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ORIGINAL ARTICLE

A material selection methodology and expert system for sustainable product design

Mohammad Hosein Fazel Zarandi · Saeid Mansour · Seid Ali Hosseinijou · Milad Avazbeigi

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Abstract Material selection is one of the main phases of product design process that has great impact on the manufacturing of sustainable products. One of the best approaches of material selection for sustainable products is life cycle engineering (LCE). But LCE is a costly and cumbersome task and it is not economic to perform this task for a large number of proposed materials in order to choose the most suitable one for a sustainable product. Instead, it is more reasonable to make a preliminary filtering on the proposed materials and obtain a shorter list of candidate materials and then perform LCE on alternatives which are obtained from preliminary filtering. Since environmental friendliness of materials is a critical sustainability issue, so it is a good criterion for preliminary filtering of alternatives. In this paper, a new methodology is proposed to support preliminary filtering of alternatives from environmental viewpoint. The methodology uses the knowledge of experts in the field of eco-design. The knowledge is translated to decision making rules and a decision tree is developed to guide the choice. In order to use the capabilities of frame-based systems, an object-oriented approach for representation of knowledge is also proposed. Moreover, a prototype hybrid expert system based on the proposed methodology called material selection expert system for sustainable product design is developed to support the task of preliminary filtering. Finally, a case study from tire manufacturing industries is presented to show the validity of the proposed system. The results show that the system can determine the appropriate candidate materials and hence improve the possibility of manufacturing of more sustainable products. Eliminating alternatives that do not have the necessary conditions for sustainable product leads to a large saving in time and cost of the LCE evaluation process

Keywords Sustainable product design · Material selection · Life cycle engineering · Rule-based expert system

1 Introduction

The concept of sustainable development as it is known today emerged in the 1980s as a response to the destructive social and environmental effects of the predominant approach to economic growth. One of the earliest formulations of the concept of sustainable development is as follows: "For development to be sustainable, it must take into account the social and ecological factors, as well as economic ones; the living and non-living resource base; and the long-term as well as the short-term advantages and disadvantages of alternative actions" [1]. From a business perspective, the concepts of sustainability are often described as the triple bottom line: [2]

- Economic viability: the business aspects of a project,
- Social concerns: human health and social welfare,
- Natural or ecological issues: environmental stewardship.

M. H. F. Zarandi (✉) · S. Mansour · S. A. Hosseinijou · M. Avazbeigi
Department of Industrial Engineering, Amirkabir University of Technology,
P.O. Box 15875-4413, Tehran, Iran
e-mail: zarandi@aut.ac.ir

S. Mansour
e-mail: s.mansour@aut.ac.ir

S. A. Hosseinijou
e-mail: hosseinijou@aut.ac.ir

M. Avazbeigi
e-mail: milad.avazbeigi@gmail.com

Figure 1 shows three dimensions of sustainability and trade-off among them.

As an instrument of sustainable development, sustainable design intends to conceive of products, processes, and services that meet the needs of society while striking a balance between economic and environmental interests [3]. One aspect of sustainable design is sustainable product design. Design for the environment and eco-design are the two techniques for sustainable design [4]. The three major topics of product design are material selection, part design, and assembly design. As a part of product design, materials selection is a multidisciplinary activity, which integrates a large number of knowledge fields and professional domains. A material selection decision should capture not only the functional performance required for the application but should also consider the economical and environmental impacts originated during the product life cycle. Therefore, sustainable material selection can be regarded as a multi-objective problem, being the optimal selection and the best match found between the available materials profiles and the requirements of the sustainable product design. Sustainable material selection methodology should compare a set of candidate materials and, through the aggregation of the three indicators (social, economical, and environmental), identifies the "best material domains" [5] (see Fig. 2).

This research focuses on material selection as it is very important and has the most impact on sustainability of the product. Figure 3 depicts different phases of material selection process according to Ashby [6] and highlights the scope of this work in the process in yellow. Scope of this work is screening proposed materials using environmental constraints and eliminating ones that are not compatible with environmental regulations and preferences. The rest of this paper is organized as follows: in Section 2, literature review and motivations for this research are discussed; in Section 3, proposed methodology is explained; in Section 4, the prototype expert system is presented; and finally in Section 4, conclusions are made.

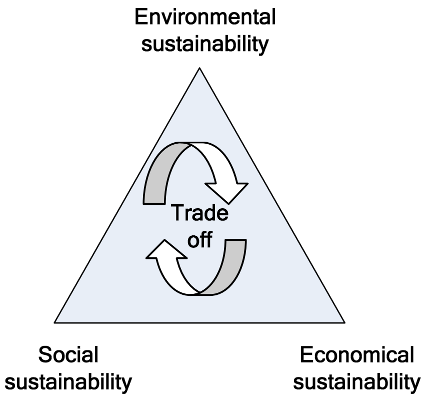


Fig. 1 Three dimensions of sustainability

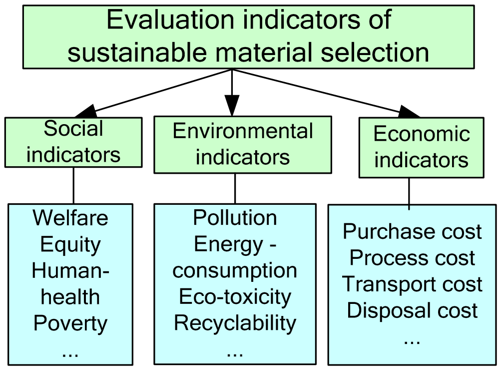


Fig. 2 Evaluation indicators of sustainable material selection

2 Literature review and motivation for the research

A number of researchers have worked in the area of material selection for sustainable product design. Holloway [7] looked at one particular method of material selection in mechanical design: material selection charts by Ashby and showed how this methodology can be extended to take environmental factors into account. Ermolaeva et.al [8] showed the application of a structural optimization system to the optimal choice of foams for the use as floor panels in the bottom structure of a car. In addition to optimal (minimized) mass and materials price used for selection of foams, the assessment of an environmental impact of candidate materials during the entire life cycle of the structure was considered. Giudice et al. [9] proposed a selection procedure that elaborates data on the conventional and environmental properties of materials and processes

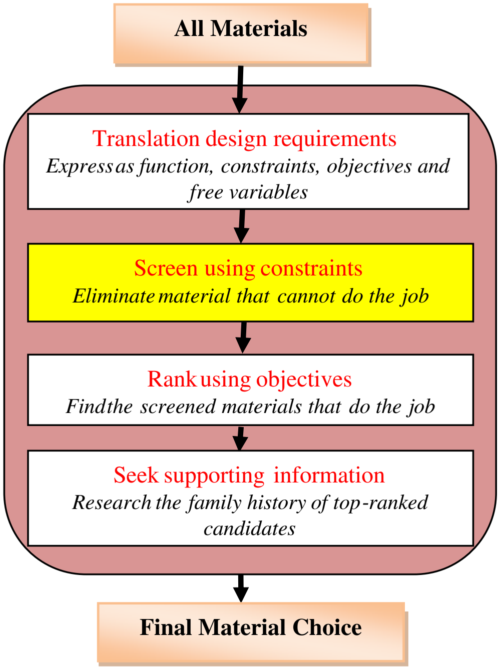


Fig. 3 Phases of material selection process [6]

and calculates the values assumed by functions which quantify the environmental impact over the whole life cycle and the cost resulting from the choice of materials. Chan and Tong [10] proposed gray relational analysis for aggregating multiple and contradictory objectives of sustainable material selection. Ribeiro et al. [11] proposed a life cycle engineering (LCE) approach to support material selection, integrating the performance of the material for the specific application in technological, environmental, and economical dimensions throughout the duration of the product. In their method, "best material domains" are presented in a ternary diagram, which allows a global comparison of the candidate materials according to different business scenarios and corporate strategies. Zhou et al. [12] presented sustainability indicators of materials and proposed an integration of artificial neural networks with genetic algorithms (GAs) to optimize the multi-objectives of material selection. Thurston et al. [13] consider customers preferences for environmental protection in material selection. Feng [14] developed a methodology for material selection in green design with toxic impact concern. His price competition model determines material alternatives in each of the multiple market life cycle stage considering customer utility function and environmental taxation. He compares the result of his method with the result of Thurston methodology in a case study. Lin and Lin [15] discuss the state-of-art research on environmentally conscious material selection methodologies for the reduction of products toxic impact. Weaver et al. [16] developed environmental materials selection charts for selection of materials to reduce environmental impact. These charts simultaneously consider one of the mechanical properties and one of the environmental characteristic of materials. Almeida et al. [17] proposed "emergy accounting" as a tool for evaluating materials selection for eco-design of beverage packages in Brazil. Bovea and Vidal [18] used life cycle assessment (LCA) for materials selection for sustainable product design. Abeysundara et al. [19] proposed a matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka. Lacouture et al. [20, 21] developed an optimization model for the selection of building materials using a Leadership in Energy and Environmental Design (LEED) green building rating system in Colombia. Shi and Xu [22], proposed the selection of green building materials using GA-BP hybrid algorithm. Chen et al. [23] developed a systematic methodology for material selection with environmental consideration. Fussler and Krummenacher [24] proposed the concept of eco-balances as key to better environmental material choices in automobile design. Yuan and Dornfeld [25–27] proposed a schematic method for characterization of human health impact of toxic chemicals for sustainable material selection in design and manufacturing. In addition to conceptual methodologies, some commercial decision support systems have been developed for assisting sustainable material selection. IDEmat is software by TU of Delft, Netherlands, for selecting low impact materials. It contains a database on the physical, mechanical, and environmental characteristics of various materials [28].

Many researchers developed intelligent and knowledge-based systems (KBS) or expert systems for material selection. Pilani et al. [29] proposed a hybrid intelligent systems approach for die design for sheet metal manufacturing that incorporates rules for material selection. Zha [30] developed a fuzzy knowledge-based decision support system for process and material selection in concurrent product design. Bamkin and Piearcey [31] justified the development of a "Design Assistant" program for the selection of materials according to knowledge-based system. Beiter et al. [32] developed a HyperCard program that used PROLOG compiler, called Logic Manager, to perform reasoning for the selection of plastics materials. Sharma et al. [33] suggested an expert system using TOPSIS method for the material selection process. Bullinger et al. [34] developed a knowledge-based system for assisting design engineers in selecting the appropriate materials for construction with fiber-reinforced composite materials. Furthermore, Chen et al. [35] integrated the expert system with the database system to provide decision-making support system for composite material selection in structural design. Sapuan and Abdalla [36] also presented a prototype knowledge-based system for selection of polymeric-based composite material for pedal box system of automotive. Meanwhile, Kumar and Singh [37] presented an intelligent system for selection of materials for progressive die components. Sapuan [38] explained the importance of knowledge-based system in the context of concurrent engineering and applied it in material selection of polymeric-based composite. Later, Sapuan et al. [39] demonstrated application of knowledge-based system in material selection of ceramic matrix composites for engine components. Amen and Vomacka [40] used case-based reasoning (CBR) as a tool for material selection. CBR is the procedure of solving new problems based on the solutions of similar past problems. CBR is a good technique for searching in databases with information of different technical solutions applied in the actual company, failure analysis, and so on. Rahman et al. [41] developed a knowledge-based cost modeling system for building design stage by optimizing the selection of materials and technology. Mohamed and Cleik [42] presented an integrated knowledge-based system for alternative design decisions, materials selection, and cost estimating mainly for pre-design of a building. A methodology for construction of a generic computer materials selector is described. In Trethewey et al. [43], a knowledge structure is presented in which materials selection and failure analysis are at opposite ends of a spectrum of materials performance.

Jahan et al. [44] review material screening and choosing methods. One of the best approaches of material selection for sustainable products is LCE. LCE refers to "Engineering activities which include: the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product life cycle and minimizing pollution and waste" [45]. Therefore, LCE can be defined as a decision making methodology that considers performance, environmental, and cost dimensions throughout the duration of a product, guiding design engineers towards informed decisions [46], [47]. LCE includes not only conventional tools, as technical performance analysis based on mechanical, electrical, and chemical properties, but also life cycle tools to analyze economic performance, such as life cycle cost and environmental performance, such as LCA. Most of researchers in sustainable material selection used LCE partially or totally in their work [8, 9, 11–13, 17–19, 21–24]. Several authors have applied LCE to different case studies in automotive [48, 49], construction [50], and computer and electronic industry [51–53], to name only a few.

The first motivation for this research is that although LCE is one of the most suitable approach for sustainable material selection but it is an expensive and overwhelming task and it is desirable to use this approach for evaluation of only a few number of candidate materials. It is more reasonable to make a preliminary filtering on proposed materials and obtain a shorter list of candidate materials and then perform LCE on alternatives in this list. Since environmental friendliness of materials is a critical sustainability issue, so it is a good measure for preliminary filtering of alternatives. Indeed, those alternatives that do not have required characteristics from environmental point of view should be omitted from LCE evaluation process. In the other words, although there are some previous researches in sustainable material selection, most of them (especially those with LCE as their foundation) need a huge number of data and computations. For example, in a method presented by Holloway [7], in order to generate environmentally oriented materials selection charts, environmental indices need to be calculated and this could cause major difficulties. Ribeiro et al. [11] applied a full LCE evaluation process in their study. They assume there are complete and accurate data about material properties, life cycle costs, and environmental profile of material candidates over their life cycle. Proposed methodology in this paper provides a list of good candidates for methods proposed in those researches. In fact, those approaches assume that a list of alternatives which qualified necessary conditions is ready. Approach of this research provides such a list. So the proposed methodology does not serve as an alternative for other methods but as a complement for them. Table 1 summarizes differences among this research and previous ones.

Another motivation for this research is from the methodological viewpoint. As you can see from the second paragraph, several expert systems have been developed for aiding in material selection. Table 2 classifies this literature from two aspects: selection criteria and application purpose. Also it shows unique feature of this research, i.e., use of environmental properties as selection criteria. In fact, to the best of our knowledge, to date, no expert system has been developed for screening material alternatives from environmental viewpoint. Authors believe that preliminary filtering of alternatives using a rule-based methodology provides a promising rich approach to sustainable material selection.

In this paper, KBS is proposed to support preliminary filtering of alternatives through an environmental feasibility analysis. The methodology uses the knowledge of experts in the field of eco-design. The knowledge is translated to decision rules and a decision tree is developed for filtering of alternatives. In order to use the capabilities of frame-based systems, an object-oriented approach for representation of knowledge is also proposed. Furthermore, a prototype expert system based on the proposed methodology called material selection expert system for sustainable

Table 1 Comparison of this research with previous researches in sustainable material selection

Item		Previous methods	Method of this research
Requirements	Data	Large database [7–9, 11–13, 17–19, 21–24].	Small database
	Data	Quantitative [7–28],	Qualitative
Methodology	Type	MCDM methods [8–12]	Rule based methodology
	Calculation	Heavy calculations [7–9, 11–13, 17–19, 21–24]	No calculation (inference)
	Speed	Low [8–12, 17–19]	High
System		DSS [11], [12]	Expert system
Application phase		Final choice [7–28]	Preliminary filtering

Table 2 Classification of previous researches that developed expert system for material selection

Reference	Selection criteria	Application purpose
[29]	Mechanical properties	Die design
[30]	Total production cost	General purpose
[31]	Mechanical properties	General purpose
[32]	Mechanical properties	Plastic material selection
[33]	Cost and functional properties	General purpose
[34]	Mechanical properties	General purpose
[35]	Cost and functional properties	Composite materials
[36]	Mechanical, economical and manufacturing properties	Polymeric based composites
[37]	Mechanical properties	Progressive die components for automotive parts
[38]	Mechanical, economical and manufacturing properties	Polymeric based composites
[39]	Mechanical and manufacturing properties	Ceramic matrix composite for automotive engine
[40]	Cost and functional properties	General purpose
[41]	Cost and functional properties	Building Materials
[42]	Cost and functional properties	Building Materials
[43]	Mechanical properties	General purpose
This research	Environmental properties	General purpose

product design (MSESPD) is developed to support the task. In the next section, the proposed knowledge-based methodology is explained.

3 Development of methodology and system

The selection of the suitable material is a difficult process that demands the management of a great amount of information about the materials properties and there are often several solutions for a particular application [54]. Each material has various properties such as mechanical, thermal, electrical, physical, environmental, economical, optical, and biological properties. However, it is a well-known fact that only a limited number of design engineers have a thorough knowledge on all these properties of a specific material, which is planned to be used in the manufacturing of the product. Therefore, the design engineer should be guided in selecting the most suitable material. Knowledge-based systems comprise expert knowledge capable of assisting the user in an interactive way to solve different problems and queries [55]. The knowledge-based systems work in full interactive mode and provide impartial recommendations and are able to search large databases for optimum solutions [56].

The KBS for sustainable material selection was developed based on heuristic rules and the experience of design experts. Classification and reasoning for selection process are carried out using a rule-based system approach. This includes knowledge acquisition, choosing the selection criteria, selection of user interface; defining the knowledge hierarchy, program code writing, program validating and testing, documentation, and maintenance. The development of the KBS involves five major phases.

3.1 Phase 1: knowledge acquisition and representation

3.1.1 Representation of problem solving knowledge in rule structure

The knowledge-based methodology uses the knowledge of experts in the fields of eco-design, sustainable design, and sustainable manufacturing. In this research, an indirect approach is used for knowledge extraction, where the rules are extracted based on reviewing the literature. In other words, there are many guidelines and checklists in the literature to assist sustainable design and sustainable manufacturing [4, 28, 57–67]. These guidelines and checklists are used for extraction of principles and axioms of the knowledge base. The axioms are collected and organized as follows. These axioms are used later to extract the rules of the designed expert systems.

Axioms (guidelines)

The choice of low-impact materials is an important saving for nature that can be performed in two different ways:

- Rejection of toxic and harmful materials. Guidelines related to toxic and harmful materials are as follows (rejection axioms):

– Avoid toxic or harmful materials for product components

- Avoid materials that emit toxic or harmful substances during pre-production
- Avoid additives that emit toxic or harmful substances
- Avoid toxic or harmful surface treatments
- Avoid materials that emit toxic or harmful substances during usage
- Avoid materials that emit toxic or harmful substances during disposal
- Avoid toxic substances, but use closed loops when necessary to do so
- Avoid exhaustive materials

▪ Selection of renewable and bio-compatible materials. Guidelines related to renewable and bio-compatible materials are as follows (acceptance axioms):

- Use renewable materials
- Use residual materials from production processes
- Use retrieved components from disposed products
- Use recycled materials, alone or combined with primary materials
- Use biodegradable materials
- Use nonhazardous recyclable materials
- Use few, simple, unblended materials.
- Use materials with low energy consumption in extraction and transportation.

Rule extraction from axioms

Mentioned axioms in the previous section are very general and when a new candidate must be evaluated, they cannot lead decision makers to a specific selection. Hence, it is necessary to extract some rules throughout the reorganization and combination of axioms. The result of this procedure is depicted in Fig. 4 as a decision tree. As a matter of the fact, IF-THEN rules are a popular paradigm for knowledge representation in knowledge-based systems. In order to extract IF-THEN rules from axioms, construction of a decision tree of axioms can be very useful. After completion of the decision tree, each leaf of the tree indicates an IF-THEN rule.

In the decision tree shown in Fig. 4, materials are categorized in three classes:

▪ Very toxic or harmful: since the research approach is LCE, it is reasonable to omit very toxic or harmful materials in LCE evaluation process.

▪ Some toxic or harmful: materials that are some toxic or harmful are divided in two categories as well, those which are necessary for use in product and those which are not. The necessity may arise from technical obligations, economic considerations, or other limitations and should be determined by experts. When a material is necessary for the manufacturing process, if using a closed loop technology is possible, the material may be a good candidate, otherwise it is not considered as a good candidate.

▪ No toxic and harmful: the third group of alternatives includes materials that are not toxic and harmful in any stages of product's life cycle. If an alternative in this group is recycled or biodegradable or recyclable or renewable, then it merits being a good candidate for developing sustainable products. Otherwise, it is not suspected to be a good candidate. If a suspected

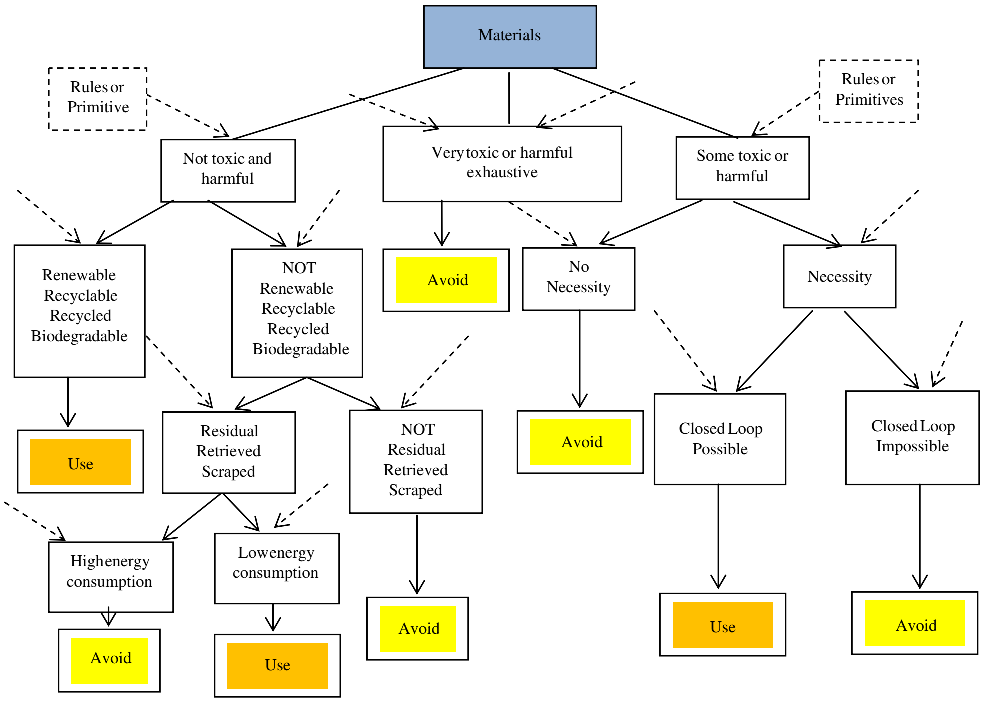


Fig. 4 Decision tree for environmental feasibility analysis

alternative is residual or scrapped materials from production processes or retrieved components from disposed products and has low energy consumption, then it is a good candidate, otherwise it is not a good candidate.

Decision tree proposed in the paper is a simple one. As you can see from Fig. 4, there are many dashed arrows in the tree. These dashed arrows indicate that the statement in the box is a primitive that should be determined through a question–answer process from outside of the system or may indicate rules that are not developed in our prototype system. If one adds these hidden rules to the tree a complex decision tree will be obtained that cannot be used effectively without an inference engine. So an expert system that contains these rules in its knowledge base and fires them logically and intelligently is needed. Rules which can be extracted from the decision tree shown in Fig. 4 are summarized below:

Rejection rules set

1. IF the material is very toxic or harmful in any stages of its lifecycle
   OR the material is exhaustive
   THEN the material is not a good candidate
2. IF the material is some toxic or harmful in any stages of its lifecycle

   AND there is no necessity to use it
   THEN the material is not a good candidate

3. IF the material is some toxic or harmful in any stages of its lifecycle

   AND there is necessity to use it
   AND there is no possibility to use closed loop
   THEN the material is not a good candidate

4. IF the material is not toxic or harmful in any stages of its lifecycle

   AND the material is not recyclable
   AND the material is not recycled
   AND the material is not renewable
   AND the material is not biodegradable
   THEN the material is a suspected candidate.

5. IF the material is a suspected candidate

   AND the material is not residual
   AND the material is not retrieved
   AND the material is not scraped
   THEN the material is not a good candidate

6. IF the material is a suspected candidate

   AND the material is residual
   OR the material is retrieved
   OR the material is scraped
   AND the material has high energy consumption
   THEN the material is not a good candidate

Accepting rules set

7. IF the material is some toxic or harmful in any stages of its lifecycle

   AND there is necessity to use it
   AND there is possibility to use closed loop
   THEN the material is a good candidate

8. IF the material is not toxic and harmful in any stages of its lifecycle

   AND the material is recyclable
   OR the material is recycled
   OR the material is renewable
   OR the material is biodegradable
   THEN the material is a good candidate

9. IF the material is not toxic or harmful in any stages of its lifecycle

   AND the material is not recyclable
   AND the material is not recycled
   AND the material is not renewable
   AND the material is not biodegradable
   THEN the material is a suspected candidate

10. IF the material is a suspected candidate

    AND the material is residual
    OR the material is retrieved
    OR the material is scraped
    AND the material has low energy consumption
    THEN the material is a good candidate

3.1.2 Representation of problem solving knowledge in frame structure

IF-THEN rules provide a powerful structure for knowledge representation. However, capabilities of frame-based structure should not be neglected. Even though knowledge is represented using a production rule system—the main module of the proposed system—knowledge is basically represented by objects in the form of classes and instances. Each object has slots, or sets of attributes, that define the state of the object and methods, or sets of procedures/rules, that describe the object's behavior. When the problem is defined, the domain is analyzed, and the classes and instances are defined; then a static picture of the problem can be created. To solve the problem base on the created static picture, there are two approaches:

Two ways for representation of the problem solving knowledge in the frame-based structure

1. Pattern matching rules

Many frame-based expert systems rely mainly on pattern matching rules to direct the problem solving. These rules include variables that can be used to match selected property value of each instances of a class. They enable user to write very general rules that capture the problem solving steps. This type of system is often referred to as *hybrid systems*, since it combines both frames and rules for representing the problem's knowledge. Assume, for example, we want to write a rule that performs the following function: *when the proposed material is very toxic or harmful in any stages of its lifecycle, then the material is not a good candidate.*

The pseudo code of this rule is as follows:

```
IF frame ?X

Instance of MATERIALS
WITH proposed=yes
WITH degree of toxicity or harmfulness=very

THEN frame ?X

WITH good candidate=no
```

And its code in Kappa-PC, an expert system shell described later in text, is as follows:

```
For All x| MATERIALS

IF x: proposed≠=yes
   AND x: degree of toxicity or harmfulness≠=very
   THEN x: good candidate≠=no
```

2. Object-oriented approach (methods approach)

Some of expert systems use more of an object-oriented approach where *methods* tied to *facets* or *messages* are used to provide a dynamic exchange of information between frames. So, in general there are two ways for inter-object communications. Both techniques rely on procedures (methods) being written and attached to the frame:

I. Facet approach

This technique relies on IF-NEEDED or IF-CHANGED facets. The method written is attached either the IF-NEEDED or IF-CHANGED facet of a given frame property. This type of method is often called a demon,

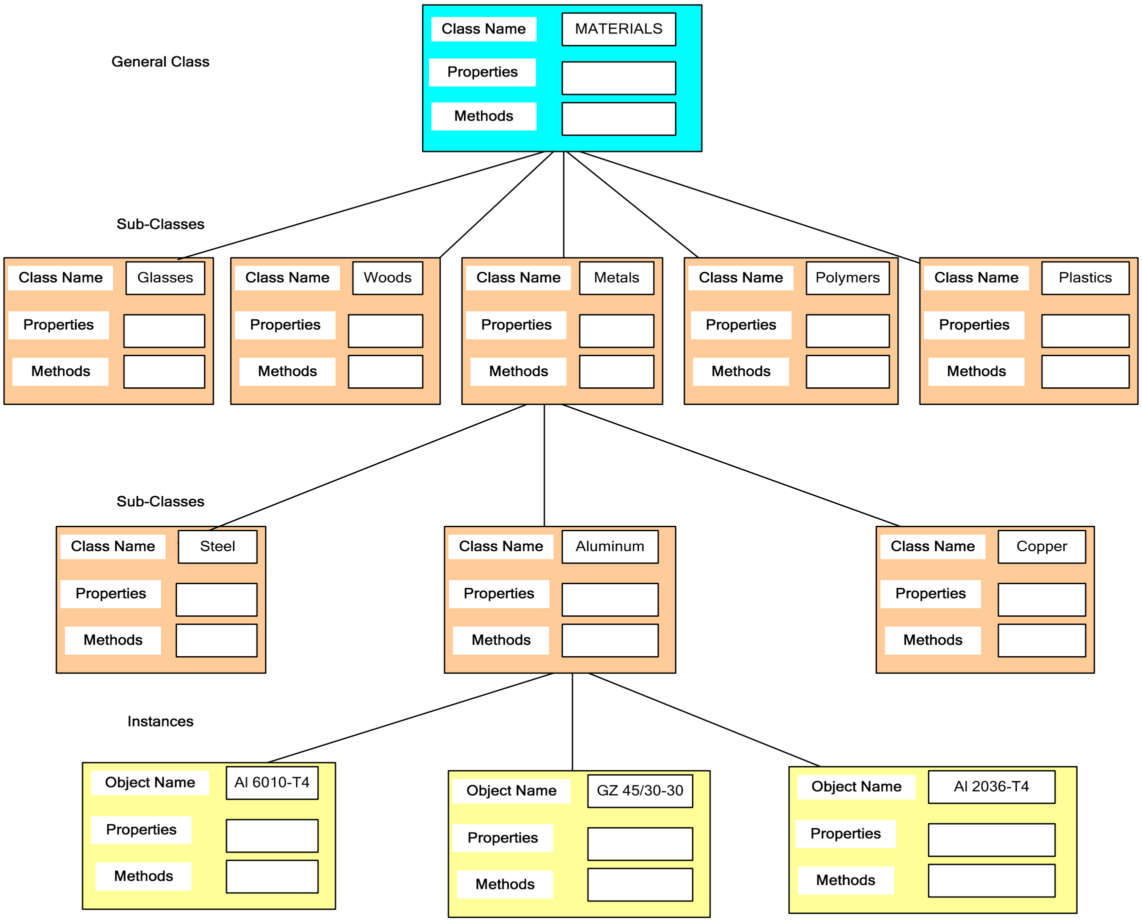
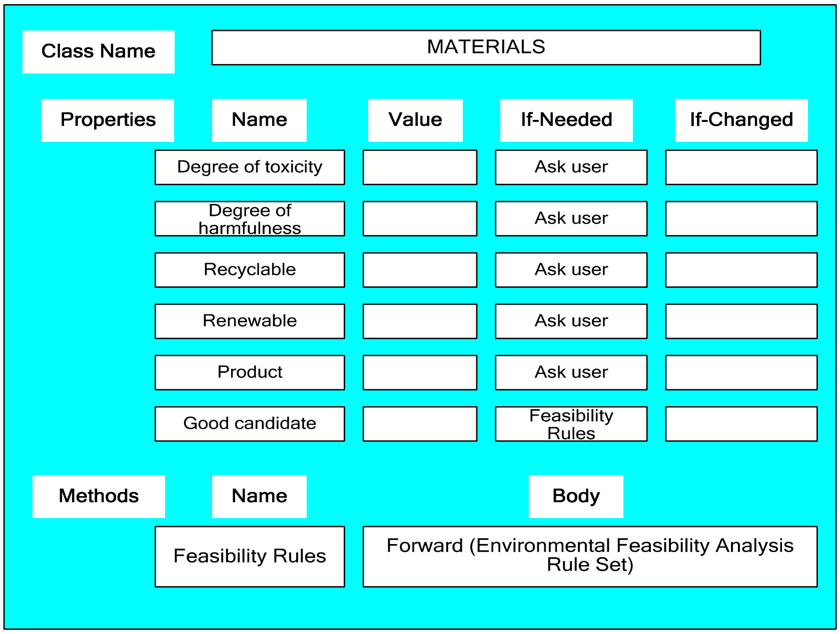


Fig. 5 Hierarchy of classes and instances

Fig. 6 Structure of general class



Class Name	MATERIALS

Properties	Name	Value	If-Needed	If-Changed
	Degree of toxicity		Ask user	
	Degree of harmfulness		Ask user	
	Recyclable		Ask user	
	Renewable		Ask user	
	Product		Ask user	
	Good candidate		Feasibility Rules	

Methods	Name	Body
	Feasibility Rules	Forward (Environmental Feasibility Analysis Rule Set)

because it does not go into action until something happens. The problem solving knowledge can be stated in two ways using methods:

- Procedural knowledge:

  In this way, one can write knowledge of problem in procedures (methods) and use these methods to control properties value. As no rules are used for problem solving, hence a pure frame-based system is achieved.
- Declarative knowledge:

  It is possible to write declarative knowledge of problem in rules and attach a method to the IF-NEEDED or IF-CHANGED facet of a given frame property that loads those rules and performs requested function. This results in a hybrid system.

  Assume, for example, use of this technique to perform the following function: *when a material proposed for a product, a rule set is loaded and determine whether the material is a good candidate or not*.

  To do this function, first we should write a rule set such as “environmental feasibility analysis rules”. Then the following method, written in the syntax of Kappa and attached to the IF-NEEDED facet of good candidate property would accomplish this:

  Backward chain (good_candidate, environmental feasibility analysis rules)

  This method loads the rule set “environmental feasibility analysis rules” that attempt to prove the goal “good_candidate” in a backward chaining fashion.

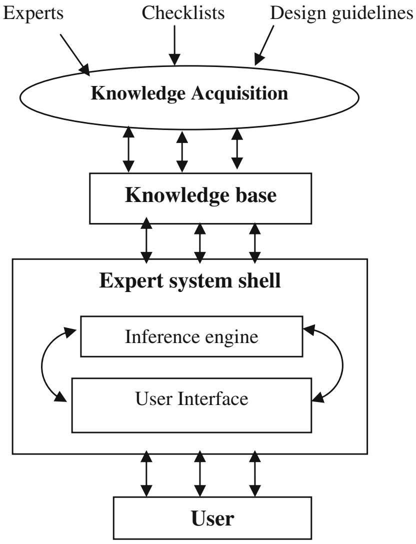
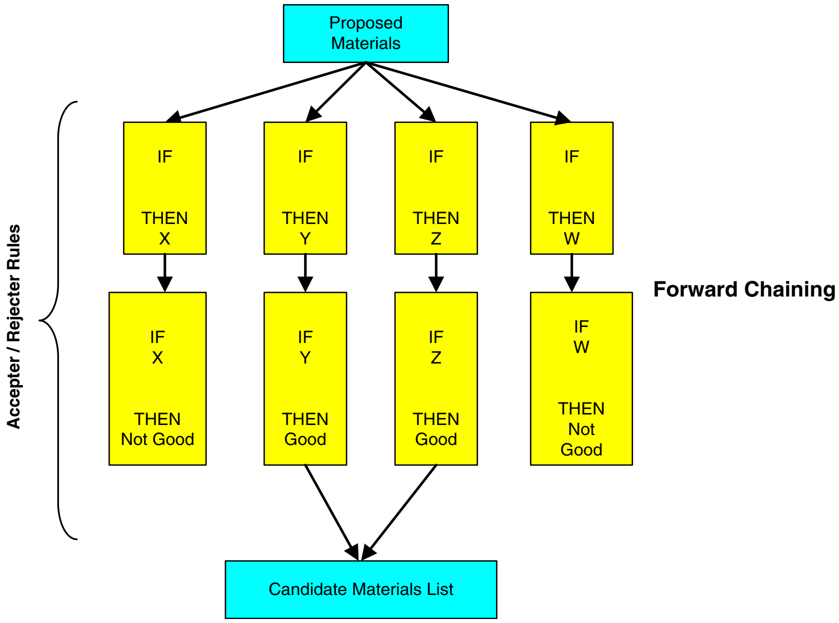


Fig. 7 The structure of the proposed system

II. Message passing approach

Another technique used in some frame-based systems is known as message passing—a standard technique in object oriented systems. This technique allows objects to communicate with each other actively. A message is a signal to an object to which the object responds by executing a *method*. In frame-based systems, when an object receives a message, it checks its list of methods to determine how it should respond. Methods used in message passing can be written to accomplish a variety of functions such as changes to the receiving object’s properties or initiating messages to other objects.

Fig. 8 Inference method for environmental feasibility analysis



3.1.3 Defining the structure of systems (hierarchy of classes and instances)

In the proposed object-oriented system, classes of objects are arranged as a hierarchy of modular objects with top-down inheritance of slots and methods. Each object is an abstraction of a real-world system component and encapsulates or hides its attributes and behavior from the other objects. Abstraction, encapsulation, modularity, and hierarchy constitute the four fundamental features of a truly object-oriented model. Figure 5 shows hierarchy of classes and instances.

3.1.4 Defining the classes and instances

In this research, the second approach, i.e., object-oriented approach is used for representation of the problem solving knowledge. Of course in this approach, facets and methods are used to solve the problem, as well. The rule set that were developed in the previous section are used by attaching method "Feasibility Rules" to IF-NEEDED facet of "Good candidate" property that loads the rule set and performs environmental feasibility analysis. Figure 6 shows the details of general class "MATERIALS". Some properties of objects are listed in this frame as examples.

3.2 Phase 2: design

After the knowledge acquisition and representation, the next task is to select the inference technique and control strategy. A prototype system is built to validate the research and to provide guidance for future work. Figure 7 depicts the general configuration of the proposed system.

The following stages are in the design phase:

(a) Selection of prototype development tool (expert system shell)

There are many expert system shells available. The selection of development tool for KBS must satisfy certain criteria in order to save time and effort in fulfilling its objective. For the present problem, selection must satisfy the following basic conditions:

1. It must support hybrid knowledge representation techniques.
2. It must have varied inference facility.

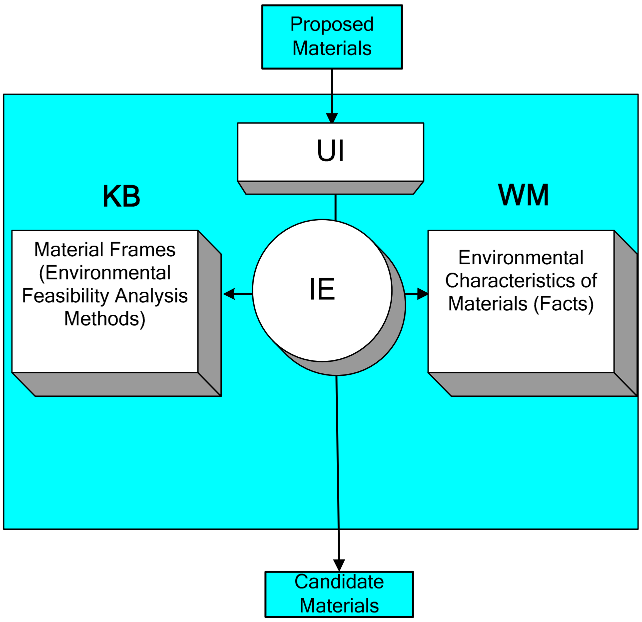


Fig. 9 Main modules of MSESPD

3. It must support good interface facilities with external programs and systems.

Considering the above criteria, Kappa-PC expert system shell [68] was chosen for the present problem. Apart from its powerful object-oriented capabilities, Kappa-PC allows for the representation of knowledge using production rules. It enables the knowledge base to be built by using heuristic knowledge, as well as permitting work with algorithms. It also provides a variety of user options.

Kappa-PC is a hybrid knowledge-based systems environment which incorporates multiple knowledge representation schemes, multiple inference capabilities, options for the choice of search and the ability to incorporate standard procedural coding into one's application. Kappa-PC is an object-oriented expert system shell written in C by IntelliCorp in the USA [68]. It can be used to develop expert systems for any problem involving a selection among a number of choices, for which a set of IF-THEN-ELSE type rules can be defined. The reasoning method or the inference mechanism of the shell consists of both forward chaining (data driven) and backward chaining (goal driven) strategies. Kappa-PC is a general expert system development with a large number of features [69]. Knowledge (or expertise) in rule-based expert systems is basically represented by production rules. In Kappa-PC, the rule-based control structures offer some choices to the user. It allows the user to decide when to apply the forward chaining and backward chaining strategies and even lets the user to specify rule priorities. In Kappa-PC, knowledge is codified in the form of objects, rules, goals, and functions. It provides a wide range of tools for constructing and using applications.

(b) Selection of inference methodology

Inference refers to the process of applying production rules to a particular situation in order to produce conclusions relevant to that situation. In general, there are two basic methods of inference as forward chaining (or data-driven reasoning) and backward chaining (or goal-directed reasoning). Forward chaining method is used in the proposed methodology. Figure 8 shows the inference method for the environmental feasibility analysis.

(c) Prototype expert system development

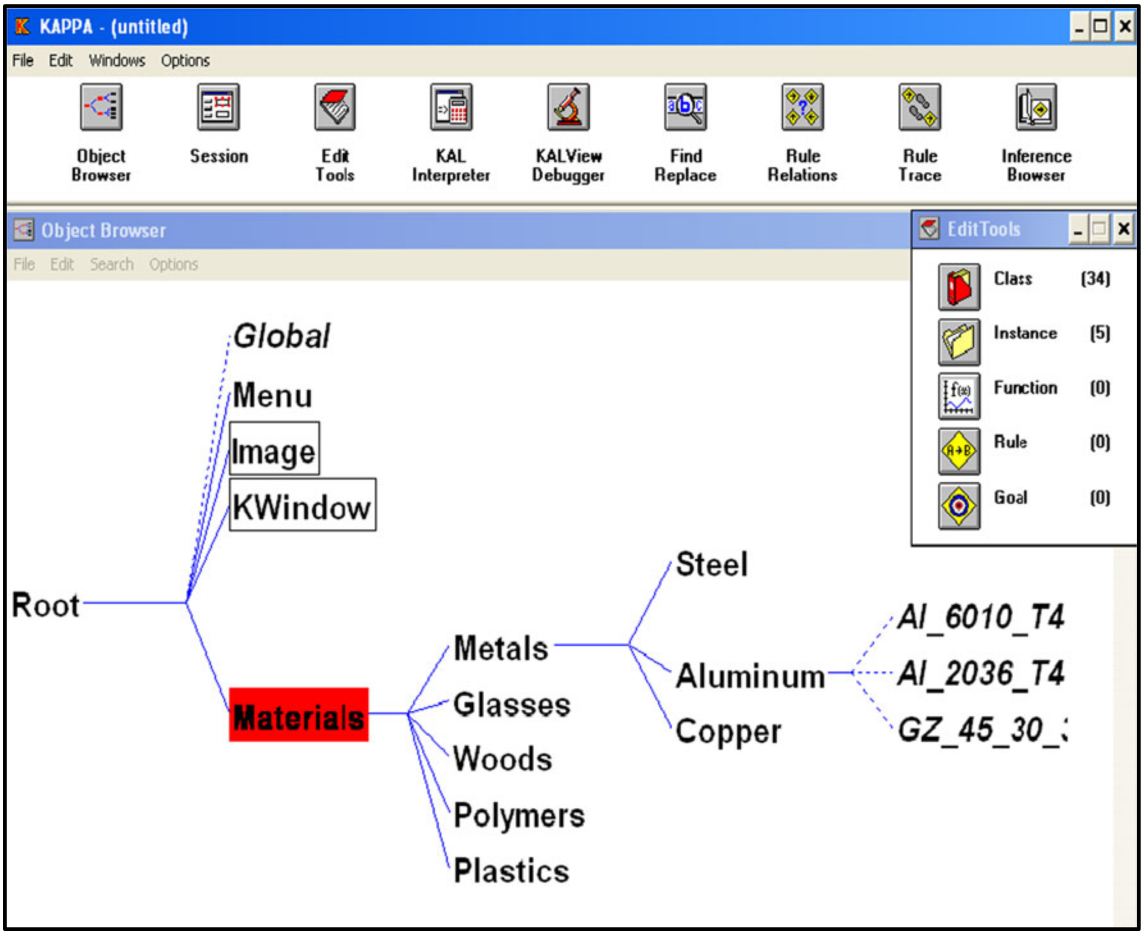
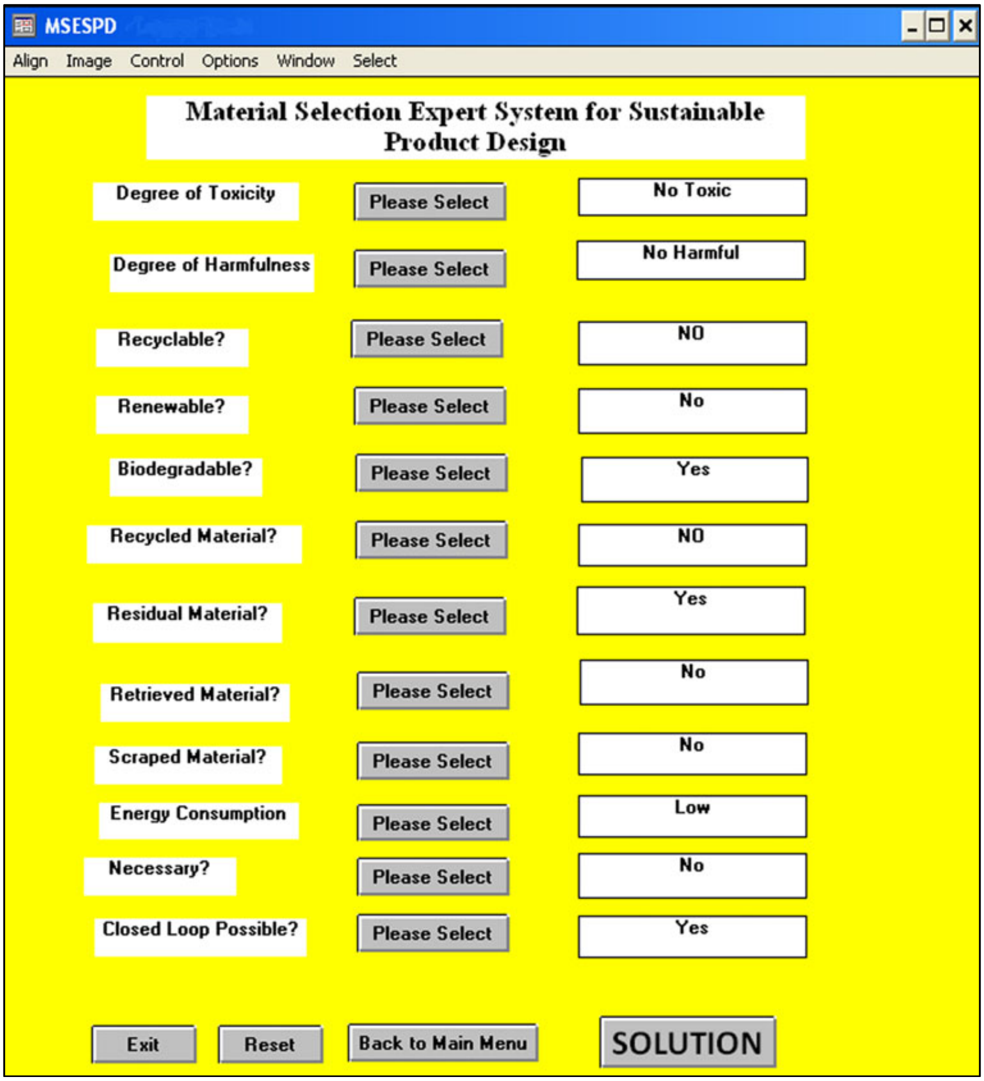


Fig. 10 Structure of MSESPD in Kappa-pc



Material Selection Expert System for Sustainable Product Design

Degree of Toxicity	No Toxic
Degree of Harmfulness	No Harmful
Recyclable?	NO
Renewable?	No
Biodegradable?	Yes
Recycled Material?	NO
Residual Material?	Yes
Retrieved Material?	No
Scraped Material?	No
Energy Consumption	Low
Necessary?	No
Closed Loop Possible?	Yes

Fig. 11 A sample session of MSESPD

The prototype is a model of the final system. Its basic structure, in terms of the way it represents and processes the problem's knowledge, is the same as in the final system.

1. Main modules

   In this section, a prototype expert system called MSESPD is developed based on the proposed methodology. In Fig. 9, main modules of MSESPD and their relationships are shown. Description of each module is as follows:

- User interface (UI): the mechanism by which the user and the expert system can communicate. User enters the list of proposed materials, answers the questions that are asked by system, and finally gets the result through UI.

This Material is a Good Candidate for Applying LCE

Press any key to continue

Fig. 12 The result screen of MSESPD

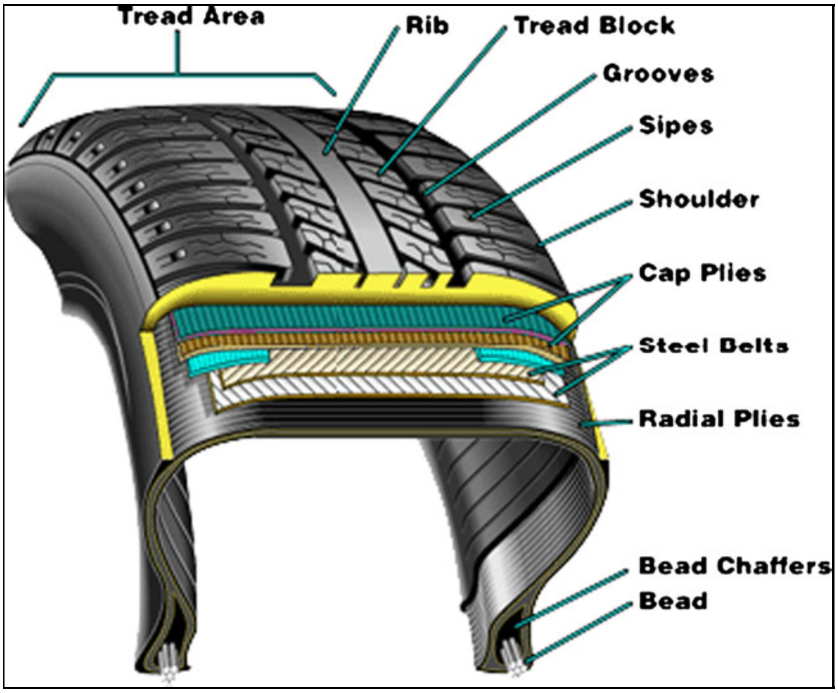


Fig. 13 One typical structure of a passenger tire

- Working memory: contains the problem-specific facts and conclusions which are derived from rules by the inference engine. In MSESPD, facts are information about environmental characteristics of material alternatives.
- Knowledge base: contains domain-specific knowledge in the form of rules and frames necessary to solve the domain problem.
- Inference engine: uses the information in the working memory along with the knowledge in the knowledge base to derive the conclusions. It inference by deciding which rules are satisfied by facts or objects and then prioritizes satisfied rules and executes the rules with the highest priority.

2. Hybrid MSESPD in Kappa-PC

3.2.1 Hierarchy of classes and instances

Figure 10 shows the structure of MSESPD in Kappa-PC environment. System hierarchy is shown in object browser

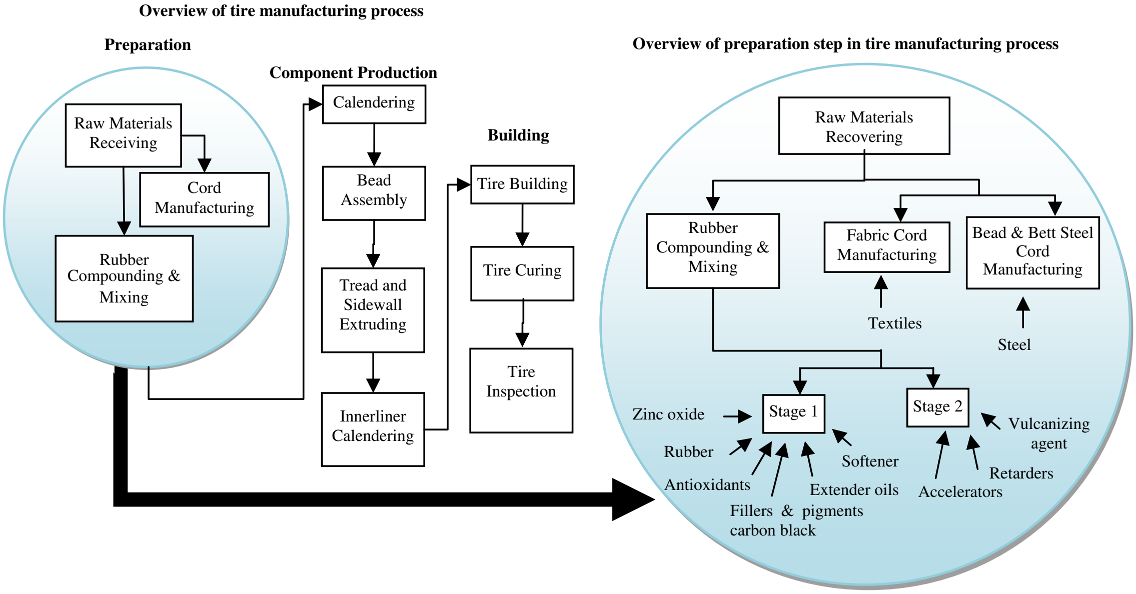


Fig. 14 Overview of the tire manufacturing process [75]

Table 3 List of concerned tire materials [75]

Material family	Specific chemicals and subcategories	
Rubber	Synthetic rubber (BIIR, BR, CIIR, CR, IR, CSM, ECO…)/natural rubber (NR)	
Polyester	Natural polyesters, synthetic polyesters (PET, PBT, PLA, PHBV, PCL, PEA, PBSA, PBAT, …)	
Nylon	Nylon 6/6, nylon 6, nylon 6/10, nylon 6/12, nylon 11, nylon 12, and nylon 6-6/6	
Steel	Carbon steel, LOW alloy steel (D6AC, 300M, 256A), high alloy steels, HSLA, Stainless steel,…	
Carbon black	Carbon black, furnace black, (single CB types were not considered)	
Antioxidants	Heterocyclic compounds	TMQ (2,2,4-Trimethyl-1,2-dihydroquinoline)
		TMDQ (Trimethyl-1,2-dihydroquinoline)
	Phenylene-diamine derivatives	IPPD (N-Isopropyl-N′-phenyl-p-phenylendiamine)
		6PPD (N-1,3-dimethyl-butyl)-N′-phenyl-p-(phenylenediamine)
		DTPD (N,N′-Ditolyl-p-phenylenediamine)
		DPPD (N,N′-Diphenyl-p-phenylenediamine)
		77PD (N,N′-Bis(1,4-dimethylpentyl)p-phenylendiamine)
		ADPA (Acetone-diphenylamine condensation product)
	Phenolic stabilizers	BPH (2,2-Methylene-bis-(4-methyl-6-tert-butylphenol))
		BHT (2,6-Di-tert-butyl-4-methylphenol)
Resorcinol	Resorcinol	
Formaldehyde	Formaldehyde	
Oils	Aromatic oil	
	MES (special purified aromatic oil)	
	Naphthenic oil	
	TDAE (special purified aromatic oil)	
	Paraffinic oils	
ZnO	ZnO	
Accelerators or vulcanizing agents	Sulphenamides	DCBS (N,N-Dicyclohexyl-2-benzothiazolesulfenamide)
		TBBS (N-tert-Butyl-2-benzothiazolesulfenamide)
		CBS (N-Cyclohexyl-2-benzothiazolesulfenamide)
		MBS ((2-morpholinothio)benzothiazole)
	Guanidine derivatives	DPG (N,N′-Diphenylguanidine)
		DOTG (Di-ortho-tolyl-guanidine)
	Thiazoles	MBT (2-Mercaptobenzthiazole)
		MBTS (2,2′-Dithiobis(benzothiazole))
	Dithiophosphates	SDT (Di-(2-ethyl)hexylphosphorylpolysulfide)
	Thiurams	MPTD (Dimethyldiphenylthiuram disulfide)
		TBTD (tetrabutylthiuram disulfide)
		TMTD (Tetramethylthiuram disulfide)
		TMTM (tetramethylthiuram monosulfide)
		TBZTD (Tetrabenzylthiuram disulfide)
	Dithiocarbamates	ZDMC (Zn-dimethyldithiocarbamate)
		ZDEC (Zn-diethyldithiocarbamate)
		ZDBC (Zn-dibutyldithiocarbamate)
		ZBEC (Zn-Dibenzyldithiocarbamate)
	Thioureas	ETU (Ethylene thiourea)
		DETU (Diethylthiourea)
	Sulfur donors	DTDM (Dithiomorpholine)
		DPTT (Dipentamethylene thiuram tetrasulfide)
		CLD (Caprolactam disulfide)
		MBSS (2-Morpholinodithiobenzothiazole)
		OTOS (N-Oxydiethylenedithiocarbamyl-N′-oxydiethylenesulfenamide)

Table 4 Harmfulness of tire materials with respect to regulatory concerns [75]

Harmfulness	Primary tire materials
High	DOTG, MBT, TMTD, ZDMC, MBSS, IPPD, resorcinol, formaldehyde,
Moderate to high	MBS, DPG, ZDEC, BDC, DTDM, OTOS, TMQ, DPPD
Moderate	DCBS, CBS, TMTM, MBTS, ZBEC, DETU, HMT, BPH, BHT, 6PPD, 77PD, ZnO, Carbon Black
Low	TBBS, MPTD, TBTD, TBZTD, ADPA, DTPD

window. This is the graphical representation of object hierarchy within knowledge base i.e. classes, subclasses and instances. One class (*MATERIALS*) and five subclasses (*metals*, *glasses*, *woods*, *polymers*, *plastics*) are added in the structure of the system. As an example, class "*Metals*" has three subclasses: *steel*, *aluminum*, and *copper*. Class *aluminum* has three instances: *Al 6010T4*, *Al 2036T4*, and *GZ4530*.

3.2.2 Defining classes and instances

In frame-based systems, for description of the objects, some slots should be created. As a rule, at the higher levels of the hierarchy, the slots should be more general. At the bottom of the hierarchy, we arrive at instances of classes. Slots shared by all instances in a given class, should be defined for the class including those instances. All instances of one class automatically inherit that class slots.

3.3 Phase 3: testing and validation

The developed expert system is tested and evaluated to ensure the software performance is converging towards established goals. The evaluation process is more concerned with system validation and user acceptance. Validation efforts determine if the system performs the intended task satisfactorily. User acceptance efforts are concerned with issues impacting how well the system addresses the needs of the user. There are three tests that are involved in the development of the expert system.

(a) Preliminary Testing

Immediately following the development of the prototype system, an informal test of the system is conducted. This test is to evaluate the complete knowledge base. The test applies all possible combinations of answers to the questions asked by the system. System-derived solutions are verified for each set of answers. The test provides the early verification of the system. This approach not only makes it easier to test the entire system, but also permits the author to continue to perform a complete test later in the projects as the knowledge base grows. Figure 11 shows a typical data input form. Figure 12 shows the result screen.

(b) Informal validation testing—a case study

The system was tested against real problems from its domain. The objectives are to determine the effectiveness of the system in selecting sustainable materials to uncover system deficiencies by using the off-line method. Past cases were used for testing. In this section, a case study related to manufacturing of tires is presented for informal validation and testing of MSESPD. Expert systems are finding an increasing number of applications in the manufacturing environment. They may be applied to almost any manufacturing area, including design, machine breakdown diagnosis, system configuration, vision, interpretation of data, and control to name a few. Although development of expert systems in manufacturing has a long history [70–73], in the field of tire manufacturing that is not the case. The work by Abou-Ali and Khamis [74] is the only one in this area. They present an integrated tire defects diagnostic expert system (TIREDDX) that can be applied during production and service.

Table 5 Eco-properties of natural rubber [76]

Stage	Eco-properties	Range	Unit
Material	Annual word production	7.7×10^6–7.8×10^6	Ton/year
	Embodied energy, primary production	62–70	MJ/kg
	CO_2 footprint, primary production	1.5–1.6	Kg/kg
	Water usage	1,500–2,000	l/kg
	Eco-indicator	340–380	Millipoints/kg
Processing	Polymer molding energy	7.13–8.08	MJ/kg
	Polymer molding CO_2	0.57–0.646	Kg/kg
Recycling	Recycle fraction in current supply	0.1	%

Table 6 Material alternatives for tire and the result of MSESPD

Code	Rubber	Polyester	Steel	Antioxidants	Vulcanizing agents	Good candidate
1	BIIR	PET	D6AC	IPPD	MPTD	No
2	IR	PET	D6AC	IPPD	MPTD	No
3	NR	PLA	D6AC	IPPD	MPTD	No
4	CIIR	PET	300M	6PPD	TBTD	No
5	NR	PLA	300M	DTPD	TBTD	Yes
6	IR	PET	300M	6PPD	TBTD	No
7	BR	PBSA	256A	DTPD	TMTD	No
8	NR	PET	256A	DTPD	TMTD	No
9	NBR	PHBV	256A	DTPD	TMTD	No
10	CR	PET	Carbon steel	DPPD	TMTD	No
11	IR	PCL	Carbon steel	DTPD	MPTD	Yes
12	NR	PHBV	Carbon steel	DPPD	TMTM	No
13	IR	PCL	HSLA	77PD	TMTM	No
14	NBR	PLA	HSLA	77PD	TMTM	No
15	CSM	PEA	HSLA	77PD	TBZTD	No
16	IR	PHBV	Stainless	DTPD	TBZTD	Yes
17	ECO	PBT	Stainless	ADPA	TBZTD	No
18	IR	PCL	Stainless	6PPD	TBZTD	No
19	NR	PLA	High alloy	ADPA	TBZTD	Yes
20	NBR	PET	High alloy	ADPA	TBZTD	No

The case study of this research focuses on passenger tire. A typical passenger tire contains 30 types of synthetic rubber, eight types of natural rubber, eight types of carbon black, steel cord, polyester, nylon, steel bead wire, and silica, and 40 different kinds of chemicals, waxes, oils, and pigments. Modern tires consist of five primary components: tread, side-wall, steel belts, body plies, and the bead. As such, tires are manufactured from many different materials including natural and synthetic rubber, textiles, and steel. The structure of a typical passenger car tire is shown in Fig. 13. The tire production process consists of three primary steps: preparation of the component materials, production of the components, and building of the tire. Figure 14 provides a simplified description of the process.

Depending on the specific function and performance of a tire, different rubber formulations based on different polymers, fillers, and low molecular weight ingredients are necessary for the various tire components. However, according to the Tire Industry Project Group (TIPG) program, the materials listed in Table 3 are common to all companies and are critical materials to the industry [75]. It can be seen that there are many material alternatives for some parts of a tire. Besides, tire industry leaders recognize that there are both opportunities and challenges associated with tire manufacturing on the one hand and sustainable development on the other. So, environmental friendliness of tire materials is a very important issue in material selection for tire design. The problem is to create a list of good tire material alternatives from environmental viewpoint from a long list of alternatives. So there is a need for an environmental profile of tire material alternatives. According to the TIPG program, the concerned tire materials were prioritized by assigning them into priority groups (high, moderate to high, moderate and low harmful) by the number of positive responses for regulatory concerns. A list of the primary tire materials with degree of their harmfulness is provided in Table 4. Also an eco-properties profile that provides data about production, recyclability, and energy consumption can be very helpful. Table 5 shows eco-properties of natural rubber as an example [76].

The use of rubber is widespread, ranging from household to industrial products, entering the production stream at the intermediate stage or as final products. Tires and tubes are the largest consumers of rubber. Synthetic rubber serves as a substitute for natural rubber in many cases, especially when improved material properties are required. Natural polyesters and a few synthetic ones are biodegradable, but most synthetic polyesters are not. PLA, PHBV, PCL, PEA, PBSA, and PBAT are the main synthetic biodegradable polyesters. Industrial polyester fibers, yarns, and ropes are used in tire reinforcements. Table 6 shows 20 material alternatives for tire and the result of MSESPD. Alternatives have been formed based on five materials included in a typical passenger tire, i.e., polyester, rubber, steel, antioxidant, and vulcanizing agent. Polyester, rubber, and steel are direct material of tire and antioxidant and vulcanizing agent are indirect materials. During the tire-making process, indirect materials are generally consumed during the curing process, so that little if any of these materials are found in the finished product. Using indirect materials to form alternatives means that manufacturing sustainability issues are considered in our analysis. In fact, MSESPD can support material selection for environmentally conscious manufacturing.

The decision making process is as follows. Each of five materials in an alternative is used as an input to MSESPD and the system checks whether the material is a good candidate for LCE analysis or not. It is necessary that all five components of an alternative pass the test that an alternative is considered as a good candidate. Using this decision making process, four alternatives—5, 11, 16, 19—are accepted as good candidates. These are alternatives which qualify required characteristics, hence it is reasonable to perform complex LCE computations for them. For example alternative 5 is made of natural rubber, biodegradable polyester, and low harmful antioxidant and vulcanizing agents in manufacturing phase. After applying LCE computations on these four selected materials, the best candidate is chosen for manufacturing of the tire.

Application of the proposed methodology includes all of material selection decisions where sustainability considerations are important. Also, because one can incorporate process material as alternatives, the system can be helpful in material selection for environmental conscious manufacturing. Specially, the methodology can be time and cost saving when the selected approach for sustainable design and manufacturing includes life cycle assessment of material alternatives. Since sustainable design and manufacturing is a dominant paradigm in recent years and it is expected that its dominance continue and grow in future, so the proposed methodology could have increasing application in production and manufacturing environments such as automotive, construction, home appliance, furniture, etc.

(c) Field testing

The developed system is deployed into the work environment and exposed real world problems. The objective of the test is to determine if the system meets its original goals. This test also determines the validation of the system and assesses the user's acceptance. In this research, no field testing is conducted due to this fact that developed system is a prototype. As a future work, it is our hope to develop the complete system and conduct filed testing for it.

3.4 Phase 4: documentation

The documentation serves as the diary of the project. It contains all the material collected during the project and used as reference. The information that needs to be retained and recorded in the documentation serves three purposes: reference for developing expert system, reference for writing the final report, and reference for maintaining the expert system.

3.5 Phase 5: maintenance

The final phase of this research project is the system maintenance. Maintenance is required since most expert systems contain knowledge that is evolving overtime. The company may develop new products or change its strategies for sustainability. This changing state requires appropriate modifications to the system. Due to security purposes, it is important that only designated individuals are allowed for maintaining the system.

4 Conclusion

The selection of suitable materials for development of sustainable products is a complex process that requires a deep knowledge and experience about materials. In this paper, knowledge-based methodology is proposed to support preliminary filtering of alternatives through an environmental feasibility analysis. Eliminating alternatives that do not have the necessary conditions for sustainable product leads to a large saving in time and cost of the LCE evaluation process. This paper has shown that knowledge-based methodology and expert system technology can provide a good opportunity for a preliminary filtering of alternatives from environmental viewpoint. Also, the paper shows that the material selection knowledge has the potential to be encoded with IF-THEN rules and expert systems. In comparison to the previous related researches which most of them need a great amount of computation and data as input, our methodology is a very efficient and economical solution. In fact, the proposed methodology does not serve as an alternative for other methods; but it is a complement for them and provides a list of good candidates for methods proposed in those researches. The proposed methodology finally is implemented for a real-world past case in tire industries. After implementation of the methodology for the case, from a list of 20 alternatives, only four items are accepted for applying LCE approach which results in 80% saving. Also, past experiences of the case and previous insights verify these results.

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