [8] developed a parametric model for the estimation of unit manufacturing costs of a new type of brake disk using the weight of the raw disk, unit cost of raw material, and the number of cores as parameters in their model, which is expressed as follows:

$$C = \mathrm{FC} + \left(C_{co} N_{co} + \frac{C_{rm}\mathrm{TF}}{1 - \mathrm{SC}} \right) W \tag{5}$$

where C is the unit cost of the disk brake, FC the fixed cost factor (coefficient), C_{co} the core cost per kilogram of cast iron (coefficient), N_{co} the number of cores, C_{rm} the unit cost of raw material, SC the srap rate (coefficient), TF cast-iron–steel conversion factor (coefficient), and W the weight.

A simple linear regression model using one of the cost drivers would not be effective because of variances between the data. However, the developed model overcame this problem by using more parameters. Validation analysis of the model by comparing the estimated costs to the actual ones of the brake disks demonstrated the superiority of the proposed parametric model over the linear regression model.

A wide range of parametric models can be found in the literature. For example, Hajare [30] modeled parametric costing of components using the product specifications. Roberts and Hermosillo [31] used approximate tool paths and process parameters from available factory resources to estimate time and cost for small surface units. Boothroyd and Reynolds [32] adopted a parametric costing approach using the volume of typical turned parts as a parameter to estimate the cost in the early design stages. Unlike the detailed-breakdown approach, the method adopted by them could be used in the early design stage without the need of a process plan. Similar work can be found in [33].

5 Analytical Cost Estimation Techniques

This approach requires decomposing a product into elementary units, operations, and activities that represent different resources consumed during the production cycle and expressing the cost as a summation of all these components. These techniques can be further classified into different categories, which are discussed in detail below.

5.1 Operation-Based Approach. This approach is generally used in the final design stages because of the type of information required and is one of the earliest attempts to estimate manufacturing costs. The approach allows the estimation of manufacturing cost as a summation of the costs associated with the time of performing manufacturing operations, nonproductive time, and setup times. Several techniques have been developed to select the alternative manufacturing operations that optimize the machining cost.

The cost model proposed by Jung [34] estimated the manufacturing cost by considering three different times including setup time, operation time, and nonoperation time. Formulation was provided. The total cost was given by

$$\begin{aligned}\text{Mfg cost} &= (R_o + R_m)[(T_{su}/Q)T_{ot} + T_{no}] + \text{material cost}\\ &\quad + \text{factory expenses}\end{aligned} \tag{6}$$

where R_o is the operator's rate, R_m the machine rate, T_{su} the setup time, Q the batch size, T_{ot} the operation time, and T_{no} the nonoperation time.

The model could not be used to evaluate design alternatives because of its availability only in the final stages of design cycle. Feng et al. [35] presented a diagraph-based mathematical model that uses the geometric features including cylinder, rectangular block, chamfer, flat surfaces, and hole, and developed an algorithm to estimate the minimum cost using an operation-based approach. The process plans of alternative design solutions with explicit modeling of the machining time of various features represented the criteria of estimating manufacturing costs. Gupta et al. [36] developed a similar methodology using manufacturing features for the evaluation of alternative process plans to estimate the manufacturing cost of the part. Wei and Egbelu [37] used geometric design data and developed a method based on a tree representation of alternate processes to estimate the product manufacturing cost. Although the approach focused on obtaining the optimum results, it did not consider direct labor cost. Furthermore, Kiritsis et al. [38] proposed a method for the cost estimation of the machining of parts based on the description of given features and associated alternative manufacturing operations. The proposed methodology was based on Petri nets to determine overall costs, including machining, moving, setup, and tool-change costs. However, getting the optimized results using the proposed methodology was time consuming.

5.2 Breakdown Approach. This method estimates the total product cost by summing all the costs incurred during the production cycle of a product, including material costs and overheads as well. The method requires detailed information about the resources consumed to manufacture a product including purchasing, processing, and maintenance details.

The cost model developed by Son [39] included labor, machining, tool, setup, space-occupied, computer software, and material costs. The model also separated the raw material cost and labor cost into different categories. The proposed model included *insurance, utility, maintenance, repair*, and *property* costs. The machining cost C_m is, hence, represented in the following equation as:

$$\begin{aligned}C_m &= (\text{utility cost}) + (\text{maintenance cost}) + (\text{repair cost})\\ &\quad + (\text{insurance cost}) + (\text{property cost})\\ &= \Sigma(C_u T_m + C_{mt}T_{mt} + C_r T_r + aF_k + bF_k)\end{aligned} \tag{7}$$

where C_u is the utility cost per unit time, T_m the machining time, C_{mt} the maintenance cost per unit time, T_{mt} the total maintenance time, C_r the repair cost per unit time, T_r the total repair time, a the insurance premium, F_k the initial investment, and b the property tax.

Furthermore, equations for other cost elements including labor, tool, setup, space-occupied, computer software, and material costs were also provided. The requirement of such detailed information restricted the use of the model in the final design stage. In addition, manufacturing costs were considered by Bernet et al. [40] as the sum of material, labor, and overhead costs, and Ostwald [1] estimated product cost as the summation of material cost, manufacturing cost, labor cost, and overhead expenses based on hourly usage of machinery or direct labor. Such traditional cost estimation and cost accounting techniques were also discussed in detail in [2].

5.3 Tolerance-Based Cost Models. The objective of such models is to estimate product cost considering design tolerances of a product as a function of the product cost. Singh [41] presented a framework for the concurrent design of product and processes considering the criteria of minimum cost, maximum quality, and minimum manufacturing lead time. Three models were presented to jointly design the products and processes. They are the unit cost of production model, the quality model, and the lead-time model. The unit cost model was expressed as follows:

$$X_0(d,j) = K_i(d,j)[X_i + f(j)] - K_s(d,j)X_s \tag{8}$$

where K_i and K_s are technology coefficients that can be found from the following equations:

$$K_i = 1/[1 - \mathrm{SC}(d,j)] \tag{9}$$

$$K_s = \mathrm{SC}(d,j)/[1 - \mathrm{SC}(d,j)] \tag{10}$$

SC is the scrap rate given by the following equation:

$$\mathrm{SC}(d,j) = \emptyset[-d/\sigma(j)] + 1 - \emptyset[d/\sigma(j)] \tag{11}$$

where j is the jth manufacturing process selected for producing a product, $X_o(d,j)$ the unit cost with tolerance d, X_i the unit raw material cost, $f(j)$ the unit processing cost for jth process, X_s the unit salvage value, K_i the technology coefficient (input), K_s the technology coefficient (scrap), SC (d,j) the scrap rate, $\sigma(j)$ the standard deviation, and $\emptyset(x)$ the cumulative distribution function of probability distribution with the mean equal to 0 and the standard deviation equal to 1.

The modeling methodology was based on obtaining the optimal tolerances and, hence, setting up the acceptance regions for the design variables meeting certain criteria. The objective of the cost model was to select the process and design variables that minimize the cost function. However, the modeling methodology eliminated the needs for design changes because it considered various design and manufacturing factors at the early stage of the design. The cost-tolerance relationships and relevant models can also be found in [42,43].

5.4 Feature-Based Cost Estimation. The feature-based cost estimation methodology deals with the identification of a product's cost-related features and the determination of the associated costs. Considerable research has been carried out in order to extract and quantify representative product features that contribute to the total cost. These features can either be design related (such as the type of material used for a specific product, geometric details, etc.) or process oriented (i.e., a particular process required for manufacturing the product, e.g., machining, casting, injection-moulding etc.). The methodology allows the selection of a particular design or manufacturing form feature for design-for-cost (DFC) system users. However, the approach can have limitations for complex or very small geometric features, especially if machining processes are used to produce these features.

Zhang et al. [4] proposed a feature-based cost estimation system for packaging products extracting 32 cost-related features in both the design and manufacturing domain. These features were

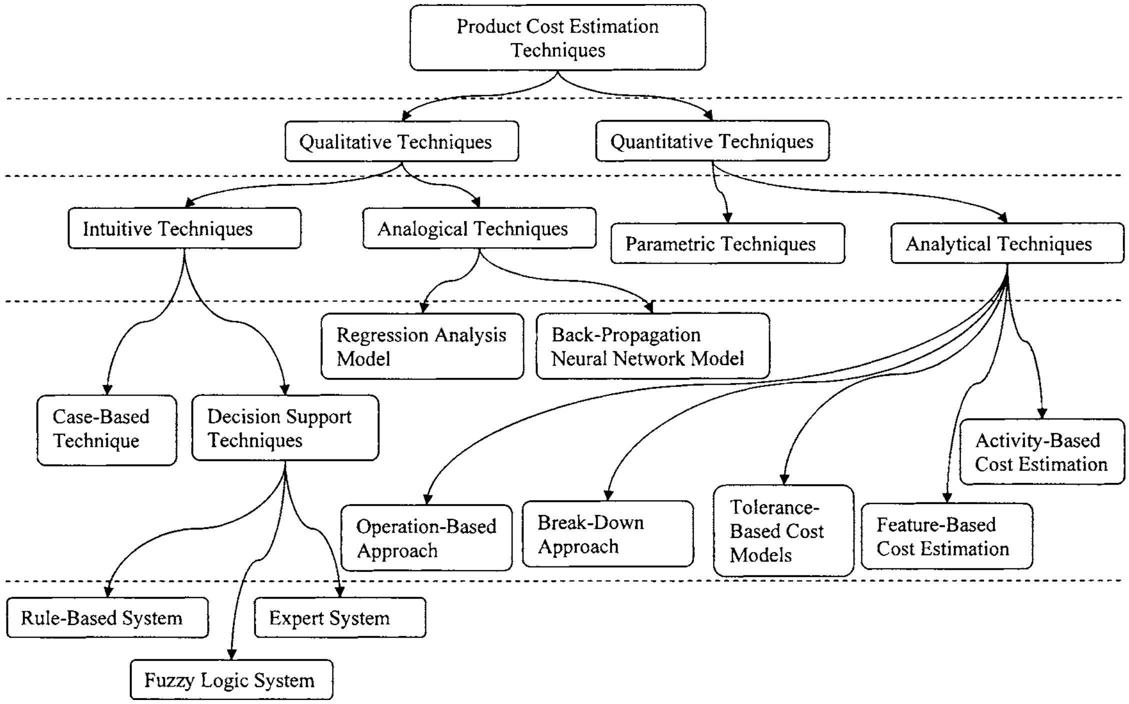

Fig. 5 Classification of the PCE techniques

then quantified based on a relative cost influence among the various possible states of a particular feature. However, no attempt was made to quantify these features objectively. Ou-Yang and Lin [44] looked into the feature-based costing by focusing on the machining-type features and developed a manufacturing cost estimation model based on feature shapes and precision. With the process planning information and geometrical data, the machining time of a feature was estimated. One limitation of their proposed framework was that it only considered conventional machining processes. Further research work in the area of feature-based cost estimation can be found in [45–47].

5.5 Activity-Based Costing (ABC) System. The ABC system focuses on calculating the costs incurred on performing the activities to manufacture a product. The method was first discussed by Cooper and Kaplan [48]. They presented the ABC system as a useful means to distribute the overhead costs in proportion to the activities performed on a product to manufacture it. Hundal [49] presented similar methods. The ABC system proved a good alternative to traditional estimation techniques since it provided more accurate product manufacturing cost estimates [50].

Various information sources for the implementation of the ABC system within a specific context can be found in [51–56]. The effectiveness of the ABC system was discussed by Kaplan [57] in providing helpful cost information to product designers for developing economic designs. The capabilities of the ABC were investigated by Tornberg et al. [58] with a particular emphasis on providing useful cost information to product designers. The study focused on modeling product design, purchasing, and manufacturing processes with graphic flow charts in the form of activity chains. With the help of the process models and the activity-based cost calculations, product designers were able to estimate the effects of different design options on product costs. The work of Tseng and Jiang [59] attempted to combine the feature-based costing methodology with the ABC approach. Their ABC analysis model could evaluate different manufacturing costs for multiple feature-based machining methods. Yang et al. [60] used process-planning, scheduling, and cost-accounting information to estimate manufacturing and machining cost through an activity-based approach. Other examples of manufacturing and machining cost estimation using the ABC approach can be found in [61,62].

Some other researchers used the ABC approach to model the manufacturing costs in a specific manufacturing setup. For example, Koltai et al. [63] estimated costs for flexible-manufacturing systems based on the ABC analysis, whereas Aderoba [64] developed an ABC model for job shops. The latter was based on the classification of all the activities into machine-based production, labor-intensive production, technical services, and administrative services. Cost rates for all such activities were provided, which were then used to estimate the cost of a new order. For example, the cost of a machine-based production activity C was given as follows:

$$C = [(M+m)t^m + (L+l)t^l + bt^b + ut^u] \tag{12}$$

where M is the cost rate for machines in the activity per hour, m the periodic rate for complimentary tools in the activity, L the labor rate for direct worker on machine activity, l the labor rates for ancillary worker on machine activity, b the building space rate for machine activity, u the utility rate for machine activity, t^m the machining time, t^l labor working time, t^b the time spent on building space occupied by activity, and t^u the time of utility being used.

Expressions were also provided for the cost rates for machines and tools, the labor rates for direct and ancillary worker, the building space rate, and the utility rate, which are not described here for brevity of presentation. The proposed method proved useful in highlighting high-cost elements; however, its accuracy depended on how reliable the activity time estimates for a new product were.

6 Cost Estimation in the Early Phases of the Design Cycle

The key to thrive for a manufacturing enterprise in the twenty-first century is based on product quality, competitive cost, fast delivery, and flexibility. On the other hand, factors (such as globalization, and mass customization) put an extra pressure on a business enterprise to survive and remain profitable at the same time. Although an innovative approach and a new product devel-

Table 1 The PCE techniques: key advantages, limitations, and list of discussed references

Product Cost Estimation Techniques				Key Advantages	Limitations	References
Qualitative Cost Estimation Techniques	Intuitive Cost Estimation Techniques	Case-Based Systems		Innovative design approach	Dependence on past cases	[9-12]
Qualitative Cost Estimation Techniques	Intuitive Cost Estimation Techniques	Decision Support Systems [13-16]	*Rule-based Systems*	Can provide optimized results	Time-consuming	[7], [9], [17]
Qualitative Cost Estimation Techniques	Intuitive Cost Estimation Techniques	Decision Support Systems [13-16]	*Fuzzy logic systems*	Handles uncertainty, reliable estimates	Estimating complex features costs is tedious	[6], [7]
Qualitative Cost Estimation Techniques	Intuitive Cost Estimation Techniques	Decision Support Systems [13-16]	*Expert Systems*	Quicker, more consistent and more accurate results	Complex programming required	[19-21]
Qualitative Cost Estimation Techniques	Analogical Cost Estimation Techniques	*Regression Analysis Model*		Simpler method	Limited to resolve linearity issues	[22-25]
Qualitative Cost Estimation Techniques	Analogical Cost Estimation Techniques	*Back Propagation neural network model*		Deal with uncertain and non-linear problems	Completely data-dependant, Higher establishment cost	[4], [8], [26-29]
Quantitative Cost Estimation Techniques	Parametric Cost Estimation Techniques			Utilize cost drivers effectively	Ineffective when cost drivers can not be identified	[8], [30-33]
Quantitative Cost Estimation Techniques	Analytical Cost Estimation Techniques	*Operation-based cost models*		Alternative process plans can be evaluated to get optimized results	Time-consuming, require detailed design and process planning data	[34-38]
Quantitative Cost Estimation Techniques	Analytical Cost Estimation Techniques	*Break-down cost models*		Easier method	Detailed cost information required about the resources consumed	[1], [2], [39-40]
Quantitative Cost Estimation Techniques	Analytical Cost Estimation Techniques	*Cost tolerance models*		Cost effective design tolerances can be identified.	Require detailed design information	[41-43]
Quantitative Cost Estimation Techniques	Analytical Cost Estimation Techniques	*Feature-based cost models*		Features with higher costs can be identified	Difficult to identify costs for small and complex features	[4], [35], [44-47]
Quantitative Cost Estimation Techniques	Analytical Cost Estimation Techniques	*Activity-based cost models*		Easy and effective method using unit activity costs	Require lead-times in the early design stages	[5], [48-49], [51-64]

opment process may attempt to deal with issues such as flexibility and product quality, they may still be time consuming and less cost effective. In addition, the prospective end user of a would-be product often demands a price quote as soon as possible, sometimes even unconcerned and oblivious of factors such as the extent of the customization, the nature of the data required, and the design complexity. To make matters worse, often a manufacturer ignores the significant factors, such as design module availability, manufacturability, and the level of accuracy required for processing time estimation. The overall situation, therefore, could either lead to an underestimation resulting in a profit loss and a blow to operational targets or a more profound strategic damage caused by overestimation leading toward the loss of customer goodwill and market share. All the above highlights the ever-increasing importance of devizing methods to forecast the cost for a new product in the early design and development phases with accuracy.

Since most of the product costs sustained during later in the production life cycle are determined during the conceptual design phase [8], the cost estimation in the early phase of the design cycle is crucial. Many researchers have emphasized the importance of cost estimation at the early design stages when 70–80% of a total product cost is determined [9,16,25,44]. Some researchers have developed methodologies with a special emphasis on early cost estimation [65,66]. A framework for developing a cost database was suggested by Sheldon et al. [67] and aimed to serve different groups of DFC system users to determine appropriate cost structures by analyzing the information provided by a cost-accounting system. Knowledge representation in such a way facilitated the generation of cost estimates at an early design stage. A framework to integrate design costs into quality function deployment (QFD) was used by Bode and Fung [68]. The approach adopted is a helpful tool for designers at the early stages of product design for making trade-off decisions between quality and cost prioritizing the attainment of technical attributes based on customer requirements.

Within the specific context of the classification presented in the current study, *qualitative techniques* are generally favorable in making cost estimates in the early design stages. This is because these techniques make use of the past data to predict the cost of a new product without requiring detailed information, such as geometric design data or process planning results. Although, the accuracy of these techniques is sometimes questionable, the rough estimates obtained in the early design phases still provide a good platform for decision making, which is employed during all the stages of the design and development process. Thus, product cost can be controlled from the conceptual design stages when the design alternatives have a direct bearing on the product cost to the shop floor execution stages when the process alternatives are the results of the choices made during the early phases of the design process.

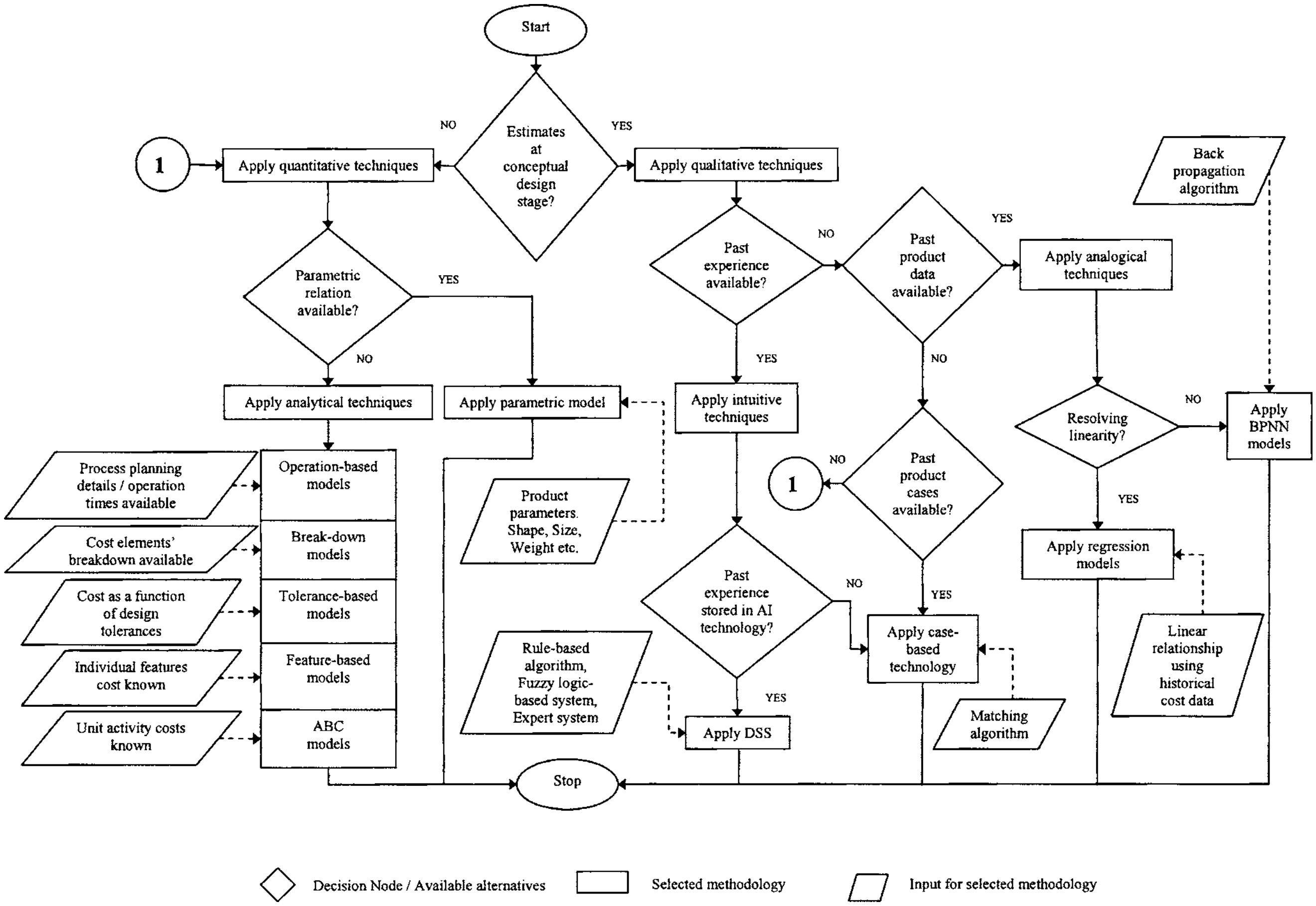

Fig. 6 Decision-support model for cost estimation methodology selection

7 Cost Estimation for Specific Applications

A number of cost estimation methods and techniques were developed with reference to particular applications. These techniques range from the evaluation of certain manufacturing and machining processes to the dedicated techniques designed to suit specific manufacturing systems, from composite material costing to the cost analysis of parts and assemblies and from dealing with specific segments in a production cost cycle to covering a product life-cycle cost. Although, these techniques might fall into any of the classified groups discussed in the previous sections, the main focus of this section is on furnishing references within the context of a given application area. The repetition of some of the references previously discussed, therefore, is inevitable, and an assortment of references and techniques from different categories may also be discussed together under a certain application area. The section is aimed at providing researchers with a platform to explore any further in a specific application area of the PCE.

7.1 Cost Estimation for a Specific Segment in a Production Cycle. Different costs are associated with various stages in a production cycle starting from the ones incurred during the early phases of a design cycle to those linked with the manufacture of an actual product on the shop floor. Many researchers devised methods to evaluate the costs associated with a specific segment in a production cycle. For example, if a methodology is applicable at the quality function deployment (QFD) stage [68], the other is developed for the costs associated with the design and development phase of a product [5]. Methods for process planning cost evaluation and optimization can also be found in [35,36,38]. Aldrich [69] estimated the cost associated with the bill of materials (BOM) using MRPII software. Cost calculation in manufacturing and machining can be found in [70]. Costs associated with conventional manufacturing processes [44], nonconventional manufacturing processes [71], and the machining accuracy [72] can also be found.

Some researchers developed methodologies that could be used for cost estimating in several stages of a product design cycle. For example, Weustink et al. [73] developed a framework for product cost control by estimating the various cost elements and storing the data in a generic way. The methodology allows cost estimation on different aggregation levels, e.g., feature level, component level, assembly level, etc. Koonce et al. [74] developed a system capable of generating cost estimates in all phases of the design stage. The system, which was prototyped in JAVA, used simple parametric cost relations in the early stages of a design, when detailed design was not available to produce cost estimates for a product. When the design was developed, estimates could be produced using design features, manufacturing features, or a process plan.

7.2 Cost Estimation for Specific Machining and Manufacturing Processes. The selection of suitable manufacturing processes is governed by an accurate estimation of the costs associated with them among other factors. Methods have been devised to predict the costs of specific machining and manufacturing processes. These include the assembly costing techniques [75,76], and the cost models for die casting [77]. Further models were developed for a hole-making process [15], welding [78], and milling and drilling [79].

7.3 Cost Forecasting for Specific Parts and Products. Many researchers focused on the application of the cost estimation techniques to specific products, ranging from standard parts

Table 2 Summary of the published literature references for various applications of the PCE

S. No.	Application area		References
1.	Cost estimation for a specific segment in a production cycle		[5], [35,36], and [38] [44] and [68–74]
2.	Cost estimation for specific machining and manufacturing processes		[15] and [75–79]
3.	Cost estimation for specific parts and products	Parts and components	[80–89]
		Special products	[4], [23], [28], and [44], [90–93]
		Composite material products	[40] and [94–97]
4.	Cost estimation for a generic system	Specific manufacturing system	[64] and [98–101]
		Specific industrial sector	[102–108]

and components to a particular product group. Schreve et al. [80] presented a cost model using mild-steel fabricated parts, whereas the one for machined components can be found in [81]. Hicks et al. [82] developed four cost-modeling approaches for various classes of engineering components. These components were defined as standard selected, standard designed, and bespoke designed. French [83] used a function cost-modeling methodology to estimate the costs of mechanical components, whereas Ulrich and Eppinger [84] used previous orders and procurement records to estimate the cost of similar components. Kendall et al. [85] presented cost information for automotive components using a simulation technique. Gutowski et al. [86] presented a process-oriented cost model to estimate manufacturing cost of advanced composite aerospace parts. Cost models for injection-molded components can also be found in [87–89]. On the other hand, cost models for specific product groups include those for PCB manufacturing [90–92], developmental equipment [93], packaging products [4,28], injection-molding tool [23], and gear-drive manufacturing [44].

Another type of products covered by cost estimation techniques is based on composite material. For example, cost and consolidation model for commingled-yarn-based composites was presented in [40]. Process-flow simulation techniques to evaluate manufacturing costs for composite products were discussed in [94]. Cost analysis of thermoplastic composites using different techniques can also be found in [95,96], whereas Walls and Crawford [97] used historical data to produce cost information for continuous fiber-reinforced thermoplastic products.

7.4 Cost Estimation for Generic Systems. Cost estimation models to suit the needs of a generic system were also developed by many researchers. For example, cost models for job-shop manufacturing systems can be found in [64,98]. On the other hand, a mathematical and simulation model to estimate the manufacturing and product cost in material requirement planning (MRP) and just-in-time (JIT) systems was proposed in [99]. Similarly, a simulation model to estimate the cost in a flexible manufacturing environment was proposed in [100], whereas the one for cellular manufacturing configuration was proposed in [101].

Cost estimation techniques were further developed for specific industry sectors [102]. For instance, work has been carried out for airplane manufacturing industries [103], electronics industries [104], automotive industries [105], aerospace and defence industries [106], telecommunications [107], and shipbuilding industries [108].

8 Overview

This study reviews the state of the art on product cost estimation. In order to better visualize the variety and breadth of the PCE techniques proposed in the literature, an extensive classification scheme is developed and followed throughout the study. A pictorial representation of the classification system adopted in the present study is given in Fig. 5. The horizontal dotted lines are used to show the different levels in the hierarchical tree diagram proposed. In addition, the PCE techniques discussed in this paper are tabulated together with the key advantages, limitations, and corresponding published literature in Table 1. The study of individual techniques also revealed the key conditions under which they can be applied. The conditions for the implementation of these techniques discussed in previous sections are summarized in Fig. 6 to form a decision-support model (DSM) for cost estimation methodology selection. The developed model is a helpful tool for estimators in making decisions about selecting a suitable estimation methodology. It can be observed that a particular technique linked with a specific class is more applicable in certain situations. During the early phases of the design cycle, when limited data are available, qualitative cost estimation techniques are more appropriate and provide a helpful starting point for a detailed analysis at a later stage. For example, the proposed case-based methodology systematically makes use of available past data to generate estimates for a similar new product. One problem linked with such techniques is the limited availability of past data, which is overcome to some extent by making use of the past experience or knowledge of the estimator generally encapsulated in the form of decision rules.

Qualitative techniques, therefore, are helpful either in furnishing rough cost estimates or serve as a decision-aid tool for designers or estimators especially during the early phases of design process. However, when the detailed design becomes available, quantitative techniques provide more accurate estimates, which are necessary for factors such as design rationalization, determination of profit margins, etc. The data requirements restrict the use of such techniques in the final phases of design and development process. Techniques such as the ABC systems overcome the problem to some extent by making use of the predetermined activity rates to calculate the total amount of activities consumed to manufacture a product rather than requiring any detailed design and manufacturing information. This, however, requires lead times for individual products in the early design stages, which may be obtained using methodologies such as the case-based approach. Therefore, a combination of the two approaches—the qualitative and the quantitative techniques—could play an important role in developing a cost evaluation system capable of providing useful cost information on various stages of design and development phases.

The significance of early cost estimation has long been a focal point for research activities in the area, as has been highlighted in Sec. 6. With the advent of computers and the advancement in technology, nonconventional approaches, such as knowledge-based techniques and neural network models, have been applied effectively utilizing past knowledge to predict the future costs in the early design phases. Current trends in cost estimation exploit the feature technology and a simpler trend is based on estimating the costs by calculating the amount of activities performed to manufacture a product. Recent research in the field focuses on getting quicker and more accurate results by developing integrated systems combining two or more approaches. For example, a mix of neural-network approach and feature technology is an emerging trend. Applying neural networks in CBR [109], cost-tolerance analysis using neural networks [110] and fuzzy-activity-based costing [111] are also among some of the new concepts. Yet another area of ongoing research activities combines rule-, fuzzy-logic-, and feature-based methodologies together. An approach that blends some of these techniques could provide more promising results. For example, there is a need to combine the feature technology with the ABC method to study the effects in detail. An approach dealing with the ABC systems and neural networks at the same time may yet be another research area.

The study also reviewed the published literature dealing with applications of the PCE techniques to different areas. Section 7 highlighted the works of different investigators within this framework. References were provided for various application areas that included the cost estimation for various stages of the production cycle, cost evaluation for different machining and manufacturing processes, costing for specific parts and products, and, finally, cost forecasting in a generic system. Table 2 provides a summary of all such references. For example, different stages of the production cycle were discussed with references starting from the QFD stage to analyzing the whole life-cycle cost. Cost evaluation for parts and products covered fabricated parts, machined parts, standard and nonstandard components, composite material products, etc. References were also provided for project cost estimation, cost evaluation in a specific manufacturing environment, and cost analysis in a certain industrial sector.

9 Conclusions

This paper extensively reviewed the pertinent literature on manufacturing and product cost estimation and provided a detailed survey along with a critical evaluation of some of the techniques developed in the area. The techniques were classified into two main groups as qualitative and quantitative, which were further subdivided into two categories each. The paper examined all the categories, in detail, with references to the published literature. Mathematical models were presented on some occasions to illustrate certain techniques. The significance of cost estimation in the early phases of design and development process was then discussed with a focus on the proposed classification. Cost estimation work was also discussed with respect to particular applications in the area. Finally, an overview of the work was presented with a pictorial representation of the proposed classification, a decision-support model for cost estimation methodology selection, and a summary of the literature review in tabular forms. Key advantages and limitations of the techniques discussed in the study were also summarized. Current trends in the PCE were then discussed briefly along with a few suggestions for future research directions in the field. Although, the study conducted is not exhaustive, it provides a comprehensive source for carrying out further research in the area.

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