Vol.66: e23220658, 2023
https://doi.org/10.1590/1678-4324-2023220658
ISSN 1678-4324 Online Edition

Article - Engineering, Technology and Techniques

A Lean Knowledge-Based Decision Support System for Cost Estimation in the Foundry Industry

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Editor-in-Chief: Alexandre Rasi Aoki
Associate Editor: Fabio Alessandro Guerra

Received: 01-Sep-2022; Accepted: 19-Jun-2023

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HIGHLIGHTS

- The development of a knowledge-based system has been presented.
- The proposed system assists the designer in decision making at planning stage.
- It supports the foundry process practitioners (using sand casting process) of manufacturing sector of Pakistan.
- The proposed system is validated through industrial case study under lean environment.

Abstract: Precise cost estimation is the first and crucial step for decision-makers at the planning stage of product development. Due to the unavailability of knowledge and the complex nature of manufacturing processes, materials, and product designs, the selection of suitable alternatives based on estimated cost has become more challenging. The purpose of this paper is to present the development of a knowledge-based system (KBS) for assisting decision-makers in identifying suitable alternatives for precise cost estimation in a mistake-proof environment. The system architecture is comprised of three layers namely the database layer, application layer, and end-user layer, and developed using knowledge-based engineering, set-based concurrent engineering, and poke-yoke as lean enabling approaches. Based on the captured knowledge through industrial investigation and experimentation, a real-time system application was developed using C# language and validated using a real case study in the foundry industry using sand casting as the manufacturing process. It ensured the validity of the developed system. KBS provides an extensive tool to decision-makers for accurate decision-making at the design stage using cost and other associated values. Further, it facilitates the practitioners of every business sector to capture, save, and use the identified knowledge for problem-solving in the future.

Keywords: Precise cost estimation; knowledge-based system; decision making; lean enabling approaches; sand casting.

INTRODUCTION

In today's dynamic and competitive environment, among many collective commitments, a crucial one is coping with the challenge of knowledge acquisition across the foundry industries which are producing 90% of the manufactured goods and equipment [1]. The foundry industry needs to make sure that the knowledge and skills of their experienced employees should pass to their successors and colleagues [2]. To save the knowledge and experience of their employees and remain competitive in the global world, companies need a knowledge-based system (KBS) [3]. The KBS applications are used to convert employees' tactic knowledge into explicit knowledge which can be further used for problem-solving in the coming years [4]. Knowledge-based systems help new and inexperienced employees in the decision-making process due to their user–friendly nature [5]. However, how to use the knowledge effectively in a knowledge-based system is still an issue.

Various studies have been carried out on the development of knowledge-based systems with the objective of use of knowledge in an effective way for various applications. Khan and coauthors [6] developed a knowledge-based expert system for the evaluation of digital supply chain readiness knowledge of manufacturing companies. The proposed KBS helped the managers and decision-makers to transform their supply chain from a traditional to a digital supply chain which has become essential for organizations to survive. Xiao and coauthors [7] proposed a knowledge-based system to improve the efficiency of knowledge acquisition, management, and maintenance of the expert system of rice-wheat combine harvester. Rega and coauthors [8] proposed a knowledge-based approach to the layout optimization of the human-robot collaborative workplace. The study helped the designers in the optimization of the layout of human-robot collaborative workplaces in standard compliance. Wang and coauthors [9] developed a knowledge-based decision support system for In Vitro Fertilization treatment. The proposed system performed well in the accuracy of advice perspective for protocols and medications. Grillo and coauthors [10] developed, tested, and validated a knowledge-based assessment system to evaluate the innovation capability of small and medium enterprises in a sample of companies. It was based on the combined use of cognitive mapping and the decision expert technique. By incorporating knowledge-based engineering, rules of AGMA (American Gears Manufacturer Association), and parametric modeling in CAD. Reddy and Rangadu [11] developed a knowledge-based parametric CAD modeling system approach for spur gear design to reduce the design time. Pathak and Agrawal [12] proposed an analytical model for an excellent design of the knowledge-based system to enhance the performance of the organization. Khan and coauthors [13] developed a knowledge-based system for the evaluation of overall supply chain performance.

Further, much research has been carried out on the development of knowledge-based decision support systems for cost estimation purposes. For example, Ko and coauthors [14] developed an embedded knowledge-based cost evaluation system for the cost estimation of mold parts. In addition to this, some of these knowledge-based systems were developed for both purposes as decision-making support systems for manufacturing process selection, material, and design selection, and as a cost estimation solution based on the selected alternative such as Shehab and Abdalla [15] developed an intelligent knowledge-based system for product cost modeling of machining parts as well as molded components. In this study, the input of the system included process data, material data, and geometric knowledge. Relevant knowledge was shown in an expert system database through frames and rules. Based on recommended process, material, and design, the manufacturing cost of the product was estimated. Chan and Lewis [16] developed a new CAD tool to make the designer of SMEs (small and medium enterprises) capable to incorporate cost and manufacturability knowledge into their decision-making process for process selection, material selection, design selection, and ultimately cost estimation. It shows that companies and academic researchers are working on the use of knowledge in an efficient decision-making process for engineering-related problems. However, accurate (without any waste), and timely capture of dynamic knowledge and reuse is still a problem.

Lean thinking is a philosophy that aims to provide a new way to think about how to organize human activities to deliver more benefits to society and value to individuals while eliminating waste. From the last two eras, lean thinking approaches have gained worldwide attention [17]. The concept of lean product and process development is considered the third and new era of the lean journey. LPPD deals with product design development features including the manufacturing process, material, and design dimensions [18]. After seeing the successful implementation of this concept in European companies, other manufacturing companies have also started to practice this concept in their daily routine work. For this purpose, various lean tools, procedures, and principles have been developed which made the companies capable to take the boundless potential of their manufacturing operations [19, 20]. According to Khan and Al-Ashaab [21], LPPD has several enablers however, Knowledge-based Engineering (KBE), Set-based Concurrent Engineering (SBCE), and Poke-yoke have been found most important ones and are selected for this research work.

KBE is the use of advanced dedicated tools to capture, use, and convert available knowledge into a form that is ready for use [22]. The process of generating knowledge includes interfaces between different sources of information and knowledge such as humans and computers. There exist sequences of tasks that take the form of associations, interpretations, and reflections. Saved or remembered in different ways (databases), this knowledge becomes the source of motivation to create something new [23].

Set-based concurrent engineering (SBCE) is an approach to developing new ideas by comparing different sets of designs instead of considering one [24]. The SBCE process helps the designers in identifying excellent solutions from the large range of alternative solutions through the elimination of weaker solutions [23, 25]. The concept of SBCE can be taken as a tool for improving project management to decrease product development time and cost to ensure the quality expected by the customer [26].

Poke-Yoke (PY) has grown from the concept of lean manufacturing. The major was the prevention of passing defective parts into the customer’s hand [27]. PY can be defined as a practice to eliminate errors during product design to get more precise and accurate results. It avoids the passing of faulty knowledge at the conceptual design stage where less information is available for decision-making [28]. According to Mital and coauthors [29], one of the following principles must be adopted to avoid mistakes during product development; (i) redesign the product and process to eliminate all the possible errors, (ii) for consistency, replace the existing process with more reliable one, and (iii) before moving to next step, first detect the errors and remove it. If it is not possible to completely remove the errors, try to lessen them to reduce their effect. In the developed KBES, the objective of poke-yoke is to avoid mistakes during product design and development by following the principles given above.

The above review of the relevant literature shows that many knowledge-based systems have been developed for different types of applications. The key limitations of the developed knowledge-based systems include:

- Most of them were developed for machining processes [15] and mold parts [14] lack the capability of their implementation for other business sectors such as the foundry industry.
- Knowledge-based systems help new and inexperienced employees in the decision-making process due to their user–friendly nature, however, how to use the knowledge effectively in a knowledge-based system is still an issue.
- Although researchers are working on the use of knowledge in an efficient decision-making process of engineering-related problems, however accurate (without any waste), and timely capture of dynamic knowledge and reuse is still a problem.

To overcome these limitations, a knowledge-based decision support system is presented in this study to support decision-making for cost estimation in the foundry industry under a lean environment. The specific objectives of this study are to:

- Propose a knowledge-based system to support decision-making for cost estimation in the foundry industry.
- Developed a KBS application using Visual Studio 2013 software linked with SQL server database.
- Validate the developed knowledge-based system through an industrial case study to ensure the validity and effectiveness of the developed system.

To achieve the objectives mentioned above and proposed KBS for cost evaluation of foundry parts, the remainder of the paper is organized as follows. Section 2 will provide the proposed methodology adopted for the accomplishment of this research work followed by section 3, presenting the development of a knowledge-based system under a lean environment. Section 4 discusses the system scenario. Section 5 describes the validation of the proposed KBS in a collaborative company followed by the conclusion of the paper in section 6.

RESEARCH METHODOLOGY

This section presents the methodology adopted to conduct this research. The overall research work was divided into four phases as shown in Figure 1. In phase 1, a detailed literature examination was done covering areas related to knowledge-based systems (KBS) for different applications including cost estimation, KBS for different manufacturing processes, and lean thinking and enablers. During this phase, characteristics of the knowledge-based systems and lean thinking enablers were recognized which were further used for the development of knowledge-based systems to support decision-making for cost estimation under a lean environment. Phase 2 deals with the development of the proposed knowledge-based system architecture. It leads to the development of application forms of the system following the steps of set-based concurrent engineering while keeping the knowledge–life cycle stages as reference. The system application was developed using Visual Studio 2013 linked with a SQL server as a database. Finally, the developed system has been validated through an industrial case study in phase 4.

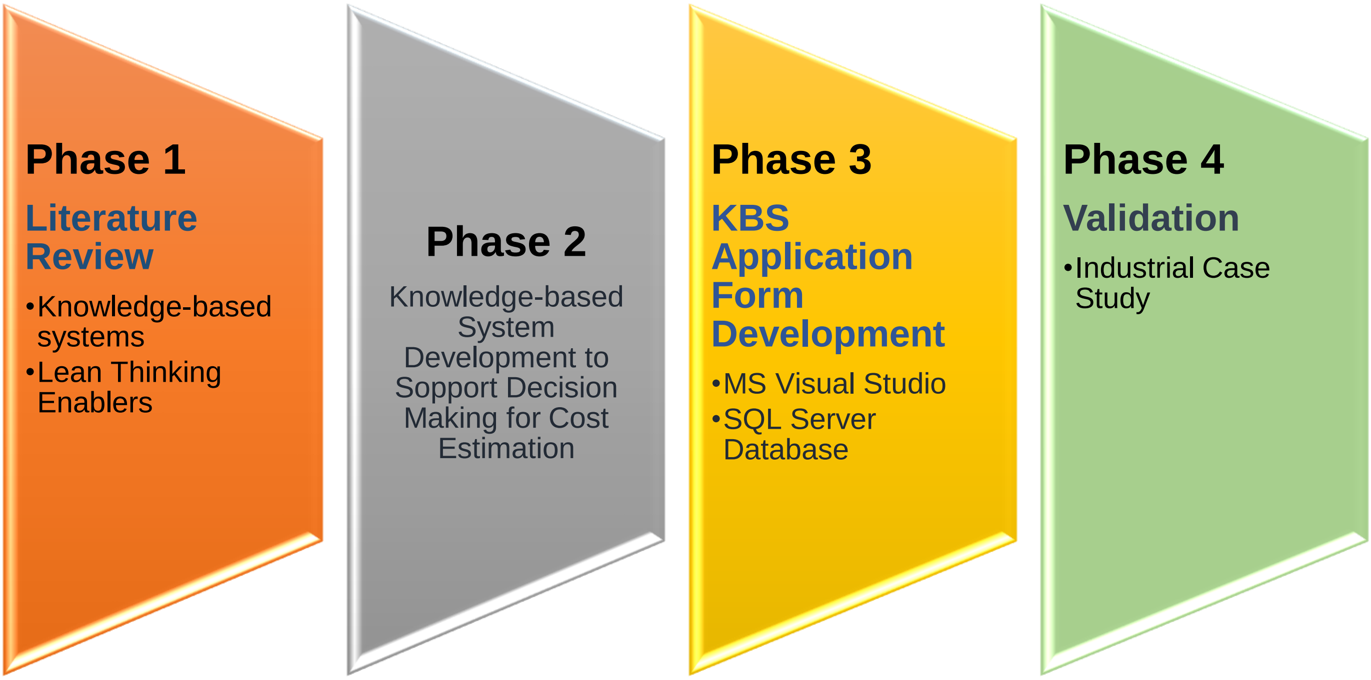

Figure 1. Research methodology

SYSTEM DEVELOPMENT

The proposed knowledge-based decision support system provides assistance to the designers in effective decision-making regarding the selection of various alternatives for cost estimation during product development. The architecture of the developed system is comprised of a user interface and three layers namely (i) database layer, (ii) application layer, and (iii) end-user layer as shown in Figure 2. Further, the detail of these layers is given in the following sections below.

Database Layer

The database layer has been used to save information on all stages of product development. It has been developed using the concept of knowledge-based engineering. For the ease of end-users, the database layer saves real-time data in different sub-databases. These sub-databases include the user database, material database, geometric features database, value database, process database, previous projects cost database, and castability assessment database. Each database can only be accessed by inserting a unique ID given to all users. To make the user capable of getting full access and extracting the previous knowledge, the developed system stores all the data in the database layer.

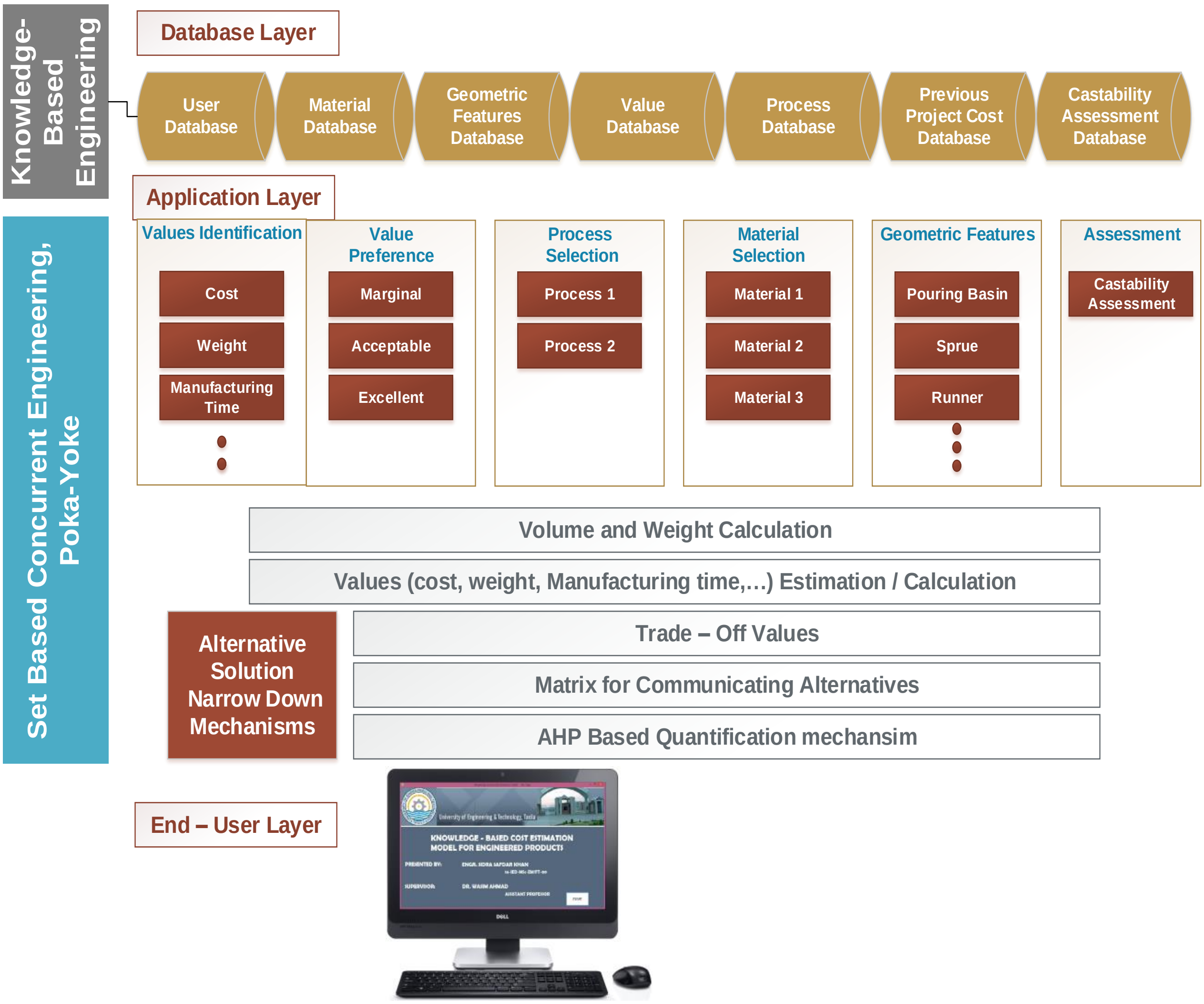

Figure 2. System structure

Application layer

For data input to the system, an application layer has been developed in the proposed knowledge-based system. This application layer has been developed under the guidelines of set-based concurrent engineering.

To get product cost and other associated values, the application layer provides a cost estimation method. This method consists of a sequence of steps namely; (i) values identification, (ii) values preferences and target setting, (iii) process selection, (iv) material selection, (v) geometric features selection and, (vi) casting castability assessment. Value identification is considered the first step of the application of lean thinking. In this study, value identification has been performed to identify the customer values, company values, and all other stakeholder values that are associated with the concerned problem. It leads to setting the preferences and targets against each value in the next step of the cost estimation method. Steps three to five have been used to select the best solution from the available set of alternative solutions. For this purpose, a set-based concurrent engineering lean enabler has been incorporated into the proposed knowledge-based system. These optimum solutions are selected based on quantification number as the alternative with minimum quantification number is considered as a weaker solution and eliminated. The remaining solution is considered as the best solution. After the selection of the best material, method, and design features, the system then actuates the designer or user to check the castability of the selected solutions to answer the question that whether all the selected solutions are castable or not in the available foundry facility. For this, the study used the poke-yoke lean enabler. It avoids the passing of wrong information to the whole procedure of cost estimation. Using the PY enabler, if-then rules have been proposed and integrated into the developed KBS. An example of these rules is given below:

IF
The selected material is aluminum Alloy A380 And
The selected Process is Sand Casting And
Available furnaces in foundry shop can melt metal up to 700 ℃ And
Any other rule
Then
The part with given geometric features (35×20×10 cm) is castable in the foundry facility

In this step, the system actuates the user to put necessary information while following this method. The system assesses these specifications using data saved in the castability assessment database leading to the comparison of estimated costs and other values against the set targets. These values have been evaluated using the tools such as a matrix for communicating alternatives, and quantification numbers. These tools support the user in taking the right decisions in the selection of various alternatives during product development. In this study, the application layer is directly linked with the database layer to save the information/data gained.

End-user layer

Human-computer interactions are becoming more complex to tackle for more features whilst at the same time having to present a simpler, durable, and user-friendly interface. In this study, an end-user layer has been developed which is used to come across the proposed knowledge-based system to support designers or even new users for decision-making at the design stage of product development. The developed KBS interface comprised many features including accept input, save input, next step, and back step buttons to update or make changes in the previous screens. The end-user layer of the proposed system has been used to form the front end of the application. It is directly connected to the application layer and database layer.

SYSTEM WORKING SCENARIO

The working flow chart of the developed knowledge-based system has been illustrated in this section. The interaction between different elements of the database layer and application layer has been presented as described in system architecture (section 3). The system working flow has been proposed by following the method of cost estimation under the guidelines of SBCE as depicted in Figure 3.

The first step starts with user information. It takes the user's data as input and creates an account in the user database leading to the generation of a user ID automatically. The system then saves the user information into the user database and adds this information to the account list so that next time users can access their account directly without the need to enter user information again. The generation of user ID leads to the identification of product values and the setting of preferences and targets against each value of the product in step 2. The system can verify all the selected values, preferences, and target information. If a user provides the wrong information, the system would generate a message labeled with the problem occurrence. After entering the values preferences, the system then saves the data in the value database.

The next step is the selection of the casting process. In this step, the user has the option to select the casting process from the process selection database. The system can provide two casting processes namely sand casting and investment casting process. Along with the user ID and user name, the system keeps the selected process in-process database. Casting material selection has been performed in the fourth step. The developed system provides the user an opportunity to select the casting material from the material database or of his own choice. Using the developed system, the designer can select a maximum of three materials. After the selection of the most suitable materials, the system then generates the physical and mechanical properties of these materials and stores the information in a material database.

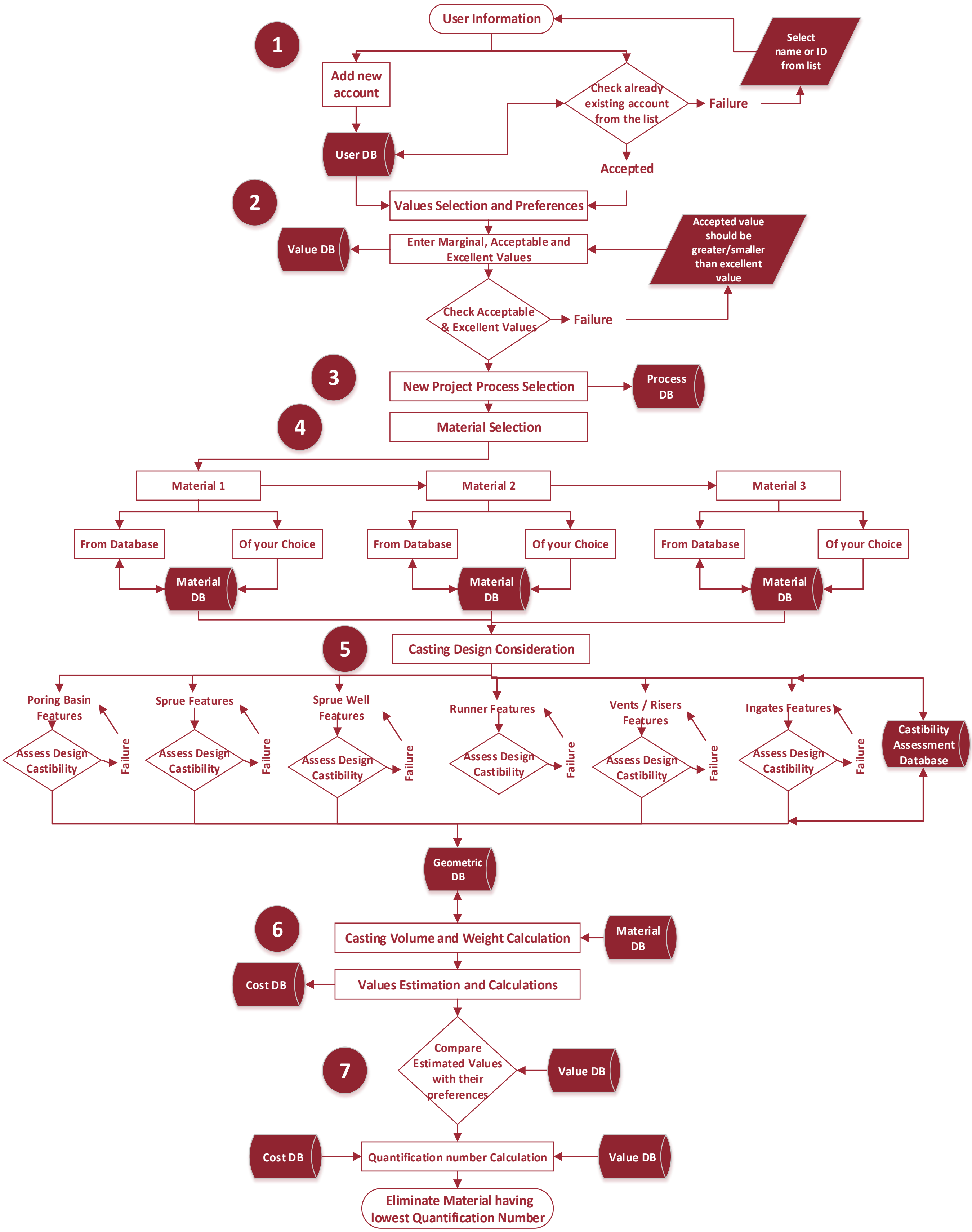

Figure 3. Working flow of the proposed system

In step 5, casting design consideration has been performed. In this step, the designer provides the various features of the product including geometric features (length, width, and height of the product) and design features of the gating system (sprue design, pouring basin design, runner, and ingates design). After the selection of suitable casting features, the system then actuates the user to perform the castability assessment (either the product with the specified casting features is castable within the available foundry shop). For this purpose, Poka-yoke rules (if-then form) have been developed, stored, and used by the system in this study. These rules were developed using the information extracted through real-time experimentation and on-the-site-visit observations during the industrial field study. During the assessment of the castability of the product design features, information is extracted and stored in the castability assessment database.

The castability assessment has been performed to avoid mistakes during casting design considerations development. Assessment of casting design consideration leads to the calculation of casting volume and weight in step 6. In addition to casting volume and weight, the system also estimates the cost and other values against each selected material. The system stores the cost data in the cost database. After the estimation of product cost and other values, the user then compares the estimated values with the target values in step 7. For this purpose, a matrix for communication alternative (MCA) has been generated by the system which provides the comparison of all values with each other. In addition to MCA, the system also provides the quantification number which has been used to select the best alternative. An alternative with a maximum quantification number is selected as the best material. It helps the designer in accurate decision-making and lessens the chances of mistakes accruing.

SYSTEM VALIDATION

The developed system has been validated through an industrial case study with one of the industrial collaborators involved in this research work. The research with the collaborative company exposed that currently, the company was practicing a formal cost estimation method in which they significantly relied on expert experience. They were using the concept of cost accounting in which cost is calculated after the product is manufactured.

It company's desired to have a knowledge-based system having the capability to store the knowledge/information of experience persons involved in solving a specific problem. With the diverse nature of product development activities and customers across the industry, the availability of accurate knowledge for mistake-proof decision-making is even more important. Any mistake at the design stage would lead to high production costs in later stages. It may also result in a huge penalty (underestimate/overestimate) and loss of opportunities (time to reach the market). Considering future growth, this research study will provide a competitive edge in the marketplace.

This research work aims at identifying the knowledge-based system's features for the foundry process, exploring the lean enablers (for values identification, mistakes elimination, accurate decision making, and knowledge capturing and storage), developing a KBS application, and validating it through an industrial case study. A forked end of a knuckle joint is taken as a case study. Its CAD model was developed using solid works software and is shown in Figure 4. Based on the management need for a knowledge-based system and because of the strategic focus for the industry, this study will take into account the following aspects:

- Knowledge-based system for sand casting process
- Best alternative selection in a mistake-proof environment
- Incorporation of customer's voice during decision-making
- Cost estimation of cast parts

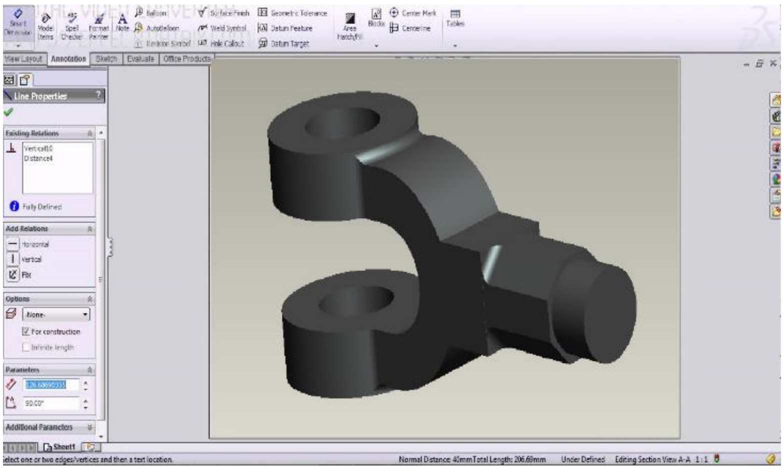

Figure 4. Structure of fork end of knuckle joint

The validation process starts with the identification of customer and company values as described in the system scenario (section 4). From the values database, the user has identified five values namely; (i) product cost, (ii) production volume, (iii) ultimate tensile strength (iv) product manufacturing time, and (iv) product maximum service temperature. Identification of values leads to the setting of values preferences and targets. The values preferences and set targets against each value are presented in Figure 5.

After identifying the required values, the system inputs the other compulsory information which comprises casting process selection, casting material selection, and casting design considerations as depicted in Figure 6. For casting the cast part, the sand casting process was selected by the user. Aluminum alloy A380 and cast iron have been selected as the casting materials for the developed case study.

Both materials have been nominated from the material selection database. After selecting suitable materials, the system then generates the physical and mechanical properties of each material such as material hardness, material density, material ultimate tensile strength, material thermal conductivity, and material maximum and minimum service temperatures. Casting material selection leads to the identification of casting design considerations. It includes the design of casting gating systems such as the design of pouring basin, sprue, ingates, sprue well, and runners. Necessary information has been provided by the user including the length, width, and height of the pouring basin, runner and ingates, diameter and height of sprue, sprue well and risers, and number of ingates and risers. The system then stores the given data in the respective databases.

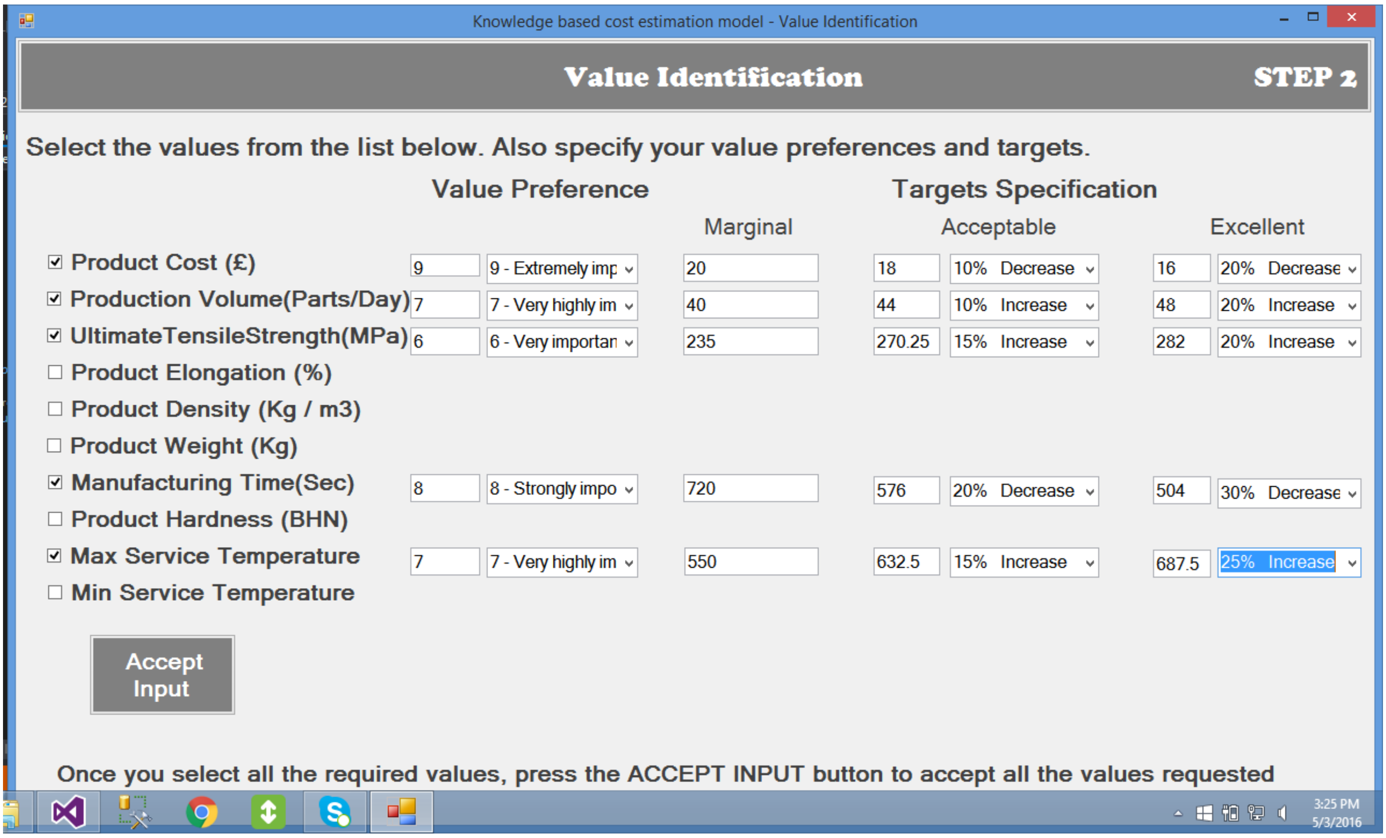

Figure 5. System snapshot of value identification

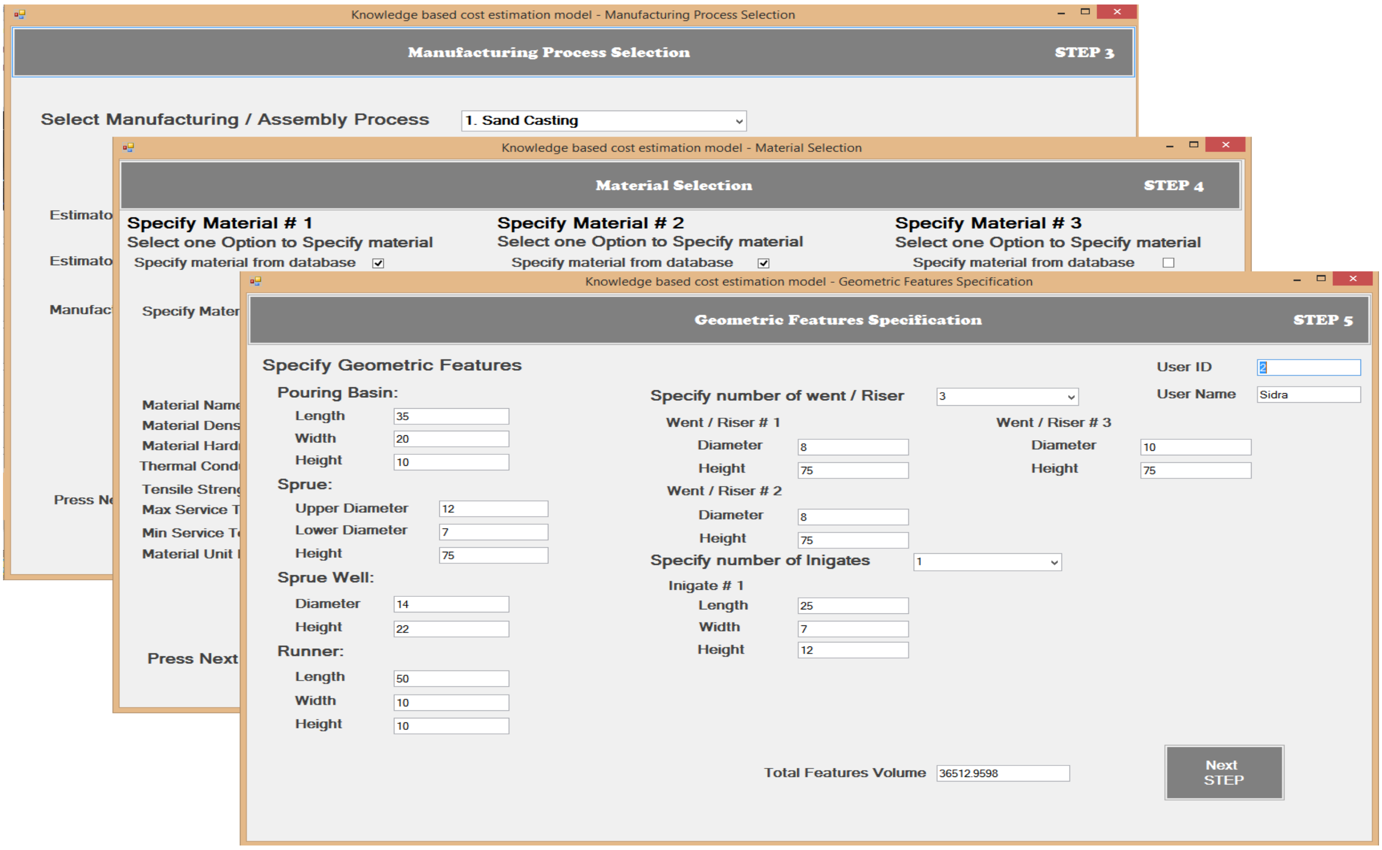

Figure 6. System snapshot of process, material, and geometric features specification

After the selection of the casting process, materials, and design features, the system then generates the total casting volume including the volume of casting gating system features and end cast part. Estimation of casting volume leads to the calculation of casting weight and cost. After calculating the material cost, compulsory data regarding other cost drivers were put into the developed system. The data included time to complete the job, number of workers and activities to complete the job, labor charges, administrative charges, overhead charges, and direct other expenses (cost of pattern making, core boxes, cost of using machines, and energy cost). After inserting the required data, the system then estimates the total labor cost, total overhead expenses, and direct other expenses followed by the estimation of total product cost against each material. The developed system estimates the total cost by adding all costs including material, labor, overheads, and direct other expenses as shown in Figure 7. The system estimates all these costs by using the expressions developed by Sajid and coauthors [30].

In today's dynamic environment, where customer requirements are constantly changing, making decisions using only the cost attribute may lead to customer dissatisfaction. Therefore, evaluation of cost along with other values has become compulsory. For this purpose, the developed knowledge-based cost estimation system generates a matrix for communication alternatives as a solution narrow-down mechanism (Figure 8).

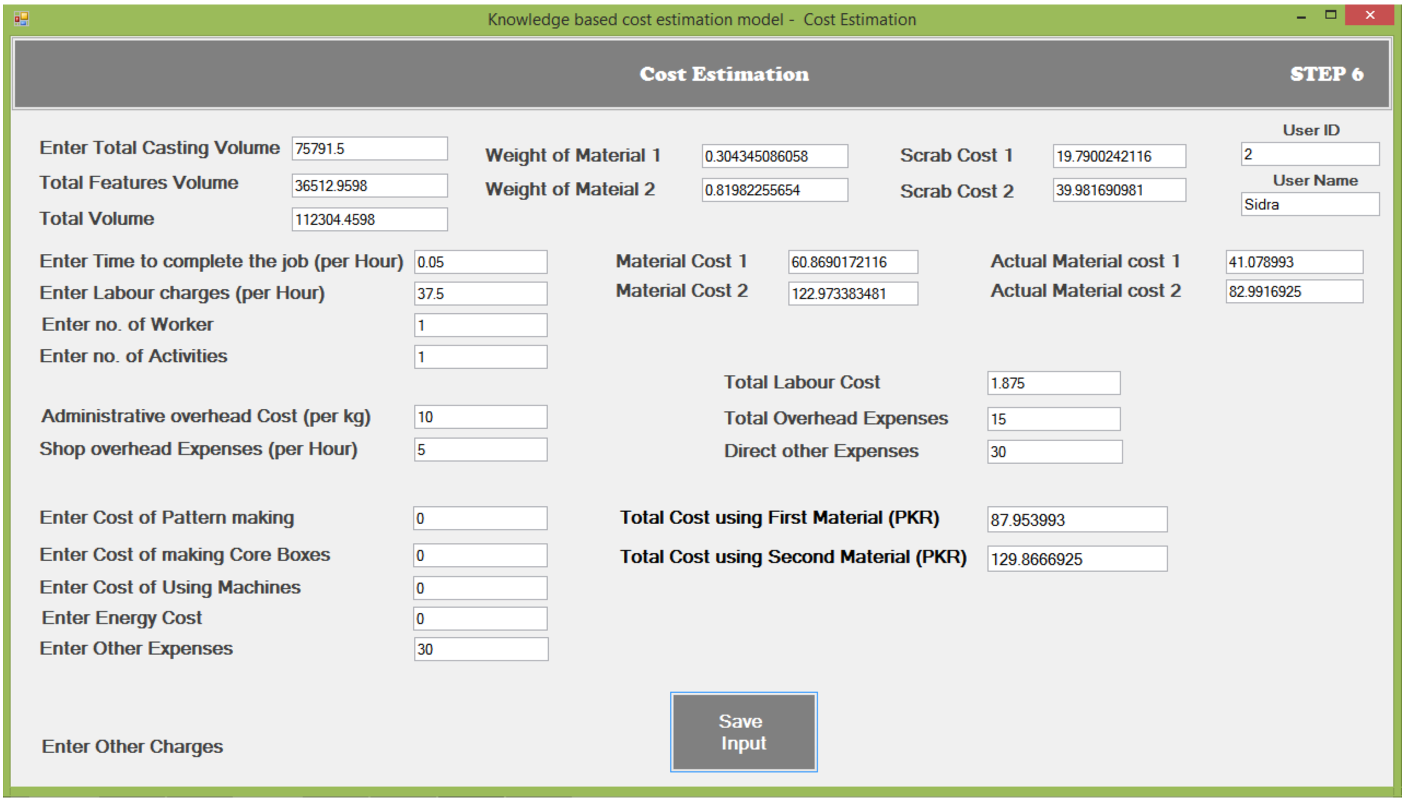

Figure 7. System snapshot of values estimation

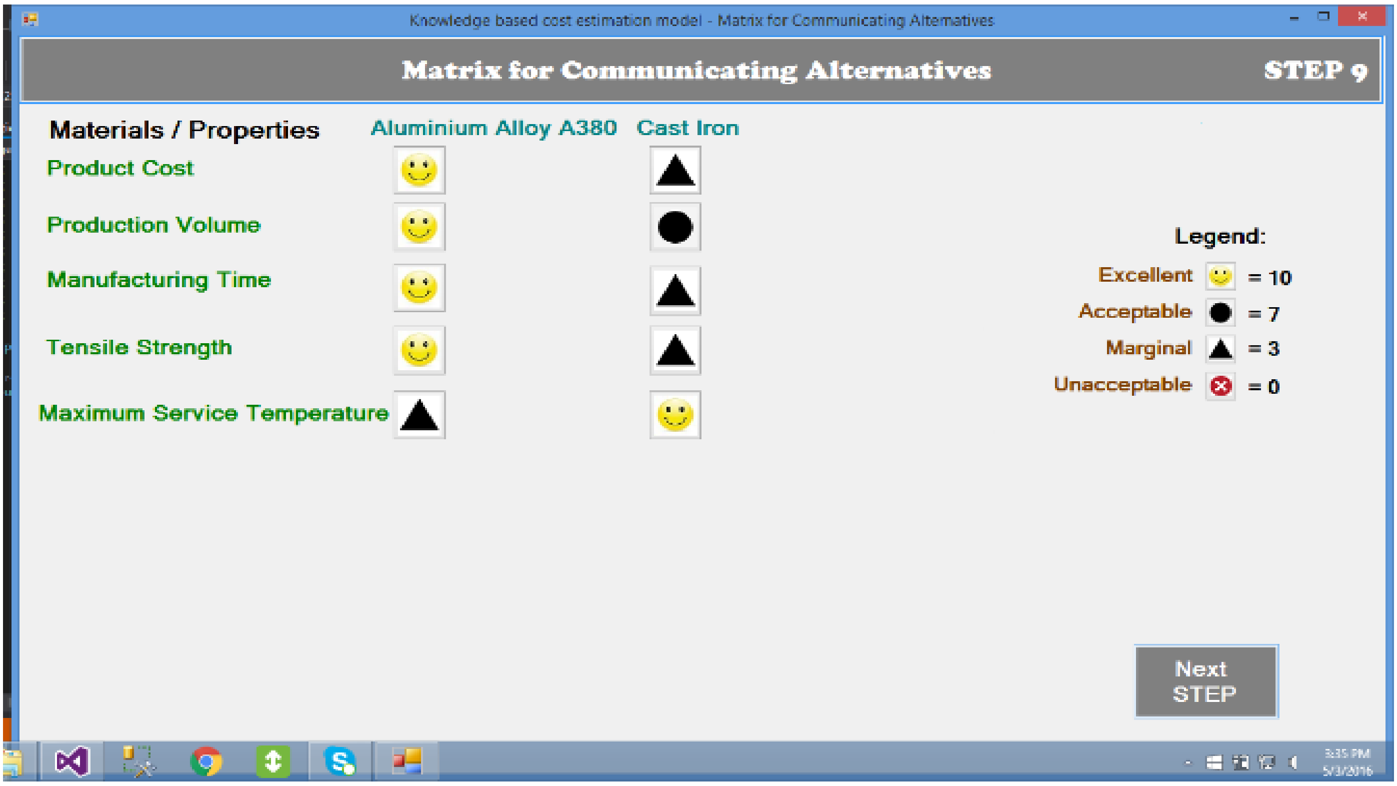

Figure 8. System snapshot of the matrix of communicating alternatives

It compares the cost and other associated values with the target values and is an effective tool for reliable decision-making. After that, the system calculates the quantification number against each alternative. Quantification numbers can be calculated by using the expression developed by Wasim and coauthors [18]. Material with the lowest quantification number is considered a weak alternative and is eliminated.

The summary of results in Figure 9 depicts that the quantification number for aluminum alloy A380 is 340 and for cast iron, it is 280. It can be seen from the results that cast iron has the lowest quantification number. Therefore, it is considered a weak solution and eliminated. Thus, aluminum alloy A380 is taken as the best material alternative for the selected case study.

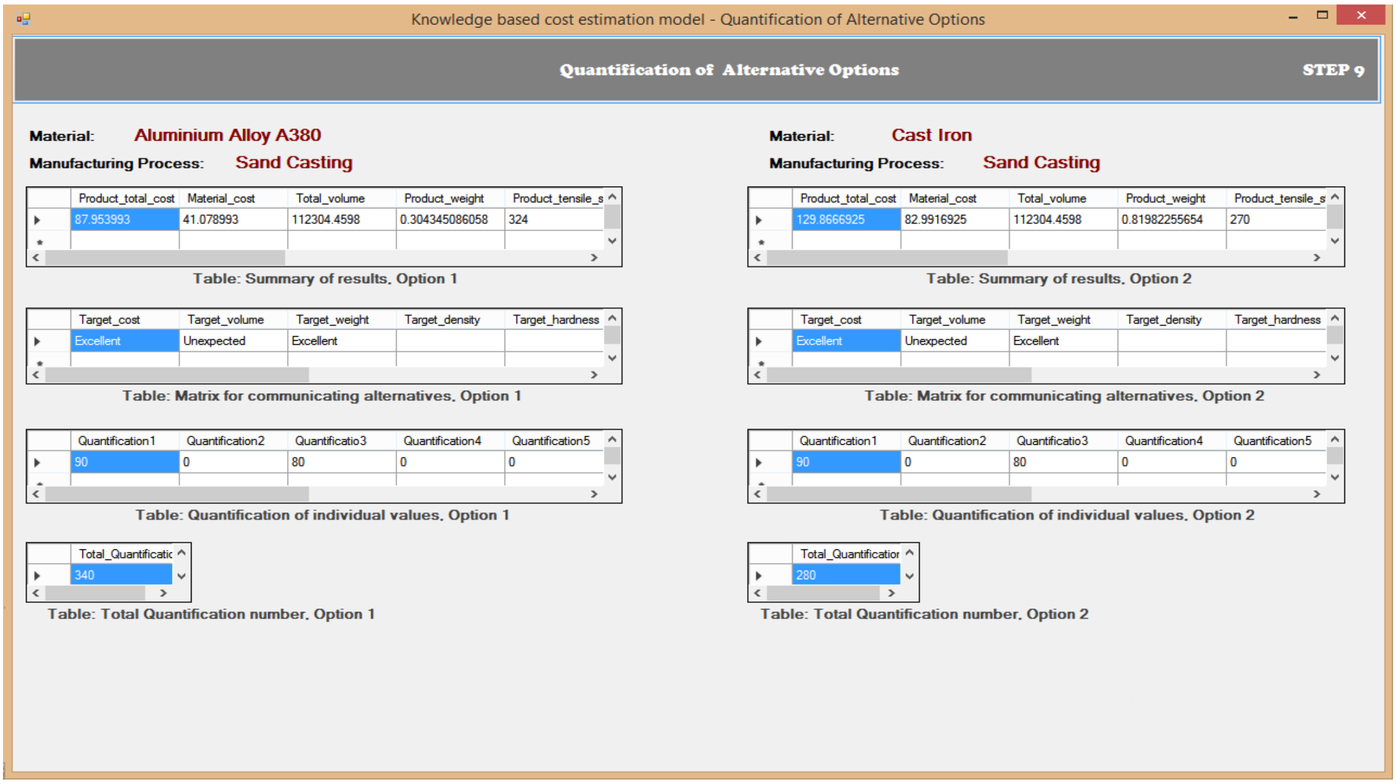

Figure 9. System snapshot of quantification number

THEORETICAL AND MANAGERIAL CONTRIBUTIONS

This research work points to two major contributions to theory. First, it proposes a structure of a knowledge-based system to estimate the cost in foundry organizations, which contains a normative theory for decision-making at the design stage of product development. This theory denotes to the development of the working flow of the system on how accurate decision-making will help to get the required results. The proposed method refers to the steps to be functional and directed during the implementation of the knowledge-based system in the foundry industry. As a result, the proposed framework provides a holistic view of KBS development and implementation, which is a unique feature in comparison with other research in the field.

Second, the incorporation of lean thinking enablers (such as knowledge-based engineering, set-based concurrent engineering, and poka-yoke) in the foundry industry may depict an important input in the field. According to Tortorella and coauthors [31], the studied research framework usually presents some unwillingness in implementing formal controlling and management practices. Further, it can be justified through two major reasons including; (i) in the foundry industry, workforce training and development does not focus on managerial skills development. These casting experts usually come with technical backgrounds that emphasize mainly aspects related to foundry tasks performance with less focus on process analysis from a horizontal perspective, and (ii) despite pushing the managers for better performance of public industries, still there exist huge difference in the mindset of managers of public and private organizations. In private business sectors, managers are required to enhance and optimize resources to sustain their business financially. While, in public sector organizations, these operations are supported by governmental institutions. Therefore, their managers don't necessarily focus on attaining economic profit and improving performance.

Research Limitations

This research work supports only the metal casting domain under the lean environment. The researcher recommends that more manufacturing processes such as sheet metal forming, piping, forging and rolling, and flat plat processing need to be explored and integrated into the existing capabilities of the developed knowledge-based systems. It will deliver a full package for those companies having vertical integration capabilities of numerous manufacturing processes in their production facilities.

CONCLUSION

In this study, a knowledge-based decision support system has been developed for cost estimation under a lean environment. The system development includes the identification of knowledge-based system features for the foundry process. The system application was developed using C# language in Microsoft Visual Studio 2013 and Microsoft SQL Server 2008 as a knowledge database. The architecture of the developed system comprised three layers namely database layer, application layer, and end-user layer. It provided a user-friendly interface that assisted the designers in easily feeding the input knowledge and evaluating the outcomes effectively. The foundation of the developed system was enabled through three lean enablers including knowledge-based engineering, set-based concurrent engineering, and poka-yoke. These lean enablers assisted the designers in making sound decisions in a mistake-proof knowledge-rich environment. The developed has the ability to:

- Select an alternative material, process, and casting design-related features at the primary design stage of product development.
- Estimate the product cost and other associated values in a knowledge-based environment.
- Save and provide information on previous projects to the designers having little or no experience.

The author believes that in addition to the current capability of the developed systems, tools will be developed in the future to make decision-making more reliable and respond timely to the mistakes accruing.

Funding: This research received no external funding.
Acknowledgments: The authors acknowledge the administrative andJ technical support provided Foundry Shop of the Department of Industrial Engineering, University of Engineering and Technology, Taxila, Punjab, Pakistan.
Conflicts of Interest: The authors declare that there is no conflict of interest.

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