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REVIEW ARTICLE

A review of conventional and knowledge based systems for machining price quotation

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Abstract Price estimation for the preparation of quotations is critical process for companies that have to struggle to get orders by offering competitive pricing. For machining companies, said process is complex because of the large amount of variation that can occur. In this case, a manufacturing expert is generally in charge of this task. However, manufacturing experts have several other important tasks to which they must attend. The use of software systems that automate the estimation of costs and prices is common, knowledge-based systems are one of the primary alternatives for two fundamental reasons: they behave the same way an expert would and they save and maintain all knowledge within the company regardless of who has worked on them. This paper covers the principal cost and price estimation methods and reviews the knowledge-based systems that have been implemented in the area of machined part manufacturing. Recommendations as to how future knowledge-based systems for the estimation of this type of pricing should develop are also included.

Keywords State of the art · Knowledge-based systems · Machining cost estimation · Machining price quotation

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Introduction

Several different knowledge-based systems have been developed in order to solve the variety of problems associated with price estimation in machining manufacturing companies. When the knowledge-based systems require a web interface, the knowledge is usually represented by means of conventional expert system technologies (CLISP, PROLOG, etc.) and a specific web interface is developed for the user interaction.

The quotation process, involves knowledge of the manufacturing process of each part, as well as the ability to determine its total cost and profit margin. This task can only be performed by a highly qualified and experienced person. The problem is that experts who can create these quotations are scarce. This causes qualified personnel to spend a large amount of time on generating quotations rather than working on other important company activities.

There are different lines of research trying to resolve the price estimation problem in the creation of quotations. Conventional systems contribute a timely solution to the problem, but knowledge-based systems are advantageous because they automate the price determination process and allow knowledge to be saved in a shared repository. This knowledge can be used to train factory employees and is easily updated. Using an estimator's experience in the calculation of prices allows for:

- The simplification of mathematical and detailed models, especially when there is little data about the product to be estimated.
- The saving of the represented experience for use in employee and expert training.
- New industry needs have made it necessary to integrate old applications with new tools and the tools of

other companies in order to integrate knowledge and solutions.

The companies' new needs make the use of the Web necessary for maintaining internal and client relationships in order to integrate knowledge and solutions. However, the techniques used by traditional knowledge-based systems may not function as well in Web environments and do not offer a comprehensive model of representation. Advances in knowledge-based and Web-based systems have led to new technology that has been incorporated little by little, improving efficiency in the manufacturing process (Xie 2006).

Even though there are knowledge-based systems for estimation that can be accessed via the Web, in this state of the art study, systems for the generation of quotations with a specific representation model, facilitating integration with the Web and providing the advantages of the integration described, were not found.

This article is a review of the different types of estimation carried out by machining manufacturing companies, and it analyzes the application of intelligent systems working in tandem with estimation methods to obtain better results.

The rest of the article is structured as follows. Section "The request for quotation process" studies the RFQ process, which includes the creation of the quotation based on the client's request. Section "Cost estimation methods" analyzes the different cost estimation methods used in price determination. Section "Price and cost estimation systems" describes the study of application software and intelligent system's use of estimation methods. Lastly, section "Results" analyzes the results of the study and Section "Conclusions" establishes conclusions.

The request for quotation process

Companies that manufacture products have been classified numerous different ways depending on the manufacturing processes and the types of products used and produced. On one hand, there are companies that manufacture standardized products that are put directly on the market or that are warehoused as stock in order to fill future orders. On the other hand, other companies manufacture based on the products ordered: versatile manufacturing companies negotiate with clients and bid against other companies for each of the orders they receive, customizing the product for each client (Kingsman et al. 1996). Versatile manufacturing companies include Engineering-to-Order (ETO) companies, meaning that the client's order requires the creation of a design, and Make-to-Order (MTO) companies, which manufacture the product based on the design provided by the client (Kingsman and de Souza 1997). These concepts have been studied, and several authors have developed complete taxonomies that broaden, define and classify these terms, as is the case with Amaro et al. (1999). Many machining parts companies are versatile manufacturing companies. Versatile manufacturing companies are usually small to mid-sized and manufacture products based on the demand of the orders received. However, to get the order it is first necessary to negotiate quantity, date of delivery and price with the client. This process is called Request for Quotation (RFQ).

The RFQ process is vital for versatile manufacturing companies. Date of delivery aside, a price estimation that is less than the cost of production can lead to financial loss for the company, as can delays in product delivery. The other extreme is a price estimation that is much higher than the cost of production, which may cause the client to place his order with a competing company that offers a better price. Another determining factor in winning or losing an order is response time once the client has requested a quotation. A slow response may cause the client to order from a company that submits a quotation much faster.

A study of 12 versatile manufacturing companies concluded that the price estimation process followed a set of common steps (Kingsman et al. 1996; Kingsman and de Souza 1997). In order to determine price, it is necessary to estimate cost in the different areas that intervene in the manufacturing of the product. Normally, cost estimation is carried out by an engineer or expert in each area of manufacturing. This expert personnel is not usually dedicated exclusively to estimation and is assigned to carry out other design or production tasks. Because of this, they usually need a certain amount of allotted time for estimation. If on top of this we add the fact that the number of qualified cost estimation experts at a company is generally small, price determination processes can take weeks to conclude.

Given the importance of the quotation process, different lines of research try to optimize the process. Some work on comprehensive solutions, while others try to improve specific parts of the process.

From a negotiation standpoint, optimization can focus on two aspects: the automation of the process online and decision support. For example, workflow systems based on Web services and agents for the collaboration between companies have been developed with practical applications for the receipt of orders process and price negotiation between a client and various providers (Wang et al. 2006). Following this line of research for improvements in price negotiation, e-marketplaces are being developed through which companies and suppliers can contact one another (Beil and Wein 2003). These e-marketplaces allow for the partial automation of the RFQ process, and bidding mechanisms between a factory and its suppliers have been proposed so that the best offer among several suppliers can be selected. Calosso et al. (2003) study the negotiation process in the MTO companies environment within the RFQ process and have proposed three lineal

programming models for use in the different aspects involved in offer evaluation and bidding.

From an analytical and reengineering point of view, the term *specification process* (Hvam and Have 1998) encompasses the sales, design and engineering of a product. This process includes handling of orders, bidding, product configuration, etc. To reduce the amount of time needed to complete the specification process, in order to improve a company's competitivity, process reengineering is necessary in some cases. Hvam et al. (2004) propose a method for the analysis and restructure of product specification processes, integrating new information technologies. They state that the reengineering process can include the introduction of new software that supports the new process, such as expert systems, which reduce the time it takes to generate a quotation. In attempts to improve the RFQ process, Kennedy and Shao (1989) have applied expert systems representing the rules that improve the efficiency of the orders process in small factories, in order to formulate recommendations on how to improve the specific processes at each one. Ahmadi and Tirupati (1996) have also applied decision support systems for the evaluation of client orders and the decision whether to accept them or not based on the activities programmed at the factory.

The special nature of ETO companies restricts the application of methodologies within the supply chain, which also affects the quotation generation process. Improvements in factory support software lessen response time, improve planning and facilitate product innovation (Hicks et al. 2000).

One of the primary problems that a versatile manufacturing company faces when it comes to dealing with quotation requests is the estimation of cost, which later determines the sales price (Kingsman et al. 1996). The several different lines of research that focus on this area are described below.

Cost estimation methods

To determine what price to offer the client, the company must first estimate the product manufacturing cost. The faster and more dependable the price estimation, the greater the possibility the quotation will be accepted. However, the estimation of cost is no trivial task. Although on some occasions the client provides blueprints and designs, some with more detail than others, at such an early stage in the production process, the information for the product to be produced is limited and imprecise.

Generally, versatile manufacturing companies do not estimate costs based on textbook specifications, but rather use those methods as a starting point for the real estimation (Kingsman and de Souza 1997). It is, therefore, common for estimations to be generated by experts, and parts of said estimations are based on unwritten rules and the previous experiences of the estimator.

The following subsections describe the classification of the different methods and estimation models used in the development of quotations with manufacturing cost calculation applications in which the Niazi et al. (2006) study is used as a base, but including the points of view of other authors.

Qualitative estimation methods

Qualitative estimation methods are those based primarily on the analysis of the new product as compared to products developed previously (Niazi et al. 2006). Qualitative estimation methods can be classified as (Niazi et al. 2006):

Intuitive methods

Based on the use of previous experience. Knowledge can be saved as rules, decision trees, judgments, etc. (Niazi et al. 2006) and is used later for estimation. These methods can be classified as (Niazi et al. 2006):

- Case-based methodology. Case-based systems compile a large number of products previously manufactured by the company, storing information related to their features and costs. When the cost of a new product has to be estimated, these systems look for a previous case that is similar in order to produce an estimate. Once a similar case has been found, a function is applied that adapts the previous case to the new circumstances for which the estimate is required. According to Duverlie and Castelain (1999), these case-based systems provide a quick solution, and, as they only consider one part of the known parameters, can offer different alternatives for the unknown parameters based on previous cases. This is usually useful when there is no formal knowledge of the production area. In the adaptation phase, other methods (such as fuzzy logic systems) can be used and, although in some cases it is imprecise, the system always provides a similar case that the user can adapt. However, the disadvantages of this methodology include the difficulty of using general criteria to index the cases and the need for a certain number of base cases, a certain amount of similarity and an adaptation function (Duverlie and Castelain 1999). Examples of case-based reasoning for cost estimation of machined parts can be found in Wang et al. (2003), Chan (2005), Chougule and Ravi (2006).
- Decision support systems. They assist the estimator make better decisions at the different estimation process levels, using the knowledge of experts in the domain (Niazi et al. 2006). These systems include fuzzy logic systems, for example Jahna-Shahi (2001), and rule-based systems and expert systems, for example Er and Dias (2000).

Metaxiotis et al. (2002) reviews the state of the art of expert systems in production planning and scheduling.

Analogical methods

Analogical methods are based on the similarity between the new product and past cases. Analogical method justification is based on three areas (Duverlie and Castelain 1999): cognitive psychology, rule-based systems and analog reasoning. These methods include (Niazi et al. 2006):

- Regression analysis. These methods can also be considered as parametric methods (Layer et al. 2002). Liu et al. (2008) provide an empirical study of regression models for the estimation of life cycle costs. Other examples can be found in Kadidal and Bidanda (1993) and Bidanda et al. (1998)
- Artificial neural networks. Some examples of the use of neural networks for the calculation of cost can be seen in Stockton and Wang (2004). Neural networks have also been used for the estimation of maintenance costs (Park and Seo 2004) or complete life cycle cost (Seo et al. 2002) based on conceptual design information.
- Duverlie and Castelain (1999) also include case-based reasoning under analogical methods.

Quantitative estimation methods

Quantitative estimation methods are based on the analysis of detailed product design, its features and the processes necessary for manufacturing (Niazi et al. 2006). Quantitative methods are found in the following (Niazi et al. 2006):

Parametric methods

Parametric methods are derived from the application of statistical methods for the definition of cost as a function of different product variables (Niazi et al. 2006). One must have the value of the different parameters in order to use these methods. The parameters used in the definition of a parametric method do not necessarily have to completely describe the product. They can be a limited group of values that describe the product's primary features. These methods work like a black box and do not require large amounts of knowledge about the product to use them, and they are also fast; however the primary disadvantage is that the parameters not taken into account when defining the formulas may be relevant in certain cases (Duverlie and Castelain 1999). So-called "statistical methods" are also a part of parametric methodology, and they use historical data and empirical tests to obtain causal information on the relationship between product features and costs (Layer et al. 2002). Layer et al. (2002) also include methods based on analysis regression optimization methods and artificial neural networks in this classification. Examples of parametric methods can be found in Dewhurst and Boothroyd (1988), Boothroyd and Reynolds (1989), Jung (2002), Lan (2002) or Ko et al. (2007).

Analytical methods

Analytical methods are based on the breakdown of the product into elements that represent the different resources used in the manufacturing process and cost is calculated as a sum of all of the components (Niazi et al. 2006). Other authors have referred to these methods as "engineering-based" (Ruffo et al. 2006), "detailed method" (Seo et al. 2002) or decomposition of the work required into elementary tasks (Duverlie and Castelain 1999). These methods also includes the "generative-analytical" method (Layer et al. 2002), which identifies the processes relevant to the creation of the product and derives costs by adding each of these processes. These methods are broken down into (Niazi et al. 2006):

- Operation-based. Calculates the cost based on manufacturing time, nonoperational time and operation preparation time. This approach is used in advanced design phases due to the nature of the information necessary for its use (Niazi et al. 2006). Process-based cost estimation methods deal with the problem of cost implications of new materials or processes in the early stage of product development (Fuchs et al. 2008) mapping characteristics of the process to cost (Kirchain and Field 2001). Examples of operation based methods can be found in Downs and Trappey (1992), Arezoo et al. (2000), Wei and Egbelu (2000) and Xie et al. (2001, a, 2003).
- Breakdown-based. Calculates cost by adding all of the costs incurred during the production cycle, including materials and indirect costs (Niazi et al. 2006). An example of this method can be found in Koonce et al. (2003).
- Tolerance-based. Calculates cost based on the tolerance margins of different aspects of the product design. A recent example of such a method can be found in Di Stefano (2006).
- Based on the product features. Based on the identification of the product's different features that are related to product cost. These features can be related to design and/or operation elements (Niazi et al. 2006). Examples of such methods can be found in Ou-Yang and Lin (1997), Ben-Arieh (2000), Maropoulos and Baker (2000), Maropoulos et al. (2001), Sharma and Gao (2002), Tang et al. (2003) and Shehab and Abdalla (2006).
- ABC method (activity-based costing) (Cooper and Kaplan 1988). Calculates costs incurred when carrying out the activities necessary to the manufacture of the product. Examples of such an estimation method can be found in Aderoba (1997) and Locascio (2000).

Estimation methods discussion

Generally, even though the authors make their classifications based on similar concepts, the terminology used is far from homogenous. Lan and Ding (2007) and Chougule and Ravi (2006) classify estimation methods as intuitive, parametric, analogical and analytical, while Shehab and Abdalla include up to three different classifications (Shehab and Abdalla 2001, 2002a,b).

An aspect taken into account by Niazi et al. (2006) is that of traditional estimation methods. Said traditional methods are classified as (Zhang et al. 1996):

- Detailed breakdown methods.
- Simplified breakdown method (designed for estimation during the initial design phases).
- Methods based on the technological group (based on similarity).
- Regression-based methods.
- ABC method.

Other methods that are not included in Niazi's classification are based on calculating price estimations by evaluating the profit and level of risk associated with the project (Muntslag 1994), instead of using production costs.

Of the methods cited, the parametric methods provide fast estimations and can be based on a limited number of parameters, which makes them ideal for use during the initial development phases and for cost estimation when generating a quotation (Veeramani and Joshi 1997; Chougule and Ravi 2006). The analytical methods are amongst the most reliable. However, said methods are not usually appropriate for the initial development phases because of the detailed information they require.

The use of a single estimation method is usually not enough to generate a reliable estimation during the initial phases. It is generally necessary to combine several different approaches in order to obtain the best result (Duverlie and Castelain 1999; Layer et al. 2002; Lan and Ding 2007). For example, comparative studies of analogical and parametric methods conclude that, even when better results are obtained through the analogical approach, it is reasonable to combine both methods (Duverlie and Castelain 1999): find a previous case that is similar to the problem to be resolved and adapt it to the objective case with parametric formulas.

Price and cost estimation systems

Different models and IT applications have been developed to apply the estimation models described in the previous section. The fundamental requirements of a price estimation system consist of providing reliability and speedy estimation (Chen et al. 2003).

One of the problems detected in this study is the shortage of systems dedicated to estimation during the quotation process. For this reason the study has included cost and price estimation models and systems oriented towards the initial phases of the manufacturing process that make it possible for employees to generate quotations depending on the information they require.

The estimation process is slow and requires the collaboration of numerous company departments, explaining why specific methods for the estimation of manufacturing costs and prices have been developed. However, even though there are different machining cost estimation models and methodologies, they are not always specifically oriented toward quotation estimation (Veeramani and Joshi 1997). The following subsections describe the principal systems and models found, distinguishing between conventional technology-based systems and systems based on artificial intelligence techniques.

Applications and models based on conventional technologies

This section shows the primary systems for the estimation of cost and price of manufacturing machined parts, as well as the principal methodologies proposed for the same purpose that are not based on artificial intelligence techniques (see Table 1). Table 1 shows how more Web integrated systems have appeared over the last few years, and many of them are more general systems that include cost estimation modules. Although all of them obtain significant results, the practical experience viewpoint is not explicitly reflected in the implementation of these systems.

Quick analysis of the table shows that since the 1970s it has been proposed that IT can help resolve one of the most important problems faced by factories, the determination of manufacturing price during the phase previous to design. With the passage of time, more Web integration systems appear, the fruit of new communication necessities that arise in companies with the globalization of markets and the increased mobility of personnel.

Parametrics approaches

Amongst the methodological studies, the most widely cited authors are Boothroyd and Dewhurst, for both their estimation models and there design rationalization projects (Dewhurst and Boothroyd 1988) and project development cost optimization (Boothroyd and Reynolds 1989). Lan (2002) proposes a model for the cost estimation of machined parts that is based on a numeric simulation model based on the Lagrange multipliers that were previously implemented

Table 1 Conventional cost estimation systems

Reference	Web-based	Application area	Description	Method
Doney (1971)	No	Job-shop	Application for the price estimation in the RFQ process. It is a modular application, programmed in C	Analytical
Downs and Trappey (1992)	No	Generic	Methodology for the development of cost estimation software	Analytical
Muntslag (1994)	No	ETO Enterprises	Price estimation model based on benefit/risk analysis	Risk/benefit
Taiber (1996)	No	Computer Aided Process Planning	System for the automatic generation of manufacturing processes based on the features of the part. The system provides cost estimation for each process	Analytical
Aderoba (1997)	No	Job-shop	Model for estimating production time and cost based on the ABC method. The model can be used for RFQ evaluation	Analytical. ABC based
Veeramani and Joshi (1997)	No	Machining	Veeramani and Joshy propose the architecture of an RFQ estimation system and two estimation methodologies based on similarity	Analogical
Ou-Yang and Lin (1997)	No	Machining	Cost estimation system based on the design of the part. The design is stored in CAD files	Analytical
Duverlie and Castelain (1999)	No	Generic	Comparison of a parametric model and case based reasoning	Parametric/intuitive
Ben-Arieh (2000)	No	Machining	System for cost estimation of machined parts. The system determines the manufacturing process required based on the features of the part	Analytical
Maropoulos et al. (2000); Maropoulos and Baker (2000)	No	Machining	Cost estimation model based on the machines and operations required for the machining process. The machining process is determined based on the features of the part	Analytical
Locascio (2000)	No	Electronic components	Cost model based on the production time and the assembly time for the part. The production time is based on the activities required for manufacturing the part	Analytical. ABC based
Layer et al. (2002)	No	Several	A review of cost estimation research in Germany up to 2002	Several
Lan (2002)	No	CNC machining	Numeric simulation model for minimizing machining costs and machining time	Parametric
Jung (2002)	No	Machining	Cost estimation model based on four relevant features of a part	Parametric
Koonce et al. (2003)	No	Generic	Cost estimation model based on the breakdown of the product into cost components	Parametric/analytical
Chen et al. (2003)	No	Generic	Chen et al. identify requirements for a computer-aided cost estimation tool based on axiomatic design	Intuitive/analytical

Table 1 continued

Reference	Web-based	Application area	Description	Method
Beil and Wein (2003)	Yes	Generic	Electronic bidding mechanism for the RFQ process. Based on the bidding information, the system estimates the cost of each supplier in order to select the best quotation	Others
Ben-Arieh and Li (2003); Qian and Ben-Arieh (2008)	Yes	Machining	Agent-based architecture for the coordination of the RFQ process amongst several companies. The paper presents an estimation model based on ABC/Parametric method but the cost estimation module of the system is customizable. This model is extended in Qian and Ben-Arieh (2008)	Parametric
Brinke et al. (2004)	No	Generic	Generic architecture for the estimation of manufacturing costs based on customizable modules	Customizable
Venkatadri et al. (2006)	No	Generic	Model for the representation of the product's supply chain. Based on the supply chain features, the optimum price and the lead-time can be determined	Parametric
Silva et al. (2006)	Yes	Mould industry	Web-based decision support system for production planning and control. The system supports the cost estimation based on data about past similar products.	others.
Jiao and Helander (2006)	Yes	Injection mould	Web-based product configurator. It estimates the production cost based on the product features	Analytical
Ruffo et al. (2006)	No	Laser sintering	Experimental cost estimation model based on different types of cost related to the manufacturing process. Each type of cost has a set of related equations for calculating said cost	Parametric/analytical
Masmoudi et al. (2007)	No	Weld operations	Decision support tool for estimating the cost of welding operations. The proposed cost estimation model links technical variables with economic variables	Analogical/analytical
Tu et al. (2007)	Yes	Mass customization	Cost estimation model based on cost indexes for well-known products. The model is adaptable to new products.	Analogical
Lan and Ding (2007); Lan et al. (2008)	Yes	Stereolithography parts	Web-based system based on two cost estimation models: a parametric model for early estimations and an analytical model for detailed estimations	Parametric/analytical
Oduoza and Xiong (2008)	Yes	Small make-to-order companies	Decision support system for processing customer enquiries. Applies a multiple-objective, linear programming model for estimating the company's revenue	Parametric

in Matlab for their evaluation. Jung (2002) developed a machined parts cost estimation system by applying a mathematical model of estimation based on four highly significant features related to the price of the parts used. Oduoza and Xiong (2008) present a web-based decision support system for the client's enquiry management in small, make-to-order companies. The cost is determined by means of a dynamic bill of materials and the revenue is estimated with a linear programming model.

Analytical approaches

Many of the studied systems are based on analytical methods. Doney (1971) presents a modular application for the determination of machining parts price for a factory. In Doney's approach each module represents a component of the calculated cost.

Aside from the previously cited Doney (1971) application, efforts to develop systems have continued in different areas and with different objectives. In some cases, the calculation of cost is not applied directly to price estimation, but rather as a manufacturing process or design alternatives selection criterion. For example, Taiber (1996) applies an analytical model for the selection of manufacturing alternatives to a CAPP system. Taiber approves of the application of genetic algorithms for the generation of manufacturing alternatives, but mentions that the validation of processes obtained by this means may produce problematic results. He therefore proposes a combinatorial generation algorithm, determining the cost of each of the proposed alternatives. Ou-Yang and Lin (1997) developed a cost calculation system for the generation and evaluation of manufacturing processes based on an analytical model using performance parameters from CAD files with parts designs and databases with manufacturing and cost parameters. Other systems, such as that of Ben-Arieh (2000) determine the manufacturing process by assessing the features of the part to be manufactured and calculate the cost by combining variant approaches (based on previous data) in order to determine the manufacturing parameters, calculate manufacturing time and estimate the final cost of the part with a detailed model. Similarly, in the Maropoulos et al. (2000) and Maropoulos and Baker (2000) systems, the operations necessary for the machining process depending on the features of the part are selected. These systems determine the machines that can conduct the operation and calculate manufacturing time and cost.

Aderoba (1997) proposes an analytical estimation model, based on the ABC model, with the principal objective of estimating the manufacturing cost of new products, but that can be applied to the evaluation of orders. Locascio (2000) proposes an analytical model based on the ABC method used in a Motorola electronic components assembly plant. Venkatadri et al. (2006) propose a generic model oriented toward the RFQ phase in which the supply chain is represented, determining the optimum price depending on the manufacturing time.

On a methodological level, but regarding the development of software, Downs and Trappey (1992) analyzed cost estimation software design from a software engineering point of view. The article proposes an approach to estimation based on a group of blocks stored in a database, which can be either operational or material. Each block uses a group of equations to calculate the costs associated with the features they represent. In this methodology, a part is represented as a group of blocks that represent the operations and the materials necessary to manufacture it. Once the sequence of blocks necessary to produce the part has been constructed, the cost can be calculated using the equations associated with each of the blocks. The extension of this type of system would consist of adding new blocks for new products to the database.

Other interesting systems used for the estimation of cost are product configurators, as they facilitate the definition of product features for later decisions and calculations. An example of this type of system is that proposed by Jiao and Helander (2006), which includes a cost calculation module and is Web integrated.

Analogical approaches

Veeramani and Joshi (1997) revise the methodologies in order to respond quickly to RFQs, suggesting that development of decision support methodologies and new electronic sales technologies is imperative to favor said quick responses. Veeramani and Joshi propose a RFQ processing framework based on similarity-based cost estimation models.

Tu et al. (2007) propose an index-based model for the estimation of costs in mass-customization manufacturing companies. In Tu et al.'s model, each manufacturing process has a related cost index structure. These indexes can be used to estimate costs of standard processes (generative method, i.e. known products), or can be adapted to non-standard processes (i.e. new products) based on their similarity to standard processes (identifying and comparing the similarities between the new product and previously made products). The latter approach (variant method) requires the existence of historical information about previously manufactured products and a similarity measure for comparing new and previous products. Determining the similarity measure is a difficult problem. Moreover, in order to obtain accurate results, the historic information must be relevant. Inaccurate similarity measures, or irrelevant or inaccurate historic information can lead to erroneous results.

Other approaches

In this subsection, we include works that combine several estimation methods and other works not included in previous subsections.

Muntslag (1994) suggests that when it comes time to generate a quotation, there are too many unknown factors that can affect final price. He, therefore, proposes a price approximation by taking into account more general factors associated with order risks and the profits the order can produce for the company.

When it comes to the description of models and methodologies, the previously cited work of Duverlie and Castelain (1999) is also relevant to comparing parametric model estimation and an analogical case-based methodology. In their work, Duverlie and Castelain (1999) applied both models to the manufacturing of pistons and compared the results of both models. The conclusion was that the greatest profits are obtained by combining both, applying the parametric method for the evaluation and adaptation of previous cases.

Ruffo et al. (2006) orient their system towards manufacturing cost estimation for laser sintering production, based on the different types of cost identified by the authors and a set of equations combining parametric and analytical models.

The structure of software modules and the requirements of a price estimation software system are addressed by Chen et al. (2003) applying the axiomatic design technique.

The development of configurable modules for integration in larger systems has been studied by Koonce et al. (2003) and Brinke et al. (2004), although in the last few years, systems have been more oriented towards the decision support, as presented by Venkatadri et al. (2006), Silva et al. (2006) and Masmoudi et al. (2007). These last few created a hybrid system from analytical and parametric methods along with a products configurator used to calculate welding cost in the manufacturing of parts, linking technical and economical variables and part features (Masmoudi et al. 2007). The system is implemented on top of an ACCESS database and is not Web accessible.

Given the importance of the generation of quotations for fast prototype creation, Lan and Ding (2007) and Lan et al. (2008) developed a Web estimation system capable of providing the price of a part based on both a general and detailed estimation method, and using a CAD file that defines said part. The general model is parametric and based on a group of very simple features that allow for the calculation of the part's weight, which is used to obtain a manufacturing cost estimation and sales price. The detailed model applies an analytical method based on manufacturing time. This system uses the advantages of mathematical models of estimation, but it is not backed by a knowledge-based system, which allows for the management and evolution of said models.

Aside from the price and cost calculation models and the systems that implement them, other studies have also focused on the price estimation problem, but from the point of view of improving and optimizing the process. Beil and Wein (2003) propose an electronic bidding mechanism between different providers. Based on the bids received and the conditions of the offer, the system calculates the cost function of each supplier to decide which the best offer is. On the other hand, Ben-Arieh and Li (2003) present an agent-based system for the coordination of the quotation process amongst several companies. For the agent-based system, Ben-Arieh and Li (2003) define a hybrid estimation model combining ABC with a parametric model, although the cost estimation module can be configured for each supplier with its own cost estimation model. This parametric model is extended by Qian and Ben-Arieh (2008), to include design and development activities. Both systems follow a line of thought that has become popular over the last few years: processes automation (in this case the quotation process) making all transactions electronic and automatic, making intelligent decisions and minimizing human intervention.

Knowledge-based estimation systems

This section shows the principal expert systems oriented toward the calculation of costs and the estimation of prices that have developed over the last few years (Table 2).

As is seen in Table 2, the first expert systems in the domain appear in the early 1990s, while the inclination toward the Web becomes noticeable by 2000. Although authors such as Xie et al. (2003) remark on the advantages offered to the manufacturing process by integrating intelligent systems with the Web and the opportunities to apply factory experts' practical knowledge (Niazi et al. 2006), few Web-based expert systems have been found, even fewer that specialize in the generation of quotations.

Parametric approaches

In the early 1990s, Kadidal and Bidanda (1993) and Bidanda et al. (1998) developed an expert system for the calculation of cost of injection mould parts, using objects and rules for the knowledge representation. The system analyzes manufacturing viability and determines the processes' basic parameters, which are necessary to the calculation of manufacturing time through regression analysis. To estimate cost, the expert system not only needs the process data, but also selects the material to be used and calculates its weight. Maropoulos et al. (2003) propose a decision support system for the design phase that determines the manufacturing process and cost calculation. The Maropoulos et al. (2003) system is based on the features of the piece to be manufactured. That model described attempts to use the least amount of information

Table 2 Knowledge based systems for estimation

Reference	Web-based	Application area	Description	Method
Kennedy and Shao (1989)	No	Small factories	Expert system for advising on improvement of the RFQ process	–
Kadidal and Bidanda (1993)	No	Castability cost estimation	Expert system for estimating the manufacturing cost of injection-mould parts	Parametric
Cunningham and Smart (1993)	No	Parts for car production	Expert system for generating manufacturing plans and estimating the corresponding manufacturing costs	Analytical
Qiqin et al. (1996)	No	Production lines in factories	Expert system for production planning and cost estimation. The expert system is based on the features of the part, represented in a CAD file, and systems analysis techniques	Analytical
Kingsman et al. (1996); Kingsman and de Souza (1997)	–	Make to order enterprises	The authors identify the characteristics of versatile manufacturing companies and propose an expert system for price estimation based on heuristics	Analogical
Mohamed and Celik (1998)	No	Buildings	Expert system for estimating construction costs in the early design phase	Intuitive
Bidanda et al. (1998)	No	Castability	Rule-based expert system for analysing the casting process. The system estimates manufacturing costs based on a regression analysis	Parametric
Wei and Egbelu (2000)	No	Machining	Expert system for defining manufacturing processes and estimating manufacturing costs of machined parts based on the AND/OR tree representation	Analytical
Arezoo et al. (2000)	No	Machining	Expert system based on predicate logic for selecting cutting tools and parameters and determining optimal manufacturing costs and time	Analytical
Er and Dias (2000)	No	Cast components	Rule-based expert system for process selection of cast components based on cost comparatives	Intuitive
Jahna-Shahi et al. (2001)	–	Flat plate processing	Cost estimation model based on Fuzzy logic for the representation of non-process variables. These variables can affect manufacturing time and costs	Intuitive
Shehab and Abdalla (2002a); Shehab and Abdalla (2002b)	No	Machining and injection mould	Knowledge-based system for generating manufacturing processes and estimating their costs	Analytical, based on Ou-Yang and Lin (1997)
Sharma and Gao (2002)	Yes	Generic	Expert system for estimating manufacturing time and costs based on incomplete designs	Analytical

Table 2 continued

Reference	Web-based	Application area	Description	Method
Seo et al. (2002)	No	Generic	The authors present a comparison between a regression model and an artificial neural network-based model for cost estimations	Analogical
Wang et al. (2003)	No	Injection mould	Cost estimation system based on case-based reasoning	Intuitive
Vidal et al. (2003)	Yes	Furniture budgeting	Workflow management system for furniture budgeting	–
Tang et al. (2003)	No	Metal stamping parts	Knowledge-based system for cost estimation in the part design phase. The system incorporates production rules for linking the features of the product with their cost	Analytical
Maropoulos et al. (2003)	–	Machining	Design support system for the optimization of manufacturing costs and time, based on a low number of features	Parametric
Chan (2003); Chan and Lewis (2000)	No	Machining	Expert system for determining machining costs and operation parameters of the machining process, based on the features of the part	Analytical
Park and Seo (2004)	No	Generic	Cost estimation system for product maintenance based on artificial neural networks	Analogical
Hvam et al. (2004)	No	Cement plants	Analysis of the impact of knowledge-based systems on the re-engineering of the RFQ process	–
Chan (2005)	No	Electroplating industry	Hybrid cost estimation system for the electroplating industry. The system is based on case-based reasoning, rules and fuzzy logic	Intuitive
Xie (2006)	Yes	Generic	Web-based decision support system that integrates tools and databases	Analogical/analytical
Shehab and Abdalla (2006)	No	Assembled parts	Expert system that decides the best assembly technique for the part and calculates the manufacturing costs	Analytical
Hvam et al. (2006)	Yes	Cement plants	Knowledge-based system for estimating manufacturing price in the RFQ process. That knowledge-based system is based on a product configurator	Analytical
Chougule and Ravi (2006)	Yes	Castability	System for determining the manufacturing process for a given part, based on case-based reasoning. The system estimates the cost of the part, using a parametric model	Analogical/parametric
Bouaziz et al. (2006)	No	Dies manufacturing	Cost estimation system based on the manufacturing process and the features of the part. The manufacturing process is determined by analogy with previous parts	Analogical/analytical
Ko et al. (2007)	No	Injection mould	Knowledge-based system for evaluating the manufacturing costs of injection-moulded parts	Parametric

possible and allows for estimation in the initial design phases. Based on the product's features, this system generates various manufacturing processes that are closest to optimum, calculating for each its cost, quality and time of delivery, in order to select the most appropriate option. The cost calculation is based on activities necessary to manufacturing the part. Combining the idea of Web-based systems with systems embedded on small devices, Ko et al. (2007) propose a knowledge-based system for the evaluation of injection mould parts manufacturing cost. The system is embedded on a small USB device, outfitted with an operating system based on Linux with a Web server. Using a Web browser, the user can access the system, allowing for interaction with other conventional CAD systems. Its knowledge is represented in frames stored in XML format.

Analytical approaches

Analytical methods have been widely used in the development of knowledge based systems for estimation. The problem of the lack of detailed information in early manufacturing phases is solved by means of the knowledge represented in the system. To evaluate and calculate the manufacturing costs of parts for the Ford company in Europe, an expert system was developed that was capable of estimating cost based on the parts' features (Cunningham and Smart 1993). The system was composed of two modules: a kernel with information on how to calculate production planning cost and a module of process models with knowledge of the possible operations, cost of said operations and plan formulation. For the parts representation, processes selection and cost estimation, the expert system combines heuristic methods, fuzzy logic, object orientation, generation and testing of alternatives, simulations and depth limited first search.

Qiqin et al. (1996) integrated an expert system with CAD tools, from which they extracted the information regarding the part to be manufactured for the decision-making process, applying system analysis techniques. Based on the features of the machined part, this expert system determines the operations and machines necessary for its manufacture, planning the production line and calculating of the manufacturing budget. The system uses an evaluation module to assist the expert in making decisions.

Wei and Egbelu (2000) present a complete modular framework for estimating manufacturing costs based on the AND/OR tree representation. Each module is focused on some aspect of the cost estimation process. The framework determines the manufacturing process based on the part features and optimizes that process based on expert heuristics. The manufacturing cost is estimated by integrating the results of all the modules of the system. Arezoo et al. (2000) developed a knowledge-based system for the selection of cutting tools and the conditions of machining operations, providing the manufacturing cost based on the selected operations. Arezoo's system decides the optimal process based on the detailed features of each part and the characteristics of each tool.

Shehab and Abdalla (2002b) developed an expert system for generating manufacturing processes and calculating their cost that is capable moderating conflicts between design and manufacturing that can arise during product development. Along with the cost estimation, rules contained in its knowledge base are used to recommend appropriate machining processes, the parameters to be applied and the operations sequence. The system calculates all of the costs associated with the material, based on the model proposed by Ou-Yang and Lin (1997).

Sharma and Gao (2002) employ an expert system as a product conceptual design support tool, based on incomplete or abstract models. Features are represented by means of a hierarchy tree, and CLIPS rules are used to evaluate manufacturing time and cost for those models that still are not completely defined.

Using production rules, another Web integrated expert system for the design and manufacture of parts from metallic sheets was developed that provides a cost estimate based on the production process it determines (Xie et al. 2001, a, 2003).

Tang et al. (2003) present an expert system that covers all of the design process, incorporating production rules to link the features of the product being designed with its cost and proposing an appropriate manufacturing process along with its cost. This type of system is used primarily in alternatives, change impact and cost tracking studies.

Chan (2003) describes in detail an expert system for determining the manufacturing viability of a product and the estimation of its cost that is not limited to a specific manufacturing domain. The system, developed with CLISP and C, registers the geometry of the part to be manufactured and the design specifications, and it calculates the cost using the model described by Chan and Lewis (2000). To validate the system, Chan compared the estimation results for a group of parts with the results of industries from which information on the same parts was solicited, obtaining similar results. The author indicated that deviations in the system estimations and the results obtained from the companies could be due to the special tools at each factory, as these can affect cost and the distribution of general expenses.

Shehab and Abdalla (2006) system uses hybrid representation of knowledge, combing production rules, frames and objects, for cost estimation during the product design phase. Based on the product features, it decides the most cost effective assembly technique, calculating associated cost. The system is capable of proposing design modifications to lower cost.

Analogical approaches

Analogical methods are a good choice for the development of knowledge-based systems. The principal problems in the treatment of client orders in versatile manufacturing companies are (Kingsman et al. 1996): time and cost estimation and workload and job completion within the set timeframe. Said study (Kingsman et al. 1996) proposes a decision support expert system to generate quotations, in which a module analyzes previous quotations in order to determine the probability of acceptance of the quotation being generated, while another module generates possible delivery dates taking into account the factory's workload. From the results of previous modules, a third module generates a group of alternative quotations. The user can analyze each one and use decision rules that can help in the decision-making process. These rules are described in detail in the article by Kingsman and de Souza (1997). The estimation module saves the time and cost estimations for each product for future analysis along with a degree of confidence in estimation, similarity to previous jobs and the experience obtained with the product. The rules module presents the estimator a set of questions and, based on the responses, gives a series of recommendations (for example, reduce the profit margin to lower the price and have a greater probability of success). The inference system uses forward chaining reasoning, along with a weights system for—in the event of having several rules activated—activating those with the greatest weight.

Seo et al. (2002) used neural networks for estimating complete life cycle costs based on 19 product attributes. Neural networks have also been used by Park and Seo (2004) for estimating maintenance costs.

Intuitive approaches

Expert systems are classified as intuitive estimation methods by Niazi et al. (2006). Er and Dias (2000) propose a rule-based expert system prototype for the selection of casting processes. The selection of the process parameters and the part features are represented by means of rules. The system determines the suitable manufacturing processes and recommends the one that is economically most suitable.

There are product features that influence manufacturing time and cost and that make construction of a mathematical model of estimation difficult. This is due to multiple interrelationships that exist between different parameters used in estimation. This is why Jahna-Shahi et al. (2001) have investigated the application of fuzzy logic techniques to the estimation of cost variables that are not directly related to the manufacturing process but that affect time and cost.

Outside of the parts manufacturing sphere, cost estimation expert systems have also been applied to construction, based on designs and specifications with little detail and expert rules, as is shown in the examples of (Mohamed and Celik 1998, 2002).

Wang et al. (2003) apply case-based reasoning for the manufacturing cost estimation of parts for plastic injection molds. A neural network is used to calculate the similarity function between cases. When the system finds similar cases, it adapts the cost of the previous case by applying a function, and when there are no similar cases, it calculates cost employing the known specific methods. When the system estimates the cost of a part for which it can find no previous references the user can correct the obtained result, in the event that he/she is not in agreement, before incorporating it in the case library.

By combing case-based reasoning, rules and fuzzy logic, Chan (2005) developed a system for price estimation for the electroplating industry. In this area, the difficulty of estimating material weight leads to tremendous errors in price quotations, as there is no time to conduct tests. For estimation, Chan employed case-based reasoning. When there were no previous cases the rules and fuzzy logic modules were used to select similar cases. The system obtained results with an average error of 14.72%, smaller than the 20.05 % of that of a person in their case studies.

Other approaches

In this subsection, we present works that combine several estimation methods and other works not included in previous subsections.

Vidal et al. (2003) developed a knowledge based system that automatizes the furniture budgeting task. The system represents the workflow of the budgeting process helping to optimize the cost estimation process.

Chougule and Ravi (2006) created an expert system that estimates the cost of injection mould parts in the initial design phases. The system obtains information regarding the part's geometry from tridimensional design tools. To estimate cost, it combines a parametric model with an analogical model, applying case-based reasoning to determine the part's manufacturing process. Based on the part's geometry and the determined manufacturing process, the system calculates manufacturing cost. The model has been implemented in a platform called webICE (web-based Intelligent Collaborative Engineering), developed in the authors' laboratory.

Xie (2006) proposes a DSS that integrates several tools and databases for the design and fast development of products with the Web and that also includes a module for the estimation of assembly time and costs based on the part features.

Bouaziz et al. (2006) presented a system for cost estimation of machining dies based on a semi-analytical approach, combining the analogical approach and analytical approach.

Web integration with intelligent systems, along with the reengineering of the quotation process (Hvam et al. 2004), has produced very good results in certain areas, such as cement plant construction (Hvam et al. 2006). Another approach to the improvement of the quotation process through expert systems is that of Kennedy and Shao (1989), whose expert system advises on improvements a company can make to its order receipt process, based on knowledge about prestigious companies and consultants.

Finally, as is the case with conventional systems, expert systems capable of estimating costs and prices based on product configurators have also been created, as mentioned by Helo (2006).

Results

The generation of a parts manufacturing quotation requires knowledge of the necessary manufacturing process and its cost. For this reason it is necessary that one or several factory employees possess sufficient knowledge to produce said quotations.

A reliable quotation that is generated in a short period of time is fundamental in companies that manufacture on demand. A delay in quotation may cause a client to choose a better offer from a competitor. On the other hand, a fast but poorly estimated response can lead to economic losses for the company if an estimated price is less than the cost of production or the loss of a client if the estimated price is too steep.

There are different approaches to the automated calculation of manufacturing quotations. This article reviews the theoretic framework of cost estimation and the relevant research used in the creation of intelligent systems that attempt to improve the results of conventional systems and methods. For this purpose, the article compiles the most relevant research into the definition of estimation models and creation of intelligent systems for the calculation of quotations in companies that manufacture machined parts.

Hvam et al. (2006), among other authors, suggests that, despite the importance of quotation success, expert engineers in charge of this task have several other important tasks to attend to in the factory. In some cases, this means that a quotation can take weeks to generate.

One problem can be solved by following a set of steps, using a specific methodology (González and Dankel 1993). This approach may have an unacceptable associated cost in time and money when it is applied by a person who is not a domain expert. In the case of price estimation, the relationships between different part features and cost are numerous. The combination of said features elevates the number of possibilities exponentially, making representation through a mathematical model difficult (Jahna-Shahi et al. 2001).

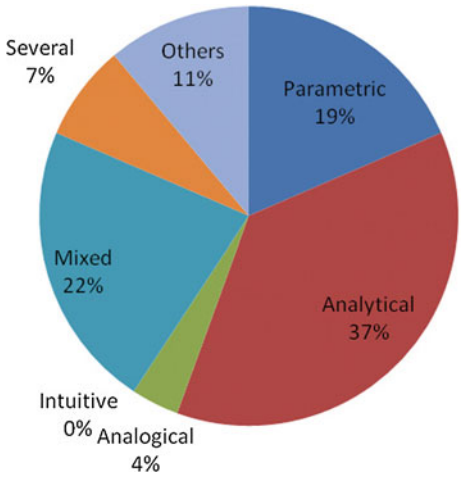

Fig. 1 Methods used in conventional estimation systems

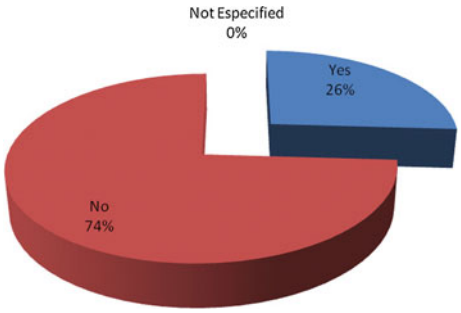

Fig. 2 Web-based conventional estimation systems

Figure 1 shows the methods used by the conventional systems that have been reviewed in this article. The majority of the systems rely on an analytical method, based on a profound knowledge of the product to be manufactured and on advanced design phases, in which knowledge of the parameters affects the estimation. The number of systems that combine various estimation methods is also noteworthy, as they all combine the analytical approach with another complementary method. As is to be expected, the intuitive and experience-based methods are reserved for the knowledge-based systems; therefore, they have no impact on conventional systems. However, the scant impact of parametric methods is surprising, as the initial phases of development require less detailed information than is required for the analytical methods. Estimation systems in the early phases of the manufacturing process are also scarce, especially in the quotation: this is evident in the difference between the use of parametric and analytical methods.

Figure 2 shows the proportion of Web-based conventional systems to the total number of systems reviewed in this article. The majority of the systems implemented are not Web focused, as development of Web-based systems only began in the last few years.

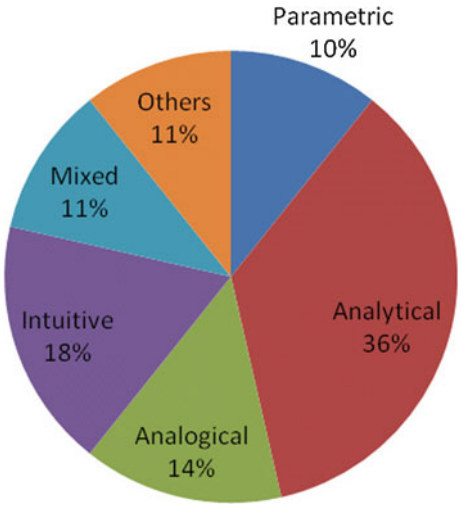

Fig. 3 Methods used in knowledge-based estimation systems

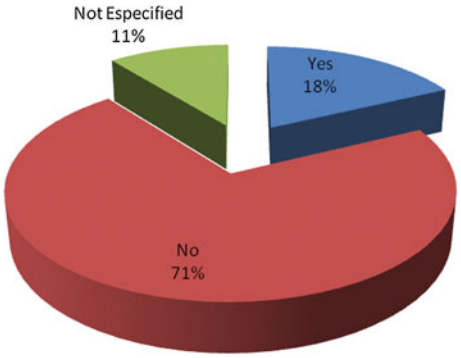

Fig. 4 Web knowledge-based estimation systems

Given that it is common not to have sufficient information to apply detailed mathematical models when the quotation must be generated, a different approach to the problem of estimation is necessary. A manufacturing expert has, throughout his previous work, acquired certain knowledge, which may not be very precise, but is useful in recognizing the principal features of the problem and formulating an optimum solution.

A knowledge-based system involves the representation of the expert's knowledge and its application to price estimation for the generation of a quotation. As shown in this article, there are different open lines of research that tackle manufacturing price estimation, for both conventional applications and knowledge-based systems. Figure 3 shows the estimation methods implemented by knowledge-based systems. As with conventional-technique based systems, the analytical approach is the most common. However, in this case, the shortage of data in the initial product development phases is made up for with the knowledge used by the system. Analog and intuitive approaches are most important in knowledge-based systems, while the parametric approach is still used in fewer systems than expected. The use of rule-based systems, case-based reasoning and approaches using Artificial Neuronal Networks is noteworthy.

Figure 4 shows the number of knowledge-based systems analyzed in this article that are Web oriented. As with conventional systems, the number of Web oriented systems is quite low as compared to the total number of systems. It is also noteworthy that they are based on the use of conventional representation techniques.

On the one hand, conventional applications are based on the implementation of the mentioned models, while on the other hand, intelligent systems attempt to complete these methods with decisions based on knowledge of process optimization and estimation parameters. A large part of the estimation systems studied are integrated in applications that encompass a larger area, such as Computer Aided Process Planning (CAPP).

Conclusions

In light of this study, it can be concluded that experience-based models constitute an open area of research. Research into new models and proposals is necessary because, as Xie et al. (2003) affirmed, there does not appear to be a widely enough accepted or applied system in the domain.

The Niazi et al. (2006) study insists that the expert systems applied to cost estimation are usually more focused on technical knowledge extracted principally from textbooks rather than encapsulating the expert's practical knowledge, in which case research on this subject has great potential. The determination of subjective factors that influence the generation of a quotation is a process in which knowledge acquired by a person through experience plays a fundamental role. Furthermore, the representation of an expert's knowledge not only allows for the creation of expert systems, but also means the explicit permanence of knowledge in the organization molded into a model. This knowledge can be used in the training of new experts, making the companies less dependent on people.

A clear conclusion of this study is that the combination of various estimation methods is the ideal approach to obtaining satisfactory results (Duverlie and Castelain 1999; Layer et al. 2002; Lan and Ding 2007), because the combination of a knowledge-based system with a quantitative method that represents the calculation regularly carried out by a factory expert can generate optimum results. Figure 3 shows how knowledge based systems have been combined with other estimation methods obtaining good results.

Figures 2 and 4 shows how this research is not reflected in a large number of Web-based systems that facilitate access from any location at any time. Duan et al. (2005) note that

techniques that represent traditional knowledge may not be as effective in current Web environments, making new models and methodologies necessary. Grove (2000) mentions the need for new techniques in the application of knowledge-based systems on the internet in general and the Web in particular. Adams (2001) also mentions that not all expert systems are adequate for these environments. Since then several knowledge-based systems have been developed, but as Duan et al. (2005) indicates, the technologies are similar to those mentioned by Grove (2000) and new models and methodologies are still necessary. In the present study not a single reference is made to an integral approach to knowledge and communication.

When it comes to experience, it will not only be necessary to consider heuristic knowledge employed by the expert in his daily work. Knowledge of other systems employed daily in factories is fundamental to price estimation and general processes representation, as indicated in the Hvam et al. (2006) study. Knowledge can be saved to a spreadsheet, in a database or in a factory material's management application. Also, recent advances in technology do not necessarily involve people in the different interaction processes. Interaction scenarios exclusively with other software are possible. For this reason, the information needs of factories require the integration of heterogeneous applications that support industrial processes and the use of communication technologies to facilitate remote access to the information and development of electronic commercial systems.

This analysis shows that it is necessary to work on the representation of the expert knowledge, attempting to make this representation compatible with the new Web systems. These knowledge-based models will sustain expert systems integrated with new communication technologies. Applied to cost estimation, they will facilitate:

1. The permanence of knowledge within the company.
2. The optimization of estimates, covering the information deficit in preliminary development phases with experience.
3. The improvement of communication, allowing access to knowledge through the Web from any location.
4. The integration of existing systems and company knowledge.

If the lines analyzed in this article show an approach to the calculation of cost and price in the generation of quotations and the early design phases, not a single knowledge-based system applied to the domain that incorporates a specific representation model that combines the expert's practical knowledge with the advantages of Web integration has been found. Based on the problems identified there is a need for a knowledge representation model with the following objectives:

- Represent the expert's knowledge.
- Represent the knowledge of other applications.
- Represent detailed estimation models that compliment the expert knowledge.
- Integrate the representation with new Web technologies.

This representation model serves as a base for knowledge-based systems that facilitate integration with other knowledge-based factory systems and facilitates access to information, incorporating it with the knowledge represented.

Given the importance of estimation, knowledge management and taking advantage of new technologies, it is necessary to make an effort to create estimation systems that preserve factory experts' knowledge and that take advantage of new communication systems.

This article has revised relevant systems, both conventional and knowledge-based, and the need for greater integration in Web-based environments and for the explicit representation of expert knowledge in these systems has been. Therefore, in the future, new representation techniques should include a response to these issues, providing models that facilitate experience representation to compliment estimation models with the knowledge that exists in the applications used in the factory and that it be made accessible via the Web. This will facilitate the creation of new knowledge-based systems that not only provide fast and reliable quotations, but also add value by preserving knowledge and improving the efficiency of the manufacturing processes.

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