

# Knowledge Based Engineering: Notion, Approaches and Future Trends

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**Abstract** Knowledge Based Engineering (KBE) is a research area for product design that involves complex and iterative processes based on methodologies and technologies for capture and reuse of product knowledge. Although KBE has been proposed to support product development for the last decade, it is still far to complete. As this is an attractive research area for the past decade many approaches are developed based on parametric, function based, web-based, case-based, ontology technologies for enhancing the capabilities of KBE. This paper is an effort to collect and review existing literature on KBE evolution, approaches and methodologies. The evolution of the KBE definition is also briefly discussed along with the current limitation and future trends of KBE. The objective of the review paper is to identify the foundation and research issues of KBE in the light of parametric, function based, web-oriented modeling.

**Keywords** Knowledge Based System (KBS), Knowledge Based Engineering (KBE), Parametric Modeling, Function Based Modeling, Case-Based Reasoning (CBR), Web-based Design, Web-Oriented Modeling, Ontological Knowledge Base

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## 1. Introduction

In recent systems CAD (Computer Aided Design) is inevitable in design practices. It is desirable to have an application that supports the entire lifecycle of initial design, detail design and manufacturing. The conventional system of mass production is not suitable for present turbulent markets as the customer needs are changing rapidly. For achieving this, manufacturing sector has been undergoing a shift from mass production to mass customization. For meeting, these market needs in less time a knowledge base is required for designing the required components. If the component is similar, the parametric modeling technique is useful because it can be used where geometrical model changes frequently during the design process.

While designing a product, the designer must draw upon different types of information related to the field of customer requirements. The design process must be carefully developed to generate the most suitable design recommendation. The customers around the world are expecting a unique product that combines quality, low price and delivery at right time. For minimizing the cost of the product, it may be sensible to focus on the design phase. The design teams are working a lot on conventional computer aided solid modeling design tools in order to minimize the

time, cost and risk of design mistakes.

### 1.1. Knowledge Based Engineering

With the help of evolution of the Knowledge Based Systems (KBS), the designing time is further reduced. Moreover, KBS has become the practical method for visualizing and analyzing the design process with the help of simulation tools. Knowledge Based Engineering is one of the technology based applications of KBS pertaining to the domains of design, manufacturing and production. KBE is indeed used for mass customization as it is one of the best technologies available for rapid design [1-3]. According to Du Yao et al. [135], the objective of KBE is to guide the designer who lacks experience towards the upmost design by declining the repeated design work. The application of Knowledge Engineering Techniques and Artificial Intelligence (AI) in the CAD became as KBE [4, 5]. It has been observed that KBE produces the efficient output according to the recent research. With the advancement of KBE, the application of computer information technology in the design process is no longer a bottleneck to the designers [6]. Various forms of engineering knowledge are illustrated in Fig. 1.

Even with the advancements of KBE, the designers are not able to fill the gap between the customer's desire and product's performance as the designer develop the link between the user requirements and design features based on their own opinion. However, the designers started the trend of involving the customers into the design process at the initial stage as it became one of the important issues for

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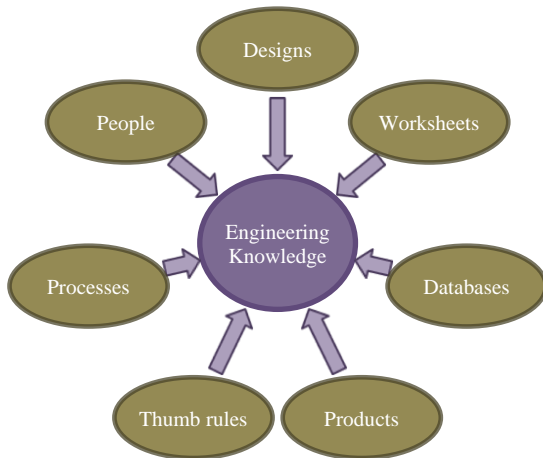
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making a quick analysis about the product quality. But, this is only possible with help of enhanced collaborative design process. The customer requirements are drawn into the collaborative design process to make sure the developed product can reach the expectation of the customer. But many researchers feel that the cognition between customer and designer is still considerably different [7] because the customers are not able to depict the expected requirements in a recognized and responsible media. This makes the designers to feel difficult to access the exact opinion of the customer. In order to fill the gap between the customer requirements and product's performance, the customer may be brought into the design process with the help of web technology for visualizing the product well before it is developed. The web-based design tools enable the customer to create and design the 3D (Three Dimensional) models over the web. Incorporation of customer into the design phase allows visualizing and feedback of upcoming product in design phase itself. Web-based technology can even make it possible to the customer to change the dimensions of the product with the help of parametric tools. Parametric tools can help in simplifying the complexity of the modeling by automating the commonly performed tasks using a predefined algorithm. The anticipated change of the customer requirements can easily and quickly put into the design with the help of KBS.



**Figure 1.** Various forms of engineering Knowledge

According to Cooper et al. [4] and Danjou et al. [5] the roots of KBE were started in 1980s. Since then it has held promise right from the first application. Apart from its applications in automotive and aerospace sector, KBE has not achieved an influential breakthrough [8] as it is still in development with constant evolving methods and technologies [9]. Though, research in KBE is accessible on different applications, very few reflect on exactly what is known about KBE. In this state of situation, this paper is an attempt to collect and review existing literature on KBE with the main objective of identifying the KBE research issues under web-oriented customer centric design field.

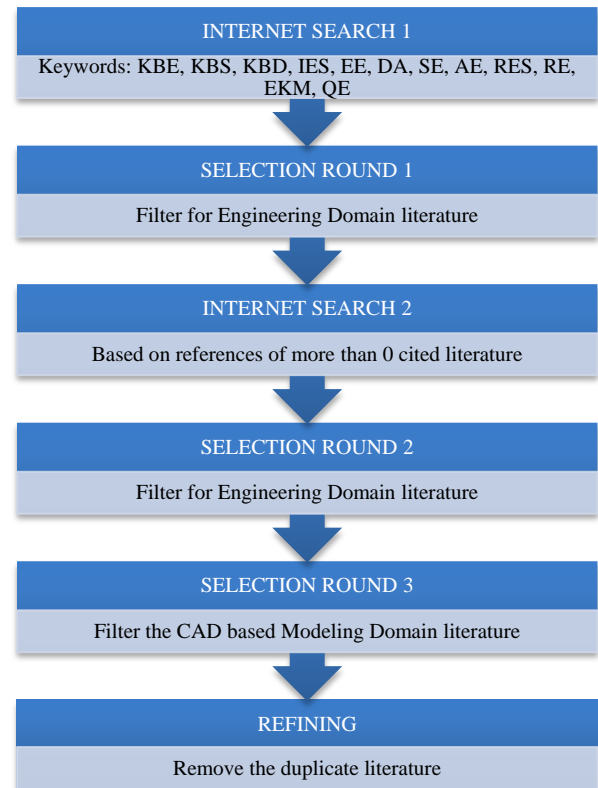
To attain this objective, a significant review of about 147

suitable research papers has been performed and is discussed in section 2. Firstly, the theoretical groundwork (definition, discussion and evolution) regarding KBE is discussed and later identification of current limitation can be evaluated.

## 2. Review Procedure

The available research on KBE briefs the theoretical groundwork even though it originates from different perspectives. However, a consolidated view of KBE is still lacking as it is the most critical to understand. The main objective of this paper is to brief KBE by selecting, classifying and reviewing the literature available at present. Later, how it can be extended to web-oriented parametric modeling will be evaluated.

First the selection of the literature has been done through internet search using the keywords like Knowledge Based Engineering, Knowledge Based Design, Knowledge Based System, Intelligent Engineering System, Expert Engineering, Design Automation, Smart Engineering, Automatic Engineering, Rapid Engineering System, Reuse Engineering, Engineering Knowledge Management and Quick Engineering. The literature with engineering background was filtered for further evaluation.



**Figure 2.** Flowchart of selection and filtration of the literature

Internet search process was again carried out on the filtered literature with the help of their references. But the filtered papers that are cited at least one time are only considered for this stage of the search. The second level of selection of the literature was performed purely based on the

topic's relevance to the engineering domain. The filtering process was done as in the first level for obtaining the literature on CAD based modeling domain. A round of refining the literature for removing the duplicate work that is available through the conferences and journals was done for achieving the vital literature. The selection and filtration process was illustrated in the Fig. 2.

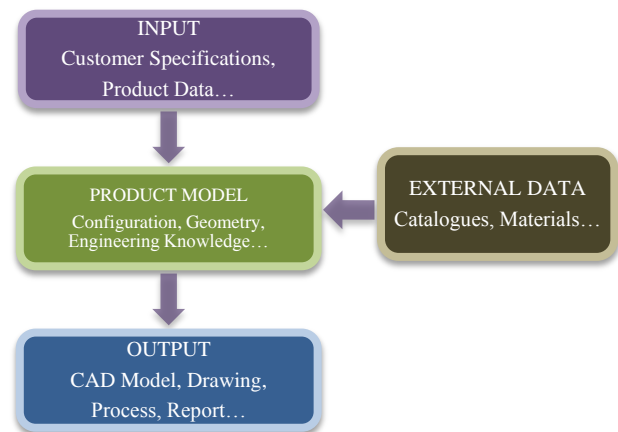
### 3. Notion of KBE

The application of KBS to the domains of manufacturing design and production can be expressed as Knowledge Based Engineering. KBE is a system that can accumulate the existing information in the growth of the product and makes it available to reuse. The early adopter of software engineering techniques in KBS is CAD. KBE has proven its effectiveness in building CAD models where both product and process information are accessible to the designer [20-22]. KBE integrates object oriented rule based technologies with CAD and other traditional engineering software tools. On the other hand, CAD developed a tendency to drive KBE to push past their current limits. The aspects of KBE change depending upon the perspective of engineering. Depending on this perspective, KBE absorbs wider skill set from modeling to programming and even artificial intelligence [18]. In the recent development of business to business type in electronic commerce KBE attracted the focus light of researchers for further development. The inventor of World Wide Web Sir Tim Berners Lee's vision is to develop the next generation of internet called Semantic Web, enabling the potentiality for KBE for collaborative design to meet the customer requirements [147].

The need of the KBE is because of volatile, insecure, user unfriendly, disorganized present day market. Apart from the need, KBE is speedy, skilled, innovative and error-proof, these features are vital to the today's market. On the other hand, KBE has the ability to improve the collaborative design through knowledge management and as a result automation, maintenance and re-use techniques are further advanced. With these gains, KBE extended the range to Product Lifecycle Management (PLM) and Multidisciplinary design optimization. The scope of KBE comprises design, Computer Aided Engineering (CAE), manufacturing and support fields.

For nearly 20 years, KBE has been used in challenging design and engineering problems, mainly in automotive, civil engineering, aerospace industries. In the beginning, KBE approach has a successful, long running and high productive application for Boeing Company in generating geometry of stringer clips [4]. However, no one realized the early promise of KBE in practice in those 20 years, since fully functioned KBE was missing even in the aerospace world where it has its high impact. Later, the companies such as ICAD, Wisdom systems encouraged the research and developed the special purpose AI hardware such as

Symbolics Lisp machines. But extremely high cost hardware became a barrier for widespread of the technology [4]. Further, these developed systems geared towards expert systems. Later, with the support of independent software vendors KBE came down to approachable cost [62]. With the advancements of fast and inexpensive computer memory KBE systems became as a commodity item. Angelo et al. [75] published the potentialities of knowledge-based engineering (KBE) methods in new product development by estimating the business value produced by a tool which combines the engineering groups of a large aerospace company. In the recent decade, World Wide Web with the association of HTML (HyperText Markup Language), XML (Extensible Markup Language), X3D (XML for 3D Models), KBE evolved as complementary to the traditional CAD systems [4]. A simple KBS is illustrated in Fig. 3.



**Figure 3.** Knowledge Based Engineering (KBE) System

When Concentra Corporation was releasing its first commercial closely integrated rule based CAD system in 1984, KBE was originated [10]. In the early stage of advancement, KBE was able to develop Simkit Tool (Model Building Simulation Toolkit) by Intellicorp [147]. Simkit was developed on one of the powerful KBS environments called Knowledge Engineering Environment (KEE). Even though KEE was capable to provide knowledge demonstration, it was not able to withstand with the time as it costs massive memory and processing requirements. However, with the spirit of the KEE, Genworks International GDL (General-purpose Declarative Language) developed modern sustainable knowledge based environment called open source Gendl project [147] and almost immediately expert systems have triggered KBE into business world from academic. Emerging data exchange standards such as HTML, XML, RDF (Resource Description Framework) and OWL (Web Ontology Language) may play vital role in the future of KBE by integrating enterprise resource planning systems such as SAP and Oracle (Example: iProd (Factory Management System)).

According to Calkins [11], Van der Laan et al. [69], Stokes [9] 80% of engineering activity comprises routine design on minor variations of preexisting design. KBE is the tool that can be used where routine design is required for

complex products or systems. The main objective of the KBE approach is to use the code based rules that can automate the repetitive CAD tasks to reduce the cost, time of design or manufacturing. KBE facilitates the designers to virtually access the ideas, characteristics and geometry of products. On intense use of KBE, the researchers found that the only challenge in KBE is to make the code simple and easy to maintain.

There is no specific definition of KBE available even after immense research in recent years [4, 12-16]. However, many researchers tried to give the better view about KBE in their papers: A system that performs the task related to engineering of large classes of similar parts with the knowledge can be called as Knowledge based Engineering [17, 12]. Nevertheless according to Chapman et al. [15] the powerful technologies like Computer Aided Design (CAD), Computer Aided Engineering (CAE) and Artificial Intelligence (AI) come together with Object Oriented Programming (OOP) to materialize as KBE. According to Bermell et al. [14] KBE is a type of KBS that can integrate

design and automation to focus on analysis, engineering and manufacturing of a product. KBE is a dedicated software tool that can acquire, store and reuse the product and process engineering knowledge more efficiently. KBE is a technique that develops computer system that requires human expertise to conduct engineering processes [4]. Cooper et al. [4] observes that KBE is the ultimate substitute to automate the non-creative and repetitive tasks in the design phase of a product by integrating the multidisciplinary concepts.

The definition of KBE as per the industry of engineering services: Infosys Labs [148] – KBE is a system that can capture the knowledge of a product to reuse its life cycle process with parameters and rules integrated with design knowledge in order to reduce the cost and time; Alcyon Engineering [149] – KBE is a system that can collect the possible information in life cycle of a product to make it reusable; Aker Solutions [150] – KBE is the strategic use of computerized engineering knowledge to improve business competitiveness.

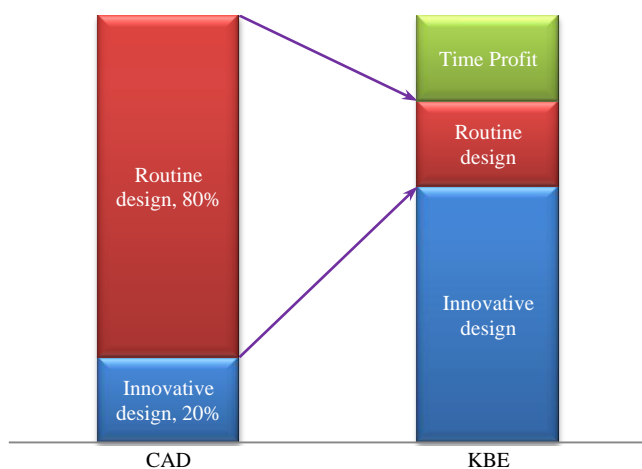
**Table 1.** Results of limited number of KBE projects

REFERENCE	FOCUS AREA	ACHIEVEMENT
Choi et al. [55]	Composite aerospace structure: cost and weight estimation	Rapid evaluation ; Supports trade-off capability
Kulon et al. [144]	Manufacturing process design: hot forging	New designs in hours rather than days or weeks. Supporting accessible knowledge base
Brewer [145]	Tooling design	73% lead time reduction
Van der Laan et al. [69]	Parametric modeling of movables for structural analysis	Up to 8% time savings in FE model generation.
Margot et al. [146]	Ontology-based approach in hybrid engineering knowledge representation for stamping die design	Total design time brought down by 6% and process of designing the trimming packets reduced by 85 - 90%.
Chapman & Pinfold [15]	Automotive body-in-white concept design	BIW mesh generation from 15 man weeks to 'minutes'
Cooper et al. [1]	Windscreen wiper system design	Weeks to minutes
Stokes [9]	Jaguar car inner bonnet design	8 weeks to 20 minutes
Jodin [143], Stokes [9]	British Aerospace Wingbox design	8000 hours to 10 hours
Bor-Tsuen Lin et al. [35]	Knowledge based parametric design system for drawing dies	10 days to 1 hour
Van der Elst & Van Tooren [82]	Aircraft wiring harness focused on electrical signals to connectors.	Recurring time for the pin assignment process for all production breaks per aircraft is reduced from hours to minutes; Gross recurring time reduced to 80%.
Emberey and Milton [56]	Engineering Design Application Development in Aerospace	With respect to traditional design process lead-time reduction of 75%.
Bor-Tsuen Lin & Shih-Hsin Hsu [77]	Automated design system for drawing dies for trunk lid outer panels and engine hood outer panels	Several working days to within one hour.
Mermoz et al. [61]	Parametric design methodology implemented on gearbox design phase.	The lead-time to reach a 3D model mature enough to discuss efficiently with other subsystems design teams has been reduced to only 2 or 3 weeks depending the size of the main gearbox.
Chih-Hsing Chu et al. [79]	Computer aided parametric design for 3D tire mold production applied to car wheels	Reduced the time for 3D model construction by 30%.
Bor-Tsuen Lin et al. [126]	Designing a drawing die for the roof panel of a vehicle	Several days to 1 hour.
Zhi-Xin Jia et al. [43]	Structural design CAD tool for punches and dies	Design time shortened to about 1/3.

Having reviewed the definition of KBE the statement of Bermell-Garcia et al. [14], Sainter et al. [12], Cooper et al. [4], Chapman et al. [15], Van der Laan [16], Baxter et al. [13] is certainly appropriate. However, most of the definitions are similar but some of them are technology oriented [8]. Moreover, the newer definitions of KBE are not specific and they focus on the knowledge associated to capture, re-use and automate the tasks. It has been observed from the review that the focus of KBE is shifting from reducing the repetitive design tasks to data management and collaboration systems. Today, it is important to expand the capabilities of KBE by pulling the new tools for adopting different approaches for implementation.

Around 20% of the designer's time is spent for searching and absorbing the information of the product, and almost 40% of design information is stored in personal stores [13]. This implies that the information for the designer is not freely accessible. Clearly, knowledge re-use of KBE can save considerable time, cost and efforts at design phase. The results of limited number of KBE projects are summarized in Table.1.

In addition, KBE can develop the fundamental knowledge about the product that in turn leads to easy preservation. KBE allows interdisciplinary exchange of information, documentation and knowledge to establish collaborative design as the development of KBE is associated with many activities in knowledge management phase [23, 12, 136]. Moreover, the process of implementing the KBE is beneficial for identifying and standardizing the design decisions. The major advantage of KBE is illustrated in Fig. 4. According to the definition of KBE, the routine design time in CAD approach is almost 80% in total design process where as in KBE approach, it is much less. Additionally, innovative design time is just 20% in CAD approach, while it is much higher in the case of KBE approach. Moreover, there will be time profit through KBE approach in compare with CAD approach [19].



**Figure 4.** Design time allocation by KBE and CAD [19]

*Observed benefits and drawbacks of KBE:*

**Benefits:**

✓ Reduced lead time:

- Suitable to develop the products with a high degree of similarity between versions.
- More knowledge can be re-used if higher the similarity.
- Design process can be performed automatically if all needed inputs are given in KBE system.
- Design configurations (geometry, material etc.) can be controlled by predefined rules.
- Cuts production cost.
- Cost and time can be reduced by 90% [62].

✓ Product optimization:

- Design is easy as trial and error goes faster.
  - Easy to search for the best design in the precise range.
- Knowledge capture:**
- Staff turnover is not a problem as most of the knowledge is already stored in knowledge base, which implies that firm can reduce the staff activities.
  - Knowledge base can become handy and can allow duplicating the knowledge in similar firms.

✓ Extra time for innovation:

- As the routine and mundane design work for product development is automated, the concentration on innovation is promising.
- Achieved extra time can enhance the firm business.

**Drawbacks:**

- ✗ Building and implementing KBE system takes a great deal of time, hardware, specialized skill and cost.
- ✗ KBE is becoming a black box as it produces some output with some input, but nobody knows what happens in between. This situation leads to the problem to transfer the knowledge to a new engineer in the department.
- ✗ Localized implementation of KBE could not register its impact on complete product development process.

KBE has been successfully deployed in different disciplines and niches such as aerospace, automotive, medical devices, dental implants, commercial building systems, electronic enclosures, toys: In ship building domain for example, Ying-Han Wu et al. [57], H.Z. Yang et al. [58], Ryszard Arendt et al. [59] has developed a method for ship design using KBE, Jin-ju Cui et al. [24] applied KBE for optimizing the structural design of ship. In aerospace engineering domain, C.L. Emberey et al. [56] applied KBE to support engineering design application development, Jin-Woo Choi et al. [52, 54, 55], extended KBE approach for weight and cost estimation, Corallo et al. [25] used KBE for low pressure turbine design, La Rocca et al. [26] applied KBE for automating the wing body design, Feng Haocheng et al. [63], used KBE for developing KEACDE



(knowledge-based and extensible aircraft conceptual design environment). In automotive engineering domain, Chapman et al. [15] developed rapid car design system using KBE approach. Ren é Berndt et al. [27], Georgia et al. [30], Y.M. Deng et al. [28], Nicolas Gardan et al. [31], Y.E. Nahm et al. [29] used the KBE approach to design intelligent CAD system. S. Kumar et al. [33, 34, 36, 37, 38, 40, 41] extensively applied KBE for selection, design, cost reduction of various dies. Bor Tsuen Lin et al. [32] extended the application of KBE by designing the stamping dies using Functional-Based Stack-Up Design System based on CATIA system. S. Kumar et al. [36, 44, 46, 47], S.M. Sapuan [42], Mümtaz İpek et al. [45] has related KBE for material selection. In the research by Dongkon Lee [60] KBE is used as a safety control system, Sameer Kumar [48] applied KBE approach for safety and recall of food based products before they expire. Web-based collaborative design system was developed by Mohanbir Sawhney et al. [51] Chun-Hsien Chen et al. [49], Peijun Wang et al. [53], Dimitris Mourtzis et al. [50] for designing the products using KBE. Robart et al. [83] developed an integrated methodology as a concept for integrating the knowledge base and human-computer interface.

**Table 2.** Commercial KBE Software packages [147]

PACKAGE	DEVELOPER
CADEC Works	Mark Design Solutions Pvt Ltd India
CADEC Edge KBE tool for Solid Edge	Mark Design Solutions Pvt Ltd India
Adaptive Modeling Language	Techno Soft Inc.
Drive Works	Drive Works
The Gendl Project	Genworks GDL
KBE Works	Vision KBE
Knowledge Fusion	Siemens PLM Software
Rulestream	Siemens PLM Software
Knowledge ware	Dassault Systemes
Pro/ENGINEER Expert Framework	Parametric Technology Corporation
Smart Assembly for Pro/ENGINEER	Sigmaxim Inc
Tacton Works Engineer	Tacton Systems
YVE - Your Variant Engineer	Tecneos software-engineering
Genus Designer	Genus Software Inc
Design++	Design Parametrics
Adaptive Modeling Language	TechnoSoft Inc
Enventive	Enventive Engineering, Inc
Pacelab Suite	PACE Aerospace Engineering and Information Technology
PCPACK	Tacit Connexions
Quaestor	Maritime Research Institute Netherlands

There are varieties of software tools available for developing domain specific KBE tools such as Smart Elements, TKSolver, ProEngineer, STONerule, ICAD and Design Link. All of these are integrated with modern CAD systems such as AutoCAD, ProEngineer, CATIA to provide smart system to design. The commercial KBE software packages are given in Table 2.

### 3.1. Recent Development of KBE Methodologies

It has been observed that the maturity of KBE application concerns the requirements to identify, capture, structure, formalize and implementing the knowledge. But KBE platforms are supporting only the implementation but not KBE development process. For managing, safeguarding and upgrading the knowledge for development and maintenance of KBE system, a robust methodology needs to be associated. MOKA (Methodology and tools Oriented to Knowledge based Applications) is one of the best example for such concrete methodologies proposes solutions which focuses on capturing, structuring, formalization and implementation [9]. MOKA is a European research project that has been developed to serve as an international standard for KBE system development [64, 66]. MOKA can be treated as a bridge between raw knowledge and KBE platform and it is the widely used methodology in automobile and aerospace industries. MOKA can be used to decompose and stock up the knowledge that can be linked to prearranged network of a problem domain to which users from various perspectives can relate. MOKA can present a framework for capturing and representing the knowledge. Developing lifecycle of KBE according to MOKA is given in Fig. 5.

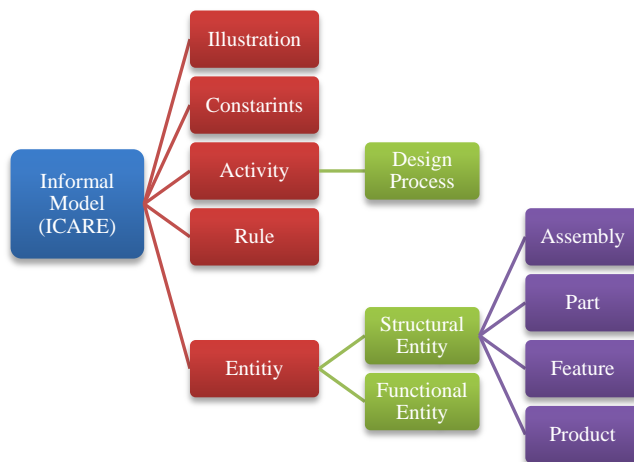


**Figure 5.** KBE developing lifecycle according to MOKA [9]

MOKA framework works at two levels: Informal level and Formal level. Informal level framework is simple and oriented towards representing and formalizing the knowledge in a language that can be understood by person who is not an expert in formalization language. In addition, informal level framework makes the acquired knowledge possible to validate. Further, this level creates a platform to share the views and opinions of the knowledge engineer, expert and software developer. Informal model proposes a realistic approach from human understandable knowledge to

formal representation in a formal model. The informal knowledge facilitates to link back the original unrefined knowledge to the text documentation. An informal model is the interrelated collection of ICARE forms: Illustration, Constraints, Activities, Rules, and Entities. Knowledge associated to the composition of designed product and its designing process is collected in the form of forms. Illustration form signifies the general knowledge, description and comments. Constraint forms are used to reproduction interdependencies between entities. Activity forms can express crisis resolving steps in design process. The modeling of organized knowledge can be allowable by Rules form. Entities forms are used for defining structure, function and behavior of the product. Fig.6. illustrates the informal model framework. The formal level framework creates the encoding form for represented and stored the knowledge into a computer [65]. Today, the formal language demonstration is an established area. In the field of engineering knowledge, the conversion of recognized demands in MOKA into ample formal knowledge representation is critical [74]. The transformation of informal model into a formal model can be done with UML (Universal Modeling Language) diagrams according to the rules specified in MOKA formal model [74]. Fig.7. illustrates the formal model framework.

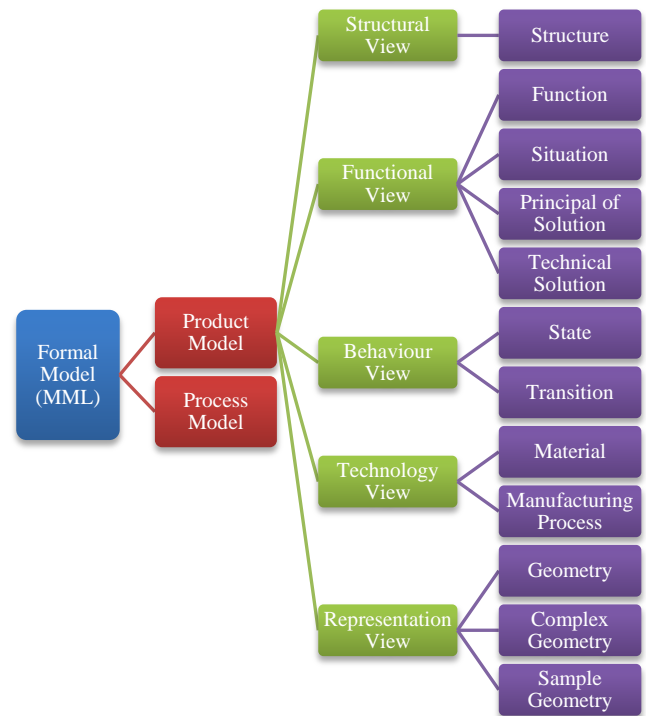
Apart from the above-stated models, MOKA not only illustrates the processes of recognition, acquisition, collection and management of knowledge but also submits the same to the computer program tool for realizing these tasks. PCPACK, a comprehensive tool developed by Epistemics, U.K., is also compatible for the creation of MOKA models. Similarly, some free open source ontology editors such as Protégé are also available for knowledge acquisition [74, 39].



**Figure 6.** Informal model of MOKA methodology [19]

The methodology of MOKA consists of six steps: identify, justify, capture, formalize, package and activate. More in-depth discussion about MOKA was given by Stokes [9], Rüdiger Klein [64], Nicolas Perry et al. [65], Wojciech Skarka [19]. Even though MOKA has been the most successful methodology for many years it has some missing

ingredients [66]: MOKA is product oriented rather than process oriented; MOKA focuses only on supporting knowledge engineer but not the end user (even though end user is the typical domain expert who holds the knowledge); As MOKA is proposed as a neutral methodology the knowledge representation mechanism and supporting tools are not completely acknowledged; MOKA is unable to consider the maintenance and re-use of knowledge.



**Figure 7.** Formal model of MOKA methodology [19]

Another available KBE methodology is KOMPRESSA (Knowledge Oriented Methodology for the Planning and Rapid Engineering of Small-Scale Applications) [67]. It focuses to support KBE implementation at Small to Medium Enterprises (SMEs). It covers the whole life cycle development of KBE by maximizing the client involvement based on the experience, and it is well known for its flexibility in application. It provided guidelines, instructions, formats, techniques and hints for analysis, design, modeling, implementation and documentation to represent, manipulate and manage the complex knowledge. DEKLARE (Design Knowledge Acquisition and Redesign Environment) project is a tool similar to MOKA pays attention for SMEs. In response to the missing ingredients of MOKA, the KNOMAD (Knowledge Nurture for Optimal Multidisciplinary Analysis and Design [66], Knowledge Optimized Manufacture and Design [68]) is developed for analytical utilization of multi-disciplinary knowledge within design and production areas. For improving the knowledge retention and application maintenance with the role of end user KNOMAD has integrated the knowledge representation with design process. Richard Curran et al. [68] acronym the KNOMAD as (K)nowledge capture (N)ormalisation

(O)rganisation (M)odeling (A)nalysis and (D)elivery. As promoted by La Rocca *et al.* [26, 72], A.H. van der Laan *et al.* [70], Lisandrin *et al.* [71], Tooren *et al.* [73] the another KBE methodology, DEE (Design and Engineering Engine) is an overall multidisciplinary design optimization approach. DEE consists of three major modules: Design Process optimization module, Multi-Model Generator (MMG) module, Detailed analysis module. DEE methodology is proven to be better than MOKA approach as it includes detailed discipline analysis and multi-disciplinary optimization techniques. On the other hand, DEE does not comprise methodological, formalized approach towards knowledge capture, formalization and delivery into business processes [68].

Based on this review, the shortfalls of KBE are: the code for execution of KBE need not be done manually as the complexity of the products is becoming amplified. MACRO expansion may be the observed alternative for this difficulty. However, many modern CAD systems are equipped with MACRO facility, there is no core underlying language available for understanding the dubious in it. Since there is no clear human readable and editable representation, the enclosed knowledge in KBE may be lost. This is where an easily editable code language becomes vital because it provides the user to retain the knowledge in the system in easily understandable malleable format with full featured editing, inspecting, and debugging environment. Recently some major CAD companies are marketing their built-in KBE functionalities. The chief promoters of this trend are Unigraphics NX with Knowledge Fusion and CATIA with Knowledge Ware. At first, it appears to be a promising idea but on assessment some major insufficiencies are demonstrated [4]. Nevertheless, KBE systems are required to have extreme information longevity. They cannot depend on user interface, operating system and transitory computers of the present day. The accumulated knowledge in KBE system must be accessible in future years also. The part of the solution for this is to standardize the system code. Along with this, another part is to make the code open source which means the application must execute on any computer operating systems.

### 3.2. Approaches Addressing KBE Issues

Along with methodologies, few approaches have pushed KBE to higher levels. These approaches are discussed below.

#### 3.2.1. Parametric Modeling with KBE

With the pioneering work of Requicha and Voelcker the solid modeling laid its foundation in 1970s [76]. Since then, the researchers turned their focus on developing the modeling techniques. In this process, advanced parametric modeling was first introduced in 1980s and it has become the new paradigm for mechanical CAD designs. But Robert Stiles [89] argues that the real origin of parametric modeling was a few decades earlier. The modeling and designing of a product in parametric modeling approach is dimension

driven and which is built on set of mathematical equations to facilitate automatic re-use of existing design process based on the results of engineering analysis [85]. In parametric modeling approach, the parameters can be changed by the operator as needed to generate the preferred part by making use of history-based method which keeps the record of how the model was generated [81]. When the operator changes parameters in the model and regenerates the part, the program repeats the operations from the history, using the new parameters, to create the new solid. Parametric design can be treated as a powerful, easy, proficient expert method for consistent product design [135].

In 1989, the development and modification of parametric solid models by graphical interaction was discussed by Maarten and Van [84]. Their objective was to define the relationship of geometric properties of constructive solid geometry primitive. With the inspiration of the above research work Suzuki *et al.* [86] detailed the importance of geometric constraints and reasoning in CAD systems in 1990. Soon, the research on parametric modeling gradually focused on 3D models. In 1993, Pérez [87] projected a methodology to allow the designer to build a geometric model by dimensional changes that are propagated to the finite element model in 3D constraint based finite element modeler. Later, with the association of artificial intelligence, parametric modeling approach elevated CAD to a new level. A lot of research on parametric modeling systems has been proposed for different expert systems to enhance the design effectiveness. Taking the advantage of pre-built knowledge base Lin and Hsu [77] and Bor-Tsuen Lin *et al.* [35] proposed an automated design system for drawing dies. Similarly a semi automatic parametric gating design system for die-casting die was developed by Wu *et al.* [78]. Myung and Han [81] proposed a framework which parametrically models the machine tool as the commercial CAD systems cannot handle the parametric design of assembly models. This system consists of commercial CAD software with API programming and expert system shell. Recently Gui and Guan [88] has used parametric modeling in CATIA software for constructing 3D model of a UAV (Unmanned Aerial Vehicle) airframe and avoided the disadvantages of 3D modeling approach such as high time consuming, low efficient, and poor interaction. Carlos [137] presented a parametric design methodology called Design Procedures (DP) that can overcome topological and geometrical limitations of traditional parametric models. Several examples of parametric models directly managed by the CAD construction tree are presented in Refs. [29, 30, 35, 69, 73, 78-81].

As Du Yao *et al.* [135] presented in their paper parametric modeling can be achieved in two approaches.

##### 3.2.1.1. Parametric Modification Method Modeling

This is an approach where the parametric modeling can be done with the help of model library. Model library usually consists of prebuilt models generated by user in advance.



This approach can access the models in library at any time of the execution and can modify the size of the model with the specified parameters to regenerate the new model that matches the required dimensions. This approach is suitable where the model to be formed is complex, standardized and consists of less variable parameters as the approach demands less programming skills.

### 3.2.1.2. Parametric Modeling Fully by Program

This is a complete program control approach where the user can straightaway develop the program to produce the parametric model based on the needs. This is the flexible and suitable approach for modeling without the support of model library. However, as the approach demands high level of programming skills it may be suitable where the model is simple but consists of high number of variables.

The early CAD systems are often criticized for their static modeling technique such as constructive solid geometry (CSG), boundary representations (Breps), or a hybrid of the two [91]. However, parametric design systems such as variants programming, history-based constraint modeling, variational design, rule-based variants, and parametric feature-based design substituted the deficit of the conventional CAD systems by enabling dynamic modeling and modification [92, 93]. In 1988, the first commercially successful parametric software, Pro/ENGINEER with 3D geometry capabilities was released into market by the former mathematics Professor Samuel Geisberg, the founder of PTC (Parametric Technology Corporation). During the releasing press meet, Samuel Geisberg expected that parametric modeling approach not only enable the designer to a variety of designs but also allows a choice to be made later in the design [90]. In 1993, French software Dassault Systèmes S.A. released its first CAD software CATIA V4 with parametric features. Later, Autodesk Inc. released AutoCAD2010 with parametric functionality, and announced in the press release as “a groundbreaking new capability”. Later, on parametric modeling approach went through the scripting interfaces of CAD software packages allowing the designers to write code to automate parts of the software. Currently, parametric modeling is no long the exclusive domain of overtly parametric tools like CATIA and Pro/ENGINEER. Parametric modeling capability drive into other CAD softwares such as Creo Parametric, NX, CATIA V5, SolidWorks, Solid Edge, Inventor, IronCAD.

Based on the review, the observations of parametric modeling system are: Parametric modeling not only provides appreciated experience about the final product’s proportions and form but also presents how the design is modified. With the involvement of KBE, parametric modeling approach proposes enhanced integration with manufacturing practice and assists to reduce the product development time. Parametric modeling offers better details of the model for analysis and prototyping. However, when developing the parametric model as the design factors are not fully considered, it is unrealistic that this approach can replace

people. On the other side, parameterization is possible on the standards, common and series products.

### 3.2.2. Function Based Modeling through KBE

In general the reason for designing a product is to meet a certain function. But the objective can be attained easily with some additional support. Unfortunately, this extra additional support is making the design process more complex [96]. The conventional CAD systems cannot carry out automatic modeling based on the given specifications as they are not built with AI to perform reasoning and to make decisions by itself. In practice, these activities are performed by the designers to fulfill the requirements. Recent advances in the field of CAD systems have greatly increased the influence of AI on the modeling phase of the design of the product by encompass human knowledge [94, 95]. Function oriented design has become an active area of research for the past decade. The intention of functional design is to present computer aided tools to connect design functions with the physical embodiments used to recognize the function [98]. In the early stage of the development of functional design approach, Chakrabarti et al. [99] pointed that knowledge of functionality is required for design, modification, comparison, evaluation of the process. In reality the definition of function given by many researchers is observed to be diverse and contradictory. However, designers agree that there is tight coupling between function and behavior. Function is what the design is going to do while the behavior is how the expected result is attained from design. The most common form of knowledge representation in functional design is rules, frames, objects and constraints. In 1996, Li et al. [100] applied rule based paradigm for automating the computational synthesis of conceptual design of mechanism. A frame based structure was used to model the kitchen appliances by Tong and Gomory [101]. Gelsey et al. [102] developed a conceptual design of supersonic aircraft using constraint based model in 1998. An easily modify and highly flexible object oriented architecture was proposed by Akagi et al. [154] for developing a sustainable functional design process by considering the objects as elements. Zhang et al. [103] proposed an integrated knowledge method that unites rule-based and object-oriented representation methods to stand for functions and functional related design characteristics in an intelligent design environment.

Andrews et al. [97] proposed the concept of design reuse in CAD systems to facilitate quick design by using already-available product’s design process. Tor et al. [104, 105] has drastically reduced the time and effort needed in configuring industrial robot by make using of behavior-driven, function-environment-structure (B-FES) modeling framework. Xu et al. [106] proposed a function-based design synthesis approach to support design reuse framework by using functional-based product information model and multiple objective optimization model for developing intelligent product structure.

### 3.2.3. Web-Based Approach in Favor of KBE

With the recent development of the Web-based technologies, many new approaches have been proposed to execute advanced product design systems. Web-based approach towards KBE has become the center of attraction for research as web technologies offer an essential path for information sharing and exchange [107]. In the research of Chun-Hsien Chen *et al.* [49], Tu *et al.* [108], Ming-Chyuan Lin *et al.* [110], Xie *et al.* [109] Web-based approaches are used to deal with the changing customer requirements as internet enhances the interactive levels among designers and customers. Web-based approaches not only consider the customer needs but also enhance the conventional design process. In the research paper, Kulon *et al.* [113] summarized Web-based KBE system to merge hot-forging design processes to a single framework for capturing the knowledge and experience of the design engineers. In addition, global collaborative design approach can be implemented using Web-based approach. For example, Ming-Chyuan Lin *et al.* [110] has developed an interactive interface for considering customer needs in the early phase of product development, Qin *et al.* [111] proposed a quick Web-based conceptual design system for examining and modifying the product design over internet, Xie *et al.* [114] developed a Web-based integrated product design platform for concurrent design and manufacturing the customized products. Moreover, web can be integrated with management technologies for keeping an eye on the design process and the working systems [112].

Apart from the design perspective, internet can provide product visualization for better understanding the product. For visualization, the product data is categorized into text forms, 2D engineering drawings, 3D solid models, animations, audio, and video. With the richness of HTML technology, the product data such as text, audio, video and animation can be handled. The other product data such as 2D engineering drawings, 3D solid models can be visualized with the support of web enabled data formats like VRML (Virtual Reality Modeling Language), DWF(X) (Design Web Format) etc. But 3D solid model can be realized by integrating the 3D entities of solid with VRML through STEP (Standard for the Exchange of Product model data) files.

Apart from the above advantages, web-based KBE approach is encountered with some disadvantages such as the knowledge available through internet is not surely reusable as it is not standardized. But it can be resolved by making use of STEP approach as it provides standardized knowledge.

### 3.2.4. Ontology Based KBE

Ontology is a precise requirement of conceptualization and illustrates a set of representational primitives with which a domain of knowledge is modeled [151, 152]. Ontology provides knowledge sharing and reuse by instituting a precise concurrence of objects and relations within a particular domain of conversation [153]. Ontology is

machine readable without being too cryptic for human understanding [152]. By establishing a common language for use and interpretation of information, ontologies allow for efficient and organized exchange and reuse of knowledge. Today, one of the fundamental problems to a designer is the exchange of product information across various applications. According to Cari *et al.* [116] ontology is a philosophical theory about the nature of existence. Ontology based KBE approach facilitates the exchange and reuse of design process while incorporating the additional knowledge [115]. This approach is applicable where the complexity in relationship between concept and knowledge exists. Using this approach searching for relevant knowledge is simple. In engineering activities semantic retrieval of engineering domain knowledge is treated as critical, but that was overcome by Xutang *et al.* [117] using ontology based approach in 2013. Ontology is a well prepared system that covers the progress, objects and attributes of the domain as well as their pertinent complex links [140]. Margot *et al.* [146] developed a KBE tool aimed at SMEs to reduce the total design time of stamping die with ontology based approach in hybrid engineering. After executing the tool, the total design time was brought down by 6% and the process for designing the trimming packets reduced by 85 to 90%. Moreover, ontology based approach offer the opportunity for progressive automation of processes in the industry. With this approach, integrating the shapeless knowledge for better conceptualization is possible for the complex designs [138]. According to Guarino *et al.* [139] ontology based approach is a concept that allows the designers to model and represent a particular domain in terms of axiomatic definitions and taxonomic structures. In the recent researches, it has been observed that ontology-based approach can help in attaining the common language for capturing the domain knowledge and it is proven that it is an advanced paradigm over the recent years [141]. By facilitating the exchange of knowledge in the process of design, Witherell *et al.* [142] presented the capability of ontology approach in representing application-based knowledge. However, ontology-based KBE approach has disadvantages in organizing the knowledge of product which is not proper for varying manufacturing environment.

### 3.2.5. Case-Based KBE

Case-based Reasoning (CBR) approach provides the methodology to solve the new problem by making use of the previously solved similar problem's solution, by reusing the knowledge of the previous situation [118, 119]. Just like as database stores the data, case-base stores the cases with indexed problem solutions. A case is an experience which represents the conceptual knowledge [134]. CBR consists of four processes: Retrieving the similar previous case from case-base; Reusing the previous similar case solution to the new case; Updating the retrieved solution with new case; Storing the newly updated solution as a new case [128]. A general CBR execution cycle is shown in Fig. 8.

Decreasing the negative impact losses of experts is one of main advantage of this system. Qiaosheng Liu et al. [120] developed intelligent and automatic design system of turntable using CBR with the help of parametric design method. Zheng et al. [122] proposed an efficient case-based knowledge model to produce process plans from previous manufacturing process knowledge. Li et al. [124] approved CBR approach for robust design of fixture. Similarly Chang et al. [125], Aitor Mata et al. [123], Seo et al. [121], Tsai et al. [119], Zbigniew et al. [127], Leung et al. [131], Gupta et al. [132], Belecheanu et al. [133] observed the capability of CBR approach. Even though the approach is considerably effective for reducing the time and cost, it has its own disadvantages. Considerable uncertainty may encounter when selecting the solution for the new problem from the previous similar problem solution as there are many solutions for a single problem. So, a successful knowledge management technique may assist for optimal selection of problem solution. In order to select the solution that does not have the similar problem solution in the case-base, AI needs to be applied for finding the similarity between slightly related problem solutions [128, 129, 130].

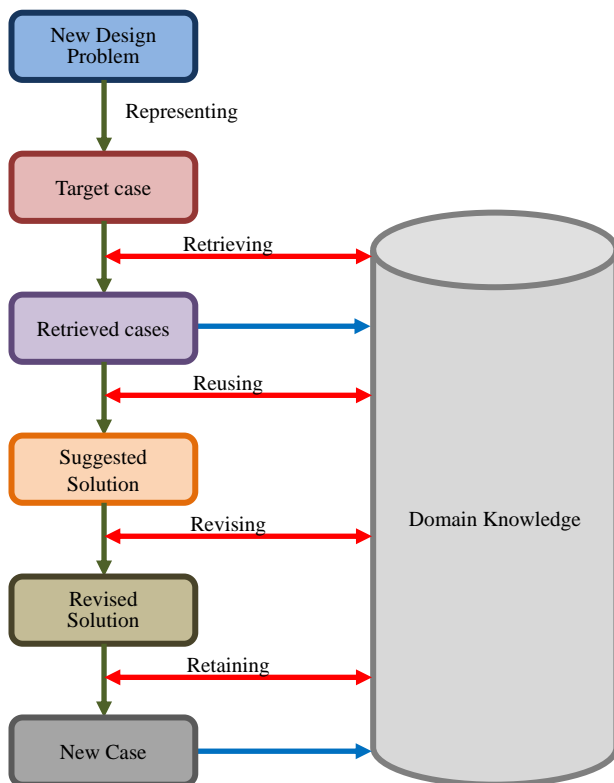


Figure 8. CBR Execution cycle [120]

#### 4. Discussion, Limitations, Future trends of KBE

With the advent of the internet and continuous development of software and hardware, KBE approaches are enhancing their capabilities in capturing, reusing the knowledge across time and space. But still, the designers are

not able meet the customer's desire because of many reasons. One of them is the knowledge management (KM) problem. KM is developed for capture and reuse of the domain knowledge to integrate the traditional engineering software with knowledge based applications. The reluctance among traditional CAD tool vendors is slowing down the evolution of KAD (knowledge-aided design) as they fear of losing the market. But recently, few vendors are making the progress towards the development of KAD and that should be encouraged in large scale. Whereas, the lack of robust knowledge acquisition system is still missing even after the immense research and it has become one more hurdle for the progress of KBE system. There is also a need in building the automatic knowledge acquisition tool. The mass collaborative product development approach demands faster knowledge accessing system but there is no dependable knowledge base available as the knowledge through the internet is not standardized. But according to recent studies, this can be handled with the rise of wikis. A wiki is a database which allows the users to interact and share the information through web pages. The group of designers can create the standardized knowledge base as global knowledge repository with the help of wiki. It is observed that KBE system became revolution with the inclusive of AI. But the compilers and editors for programming the KBE tasks are still complex for the designer as they are not professional programmers. This shortfall demands immense research on easy programming for compiling the KBE system. Additionally, research need to be done to make the software and hardware cheaper for KBE system as the available are affordable for the big companies only. Another shortfall with the present KBE system approach is from its methodologies. Even after the development of advanced MOKA and its enriched approaches, preparing the formal models is a complex task. This should be automated as an application for easy translation. Based on the review, it is observed that this area of research is still underdeveloped. Another shortfall with the present KBE system approach is it is getting developed as black-box application. In black box application, some output with some input will be produced but nobody knows what happens in between. This situation leads to the problem of transferring the knowledge to new engineer in the department as no one knows what exactly is going on in the process.

Web-based KBE approach is one of the most attractive areas for the researchers in the recent years. With the web-based KBE approach, the designers need to collaboratively design the product in dynamic information transfer environment. But updating the information dynamically is a critical issue. Web servers must also be robust along with the designers approach as entire communication will be handled by the servers only. However, recent advances in web technology are meeting this need but they cannot support the knowledge repository. So, dedicated servers for sharing the knowledge are developed in recent years and such servers are called agents. The main objective of this agent technology server is to share

the knowledge dynamically to support collaborative design system in a distributed environment on behalf of design development team. In this context, agent is software that supports the communication dynamically as soon as new information is generated. The critical objective of this technology is to share the real-time product information to make the collaborative design process in a more effective way. So, the scope for research in this area is enormous.

Case-based KBE application is the other research area where the researchers can focus. It seems that development of application is meant only for single or related purpose but it should support the other purposes by making it a custom development process. This notion is verified in this review and it is observed that most of the methodologies are focused on a single or related purpose. The impact of existing methodology seems to be limited in practice. This is the area where the researchers need to focus as the scenario is giving the impression that the knowledge loss may follow due to poor modeling of the application.

Collaboration of KBE approaches discussed in this paper is the other interesting research area where the authors are looking for. Today's competitive market made the customer the decision maker about the fate of the product. If any product is able to sustain in the present turbulent market, it implies that it is serving the customer requirements better than the competitors. So, the involvement of the customer into design process will lead to better design. Web-based KBE approach gives the environment for the customer to be in the process of design. As the customer does not have the design knowledge, the design process should enable the function-based search system for better presenting and understanding the customer requirements. So, research can be carried out with the involvement of customer in design process, based on the functionality through web-based technology. The authors are looking forward to carrying out the research to develop a web-oriented function based parametric modeling system using KBE.

## 5. Disclaimer

The commercial software systems identified in this paper doesn't imply the recommendation or endorsement by the author nor does it imply that they necessarily the best available for the purpose.

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