Materials and Design 41 (2012) 433–446

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

A framework for concurrent material and process selection during conceptual product design stages

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ARTICLE INFO

Article history:
Received 15 September 2011
Accepted 9 May 2012
Available online 23 May 2012

Keywords:
H. Value analysis
H. Selection of materials
H. Selection of material processes

ABSTRACT

The main aim of this research work is to draw up a framework proposal for integrated materials and process selection in product design. Following an in-depth review of existing studies and the factors that influence decision-making, the flow of reasoning in the process is defined and the relations among the parameters of the whole life cycle to be considered in the conceptual design phase are established. This analysis is then used to define a workflow that breaks the work down into stages and gates, and specifies how the preliminary selection is to be performed.

1. Introduction

Product design necessarily involves accomplishing the goals that stem from the analysis of an idea that arises after detecting or creating needs in the consumer. The feasibility of the design is the result of evaluating the technology and the current status of the issue. The voice of the customer is used as the basis to define the design characteristics and the product is detailed as a series of functionalities.

From the point of view of the materialisation of the product, both manufacturers and engineers are constantly searching for new materials and manufacturing processes that allow them to maintain a competitive advantage and maximise their profit margin. The process of selecting appropriate materials requires a solid definition of the specifications of the whole, the components and the relation of compatibility between them.

Yet, the path from abstraction to concretion or from creativity to focalisation is not independent of the procedure or process adopted, which is what will make it possible to obtain more or less optimised solutions. This is due to the fact that the number of materials and new manufacturing processes is constantly on the rise, thereby making it more difficult to detect an innovation and apply it.

Hence, there is a need for a strategy to translate a new idea into detailed information that can be applied in manufacturing and which transforms requirements and specifications into material-manufacturing process alternatives, as in a transfer function. This strategy leads to models for developing new products that can be descriptive, prescriptive or managerial and which fit different solutions. For example, design methodologies for manufacturing and assembly reduce the total number of parts, thereby improving the costs, reliability and quality of the final product, since it has fewer components. This therefore makes them better suited to product optimisation or innovation.

Further still, materials and process selection requires an interdisciplinary effort, duly documented information and tacit knowledge, which is not easily made explicit. Support methods are therefore needed. It is for this reason that, in many cases, they are often selected by means of ‘‘trial and error’’, the most widely used argument being that they were used in the past and lived up to expectations.

Other procedures that can be a source of knowledge for coming up with and selecting ideas are suppliers' design guidelines, sectorial studies or the knowledge acquired through quality systems and customer services. Many components are manufactured by external suppliers and exclusive rights to knowledge are therefore disappearing because suppliers or competitors can easily reuse them.

In the case of product design, it can be said that the whole is always greater than the sum of its parts and products will have functionalities, characteristics and a value that are higher than those of their components. Nonetheless, appropriate manufacturing with the correct material for each component is critical if these premises are to be fulfilled.

In order to define a model for materials and process selection it is necessary to abstract oneself to the point where the whole life cycle of a product can be visualised, thereby allowing all of the implications in the selection of materials to be taken into account (Fig. 1).

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http://dx.doi.org/10.1016/j.matdes.2012.05.016

The selection of materials, geometry and manufacturing processes is not independent from the product development model that is adopted. A broader view will lead us to observe the life cycle of the product as a whole. It is essential to establish differentiated stages, since this facilitates management and the improvement processes as a cyclical activity, that is, each new product provides the basis for some future development.

This work comprises the following parts: analysis of the current status of the issue, the framework proposal and the selection strategy for the conceptual design phase.

2. Related work

2.1. Integrated materials and process selection

Product design and development necessarily entail the task of gathering knowledge, which is essentially a description that tells us how things are related to experience. This description needs to be reflected by means of a model that is in fact a simplified representation of a phenomenon. A set of models together offer a holistic view for a larger system of phenomena that is called its "*theory*". From a theory and a set of predefined rules we obtain a methodology.

Researchers, on the one hand, attempt to describe what things are like (descriptive research) and, on the other, they work on ways to alter things, which is known as normative research. When the latter involves *improving* the object and includes practical operations that are part of the life cycle of a product, then we are talking about development projects.

If we take into account the degree of universality, then a distinction can be drawn between intensive studies (specific cases represented by means of ideographic knowledge) or extensive ones (knowledge that is common to all or most of a class of products). Furthermore, a scenario of limited resources and a sustainable economy allows for the concept of ecological development of products and their production.

The development of new products is affected by the surrounding environment and pressure from the market and this will determine the degree of success, recognition and competitive advantage obtained by those products. Moreover, incompatibility between materials and manufacturing processes can affect decisions regarding the geometry. With this scenario the designer establishes the geometry, the materials specialist searches for functionalities and limit values, and the person responsible for production ensures producibility.

The earliest work carried out in this field dates back to the early 1970s with Arimoto's evaluation of producibility (*Producibility Evaluation Method*, PEM), which focused only on modelling and evaluating machining processes and operations [1].

Later, Jacobsen addressed design by always taking the function of the component as the starting point [2]. Then Alting defended the selection of the manufacturing process by means of process/material incompatibility matrices [3].

Boothroyd and Dewhurst also developed the design for manufacture and assembly (DFMA) methodology, which focuses on eliminating inefficiency in design, simplifying the structure, cutting costs and quantifying improvements [4]. On the other hand, Swift and Booker [5] proposed a methodology based on costs, by means of models of manufacturing processes called PRIMA (Process Information Maps).

Ashby [6] was the first to develop a methodology focused exclusively on materials selection aided by screening based on limit values ("Screening") and property indices to establish comparisons by maximising or minimising ("Ranking"). At present, the CES (Cambridge Engineering Selector) system also takes into account the geometries for parts, manufacturing processes and selection functions with Eco-audit criteria.

In 2003 the Brinell Centre in Stockholm developed MATOP. This involves integrated materials selection, by mathematical optimisation, with the aid of algorithms of the behaviour in terms of functionalities and use [7].

Arizona State University developed a tool for analysing producibility, with a database, knowledge management of the material, manufacturing resources, processes and design components. The database interacts with two different user interfaces for design and engineering [8].

In nearly all the studies carried out on integrated materials and process selection, there are both generic methods and methods that are dedicated to particular products in very specific sectors. The generic methods contain indications about the steps to be taken and help to achieve a global framework by translating ideas into industrial design products and establishing the design phases and the stages of selection in parallel [9]. In these generic methods we find two phases: screening and ranking. The screening methods make it possible to discard certain elements in accordance with a set of specific rules, whereas ranking methods evaluate the different solutions by means of parameterised functions or algorithms and rank them in terms of the degree of compliance.

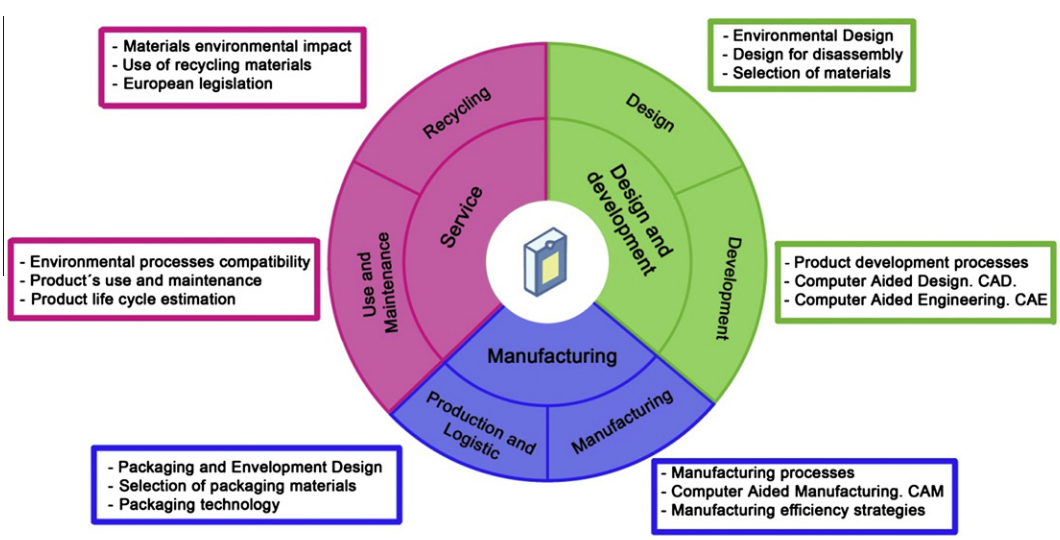

Fig. 1. Proposed framework for product life cycle.

We can also find, on the one hand, tools for selecting materials with samples of products [10] that include aspects of user-process interaction and help to specify requirements that are difficult to quantify, such as sensory properties. On the other hand, catalogue-based methods allow the user to see the personality of designs, forms and combination of materials. Attributes that are difficult to convert into numeric values need to be compared with others to be able to make the selection.

In questionnaire-based methods, functional requirements are classified in two categories: rigid (complies or does not comply) and soft (or relative). Edwards proposed a structured questionnaire consisting of checklists in order to improve the probability of optimum design by exploring the design both before and during the process of materials selection [11–14]. Pedgley, on the other hand [15], gathered real needs from the interaction of automated questionnaires and transferred them to process selection.

As regards selection systems, most of them are implemented through search engines that interact with databases. One of the best-known is the CES (Granta Design), which allows a methodological material selection from multiple objectives. Sectorial databases such as CAMPUS (Plastics Computer Aided Material Preselection by Uniform Standards), the global network for professionals in materials, minerals and mining, the International American Society of Materials – ASM – or the National Resource Center for Materials Technology USA offer advantages when the manufacturing process is known.

The University of Arizona has developed a platform of databases for knowledge about materials, manufacturing resources, processes and design components that interacts with two different user interfaces for design and engineering.

The latest trends are aimed towards methods based on artificial intelligence that are capable of processing the large number of materials that are generated each day using intelligent agents that can perceive their surroundings, process them and give a response by maximising or minimising the result of a specific function, geometry, material and process. These systems are capable of solving problems that require knowledge and reasoning thanks to the information from one or more experts in a specific area, together with predefined rules that constitute this knowledge base [15–17].

There are essentially three main types: those based on previously established rules, those based on cases – or CBR (Case Based Reasoning) – and those based on networks. The rule-based expert systems are not limited to just the screening task but also participate in the ranking process, in interpreting results and in proposing solutions [18]. Case-based expert systems address new problems by using information from solutions to previous problems, which is an application of analogies [19]. An example of networks is to be found in the use of neural networks, which imitate biological systems through mathematical models.

Multi-criteria decision-making methodologies are an attempt to take into consideration all the parameters that affect materials and process selection. They highlight conflicts that appear when trying to optimise them all at the same time and allow a compromise to be reached. For example, Chau and Parkan [20] used the RMS (Response Surface Methodology) method to analyse direct costs in the attributes and proposed a systematic approach to the process of selection by means of neural networks.

Jee and Kang [21] used the concept of entropy to evaluate the weighting of each property of the material and the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) technique to classify materials by means of multi-criteria evaluation. Shanian and Savadogo compared the results of TOPSIS and VIKOR MCDM (Vikor Multi-Criteria Decision-Making) so that "Outranking" relations could later be used in materials selection by means of ELECTRE IV [22].

Chan and Tong used grey analysis for materials selection. Situations for which there is no information are defined as black while full information is white; intermediate situations between these two extremes are described as grey, cloudy or fuzzy [23]. Edwards and Deng proposed materials selection through a combination that takes into account the multiplicity of optimal indicators [14]. Manshadi developed a numerical method focused on the weighting of two factors, namely, non-linear normalisation and digital logic [24]. Khabbaz developed a simplified fuzzy logic approach with Manshadi's method [25]. Fayazbakhsh used the Z-transformation for the statistical normalisation of the properties of materials. The same author compared the Z-transformation with the MDL (minimum description length) method of normalisation and concluded that the Z-transformation yielded better results [26]. Finally, Chuu developed a decision support method based on fuzzy logic (FMS – fuzzy multiple attribute decision-making selector method) for selecting the manufacturing process on the basis of multiple attributes [27].

Important examples of studies focused on the multi-criteria application include Rao and Parnichkun [28], who used combinatory mathematics to evaluate alternatives in flexible manufacturing systems and proposed a multi-attribute method (MADM) that uses subjective preferences for materials selection [29]. Gyurova et al. [17] used the OBS (optimal brain surgeon) method to streamline the neural networks method and eliminate unnecessary nodes. Maniya and Bhatt [30] used the preference selection index (PSI) method, the Graph Theory and Matrix Approach (GTMA) and TOPSIS. Cicek and Celik used the fuzzy logic axiomatic model (Generic Framework of the Fuzzy Axiomatic Design-Model Selection Interface, FAD-MSI). Sapuan and Mujtaba [18] analysed the uses of neural networks in Composites. Tuzkaya [31] used Analytical Network Process (ANP) and PROMETHEE to perform the selection.

Examples of methods with a clearly defined design objective include Johnson and Kirchain, who focused on cost methods for materials selection [32], or Zhou [33], who took into account the environmental factors in the life cycle by means of neural networks (ANN) and genetic algorithms (GAs) for the multi-objective optimisation of materials selection.

There are also studies that review developments in the field and help us to gain an overall vision of the current status of the issue. These include the work of Jahan [34] or Chatterjee [35], who compares the new decision support methods VIKOR MCDM, ELECTRE, COPRAS (complex proportional assessment method) and EVAMIX (evaluation of mixed data method).

As we have seen, the need to define methods that bring us closer to correct decision-making when it comes to materials and process selection has given rise to a vast amount of research in this field. This has allowed new lines of work to be opened up, since the level of complexity of products and their components requires rigorous management in all aspects of the life cycle, and materials have the greatest specific weight.

Accordingly, and to be able to make a proposal after analysing the work carried out to date, we need a framework with a general vision that allows us to define a method with appropriate tools to match each phase of the life cycle, with special attention being given to the conceptual design. The following table (Table 1) summarises the current status of the issue in the literature and the contribution made by each work from different aspects.

2.2. Discussion

As we have stated above, since the early twentieth century many works have been carried out with the aim of further developing the proper selection of materials [3,9]. However, it is not until the second half that these jobs are focused on the integrated selection of materials and processes to meet the design requirements

Table 1
Literature review.

Proposal	Description	Contribution
1978 Alting & Haudrum	Methodology	Process/material incompatibility matrices used as a starting point to develop the geometry and the selection of materials
	Morphological model of process design	
1989 Jacobsen	Methodology for design	Establishes six different ways of addressing the design, always taking the function of the component as the starting point
	Interrelation of geometry, material & manufacturing process	
1989 Materials Matter	Databases of the UK Department of Trade and Industry programme	Different selection solutions in a variety of sectors
1992 Ashby	CES	
1992 Boothroyd & Dewhurst	Software interfaces. Design methodologies for manufacturing, facilitating the manufacture of parts and design for making assembly easier	Design model. Guidelines for orienting design in concurrent engineering in order to simplify the structure of the product, reduce manufacturing and assembly costs, and quantify improvements
1996 Chalmers University of Technology	Software interfaces and consultancy system based on databases – Life Cycle Assessment, Life Cycle Inventory	Software tools for drawing up reports and offering advice on the life cycle of products
1997 Swift & Booker	Methodology for design. Methodology for cost-based process selection	Analogy by graphs and correlation coefficients
1997 Fuzzymat Bassetti FuzzyCast FuzzyGlass	Free search in multi-criteria manufacturing processes and materials databases using a fuzzy logic algorithm	Screening phase using preset values within limits Genetic and fuzzy logic algorithms
1998 Astek expert Lae	Analogy based on reasoned cases. Selection of optimal methods of joining based on existing solutions	Approach by means of a decision tree
1999 Sandwich selector Lemoine	Free search. Optimisation of materials selection and suitable dimensions for structural sandwiches	Genetic algorithm and mechanical modes of selection for creating possible solutions
2000 CAMD Landru	Free search and questionnaire. Expert system for developing the set of requirements by means of coupled equations and value analysis	Screening phase using a recursive algorithm
2000 MAPS Landru	Free search. Identification of possible applications of a material based on its properties/in-service behavioural profile	Screening
2001 R. Amen, P. Vomacka	IVF – Swedish Institute of Production Engineering Research	System of materials selection by means of case-based reasoning
2002 Failure expert Bouget	Analogy. Guidelines for analysing faults and possible solutions from a database of typical cases	Reasoned practical cases
2002 Fuzzy extrude Heiberg	Questionnaire. Optimisation of the selection of extruded aluminium alloys, including extrusion and the form through an expert system	Screening phase using preset values in a questionnaire
2003 MATOPBrinell Centre, Stockholm	Development of tools for the integrated optimisation of materials Software interfaces	Mathematical optimisation by means of algorithms of the behaviour of the materials in terms of selection and use
2005 ASU-DFM framework development procedure	Layer-independent domain for DFM and its application to die-stamping and injection moulding (Material and process based on CAD geometry)Interface between designer and knowledge engineering	Databases and management of knowledge about material, manufacturing resources, processes and design components This database interacts with two different user interfaces for design and engineering
2006 Zha et al.	Models of product families	Generation, evaluation and personalisation of product families
2006 – 2009 Shanian et al.	Expert systems based on "Outranking" relations	Materials selection by means of ELECTRE IV and comparison with TOPSIS and VIKOR MCDM
2007 Chan & Tong	Grey and fuzzy logic analyses	Provides selection techniques that fit the real situation
2007 Edwards & Deng	Selection of materials in combination	Contributes to optimal indicators in configuration and structural components
2009 Pedgley	Process selection by means of questionnaires	Automated questionnaires
2009 Fayazbakhsh et al.	Z-transformation for the statistical normalisation of the properties of materials	Compares the Z-transformation with the MDL (minimum description length) normalisation method
2009 Chatterjee et al.	Multi-criteria methods	Compares VIKOR, ELECTRE and reviews the current state of the issue
2009 Chuu	Decision support method by use of fuzzy logic (FMS), the "fuzzy multiple-attribute decision-making selector method"	Selects the manufacturing process on the basis of multiple attributes
2009 Zhou et al.	Uses environmental factors in the life cycle by means of neural networks (ANN) and genetic algorithms (GAs)	Multi-objective materials selection
2009 Rao & Parnichkun	Evaluation of alternatives in flexible manufacturing systems	Multi-attribute method (MADM) that uses subjective preferences for materials selection
2010 Gyurova et al.	OBS (optimal brain surgeon) method	Streamlines neural networks and eliminates unnecessary nodes
2010 Maniya & Bhatt	Preference selection index (PSI) method	Selection by means of GTMA and TOPSIS
2010 Tuzkaya et al.	Selection by analytical network process	Uses ANP and PROMETHEE
2011 Chatterjee et al.	Decision support methods	Compares COPRAS and EVAMIX

[1–5,36,37]. We can find them in the scientific literature and in the software tools that aid in the selection of materials [6,7,38,39].

Each product design project is best suited to a particular methodology. Among these methodologies the best known are the integrated design methodology [40], axiomatic theory [41], projects resolution and innovation tools such as TRIZ, among others [42]. Each one allows the user to set the appropriate paths to approve alternative construction stages and milestones in design and budget.

In any case, the selection of materials and processes may affect decisions made in all subsequent activities in the process of designing and developing new products. On the one hand, it is necessary to capture the voice of the customer: their needs, specifications, aesthetic preferences and constraints, which lead to requirements and functionality [10,38]. On the other, the conceptual design focuses it in order to optimise the outcome by identifying everything that is critical to quality and user satisfaction [43].

Finally, manufacturing technologies provide novel processes and new materials that expand the possibilities for creating and redesigning products, thereby changing the economic and technical viability [11,12,44]. This activity is critical in the selection of the set of properties, qualities and relevant correlations required to maximise or minimise materials properties and ensure they correspond to manufacturing specifications through an iterative process that restricts the possible solutions [6,45].

The results from the historical review and a methodological study and analysis of the works carried out by different researchers (all leaders in the selection of materials and manufacturing processes) allowed us to identify and provide inputs for new opportunities. Thus, we understood that there is a need to rely on a systematic procedure to capture the design requirements that affect the material when the design is in a phase with a lack of detail or specificity. Therefore, our goal is to propose a framework that considers all aspects of the product life cycle and to determine the material and the most appropriate manufacturing process so as to complement the methodologies developed to date, while also combining the use of various tools to optimise the decision.

3. Integrated material and processes selection framework

In its most creative phase, the design process offers a wide range of possibilities. For this reason development teams encounter many sources of fuzzy knowledge that is difficult to collect and interrelate. Moreover, the first critical factor in planning a project is the difficulty involved in setting up multidisciplinary teams and often the geographical separation between expert members in specific fields. These issues make the work inefficient. To optimise resources and focus planning, a good breakdown of the concept is crucial.

Once the concept has been defined and delimited, we can determine whether, in some way or another, the product exceeds the capabilities of the organisation. In those cases, to be able to undertake it, it will be necessary to arrange alliances or set up other temporary virtual organisations.

In the development of products that requires collaboration among different organisations, life cycle and knowledge must be managed in such a way as to produce "win–win" relations that have repercussions on the competitive advantage of all the collaborators. Consequently, management of the life cycle of the product implies structured decision-making in design (Fig. 2).

Decision-making covers different areas and adapts to the life cycle model that is adopted. In the framework proposal, a process of reflection is used to conclude the relation between these areas of selection and obtain competitive advantage. Decisions could be generally classified as technical, economic and strategic.

Technical decisions are the backbone of engineering processes and, therefore, design. For this to be possible, organisations must have facilitating elements, such as an efficient system of knowledge management. Together, economic and engineering decisions provide creativity, reliability, repeatability, cuts in access to market time and, in short, an increase in the value indicators of companies. Strategic decisions harmonise business processes and provide the basic resources for managing the life cycle of the product. All the above factors have an effect on excellence and allow competitive advantage to be obtained.

Any life cycle model that is adopted in the life cycle includes a process for identifying requirements and functionalities. The effective identification of requirements and functionalities requires a system both for collecting information and for evaluating its importance (Fig. 3).

Needs, specifications, aesthetics, preferences and restrictions go to make up the voice of the customer, which can be used to establish a rough model of the concept. The design team will have to focus on the aspects that are vital for quality (Critical to Quality, CTQs). In conceptual design, the level of detail is not high enough, but the decisions that are adopted will condition future development. A correct decision will lead to a reduction in all the costs involved. The tools proposed to facilitate selection processes are the following:

1. Documentation management that allows ideas to be translated into industrial design.
2. Matrices that relate incompatibility between materials and manufacturing processes.
3. Matrices that relate typical properties to specific requirements.
4. Models of manufacturing processes PRIMA, which take into account limitations as regards the geometry of parts.
5. Multi-criteria analysis techniques.
6. Screening preselection techniques.

For organising selection in conceptual design, a "Stage-Gate" validation model is proposed (Fig. 4). The purpose of this model is to verify the technical and economic viability, optimise the selection as regards the use of the product, its performance, durability or costs and, finally, to validate decisions and to approve plans and their budget for the next phase. This model makes it possible to ensure that the CTQ requirements and functionalities have been met.

4. Proposed selection strategy

Administering a product development project involves detecting and solving conflicts concerning criteria, requirements and functionalities.

Each product requirement is a documented need regarding a characteristic or capability appreciated by users. This source of knowledge will be used as input data to establish WHAT must be done.

Preferences and restraints help to maintain the requirements within a range of values and facilitate decision-making about HOW to do it (concept definition).

The documentary material obtained and generated by the development team will be structured on different levels that range from the most general down to the most specific (see Table 2). Consequently, organisational knowledge increases the number of intangible assets and presents an opportunity to gain competitive advantage.

The main function offers a way to eliminate materials and processes that are not technically or economically viable and to carry out the process of screening. Furthermore, the proposed main function provides a number of ways to identify a requirement:

- It defines a property of the material, which may be electrical, mechanical, thermal, etc.
- It is related to movement: support, motorisation, transmission, etc.
- It is related to compliance and reliability: robust design, failure modes, maintenance, etc.
- It derives from the value perceived by the user and may be ergonomic, about the user, etc.
- It is linked to the life cycle: durability, sustainability, etc.

Once this point is reached, a classification of manufacturing processes and achievable geometries is needed. Manufacturing processes could be classified in accordance with the specifications set out in DIN 8580 [46]. Regarding the product and its components, the geometry of the parts can be classified in three broad groups that cover the different industrial sectors:

- Structural or rigid geometries: solid of revolution, rectangular prism and thin-wall or thin-section components.

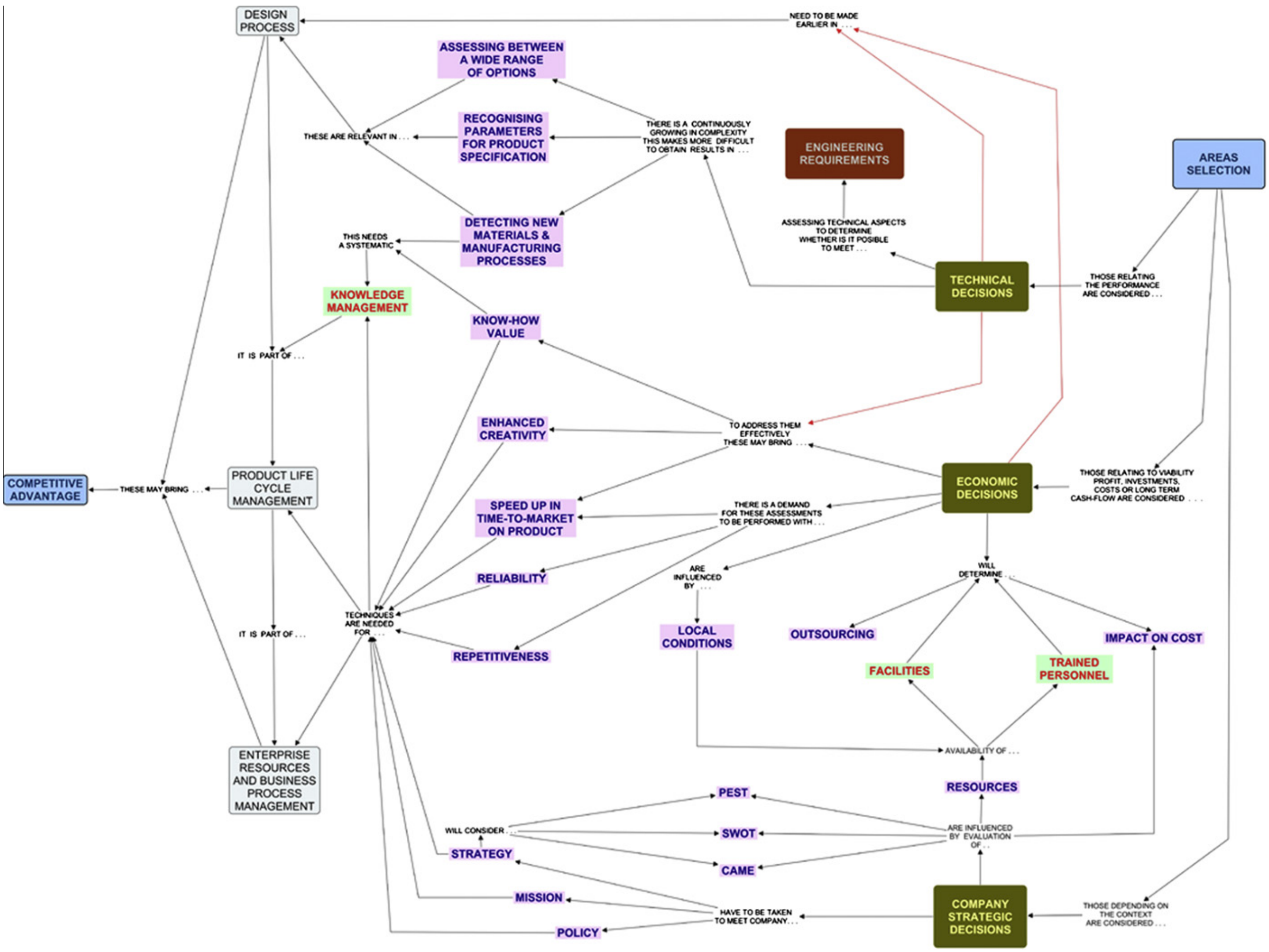

Fig. 2. Relationship between the selection areas and life cycle and competitive advantage through knowledge management.

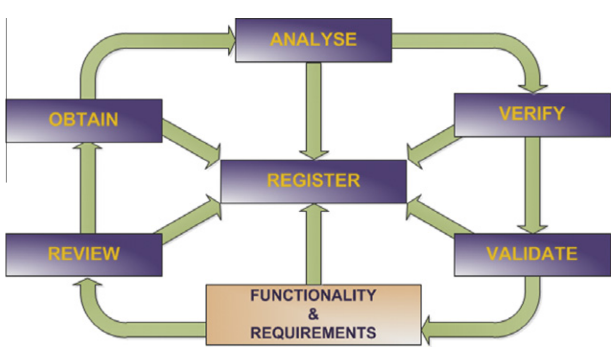

Fig. 3. The preliminary process of selecting requirements and functionalities.

- Elastic or deformable geometries (which should adapt to another rigid element or allow for a certain amount of deformation): viscoelastic amorphous materials, laminas and thin walls, and tissues, fibres, cables, belts, etc.
- Microgeometric: microstructures and micro-electromechanical systems.

Once all the inputs and interrelations during the product life cycle had been considered, we developed a framework as a way to relate the concurrent selection processes with the management models and product development (Fig. 5).The following steps are proposed for generating ideas for new products and services within the context of the selection process in conceptual design:

1. Generation of ideas for new products.
   a. Current State of the issue. Product market analysis.
      i. Perception of transverse knowledge.
      ii. Establish limitations and criteria that constitute the design concept.
   b. Market needs. Identify functionalities and requirements that provide value to the user.
      i. Perception of transverse knowledge.
      ii. Identify functionalities and requirements.
2. Analyse and diagnose. Establish the final list of product attributes and functionalities.
3. Research, innovation, documentation and knowledge management.
   a. Creativity, research and innovation.
      i. Acquire and manipulate the information about the product.
      ii. Product breakdown structure: requirements, functionalities, preferences and restrictions.
      iii. Prepare alternative designs.
   b. Preliminary analysis of materials and manufacturing engineering.
4. Concurrent analysis of materials and manufacturing engineering.

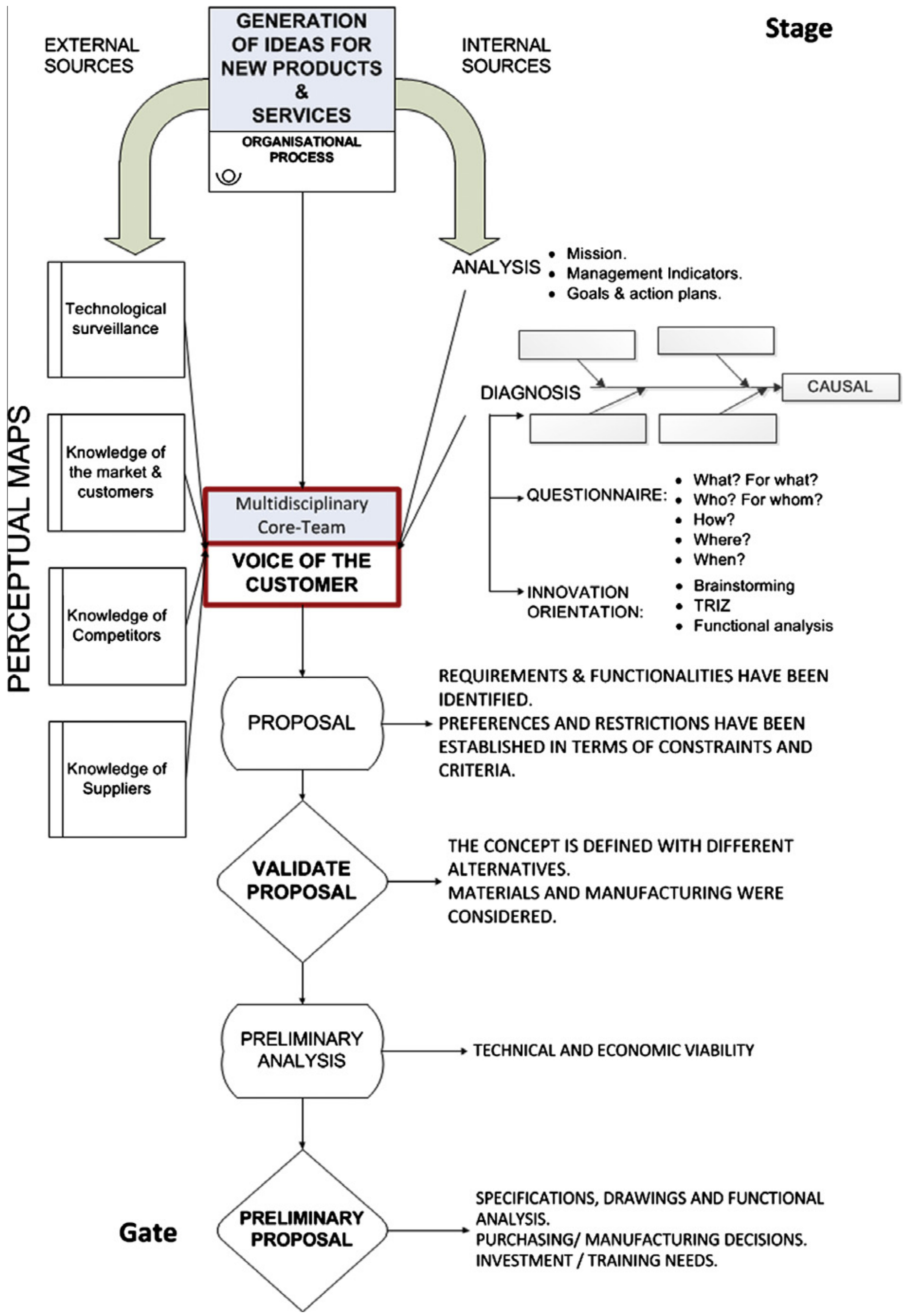

Fig. 4. Stage-gate process for approval of the conceptual design.

Table 2
The structure of the documentary material.

Concept/Property/Quality	Material	Manufacturing process
What is it? Definition	What identifies it?	What does it consist in?
How is it measured/tested?	How is it obtained or transformed?	How is it executed and controlled? Tools, implements, equipment, control parameters
What can we relate it to?	Family of materials that is similar to the one it belongs to	Variants of the process
Physical laws it complies with, analogous phenomena, etc.		
Top-down approach: start out from the general concept to end with specific details	Qualities of interest	Capacity and productivity

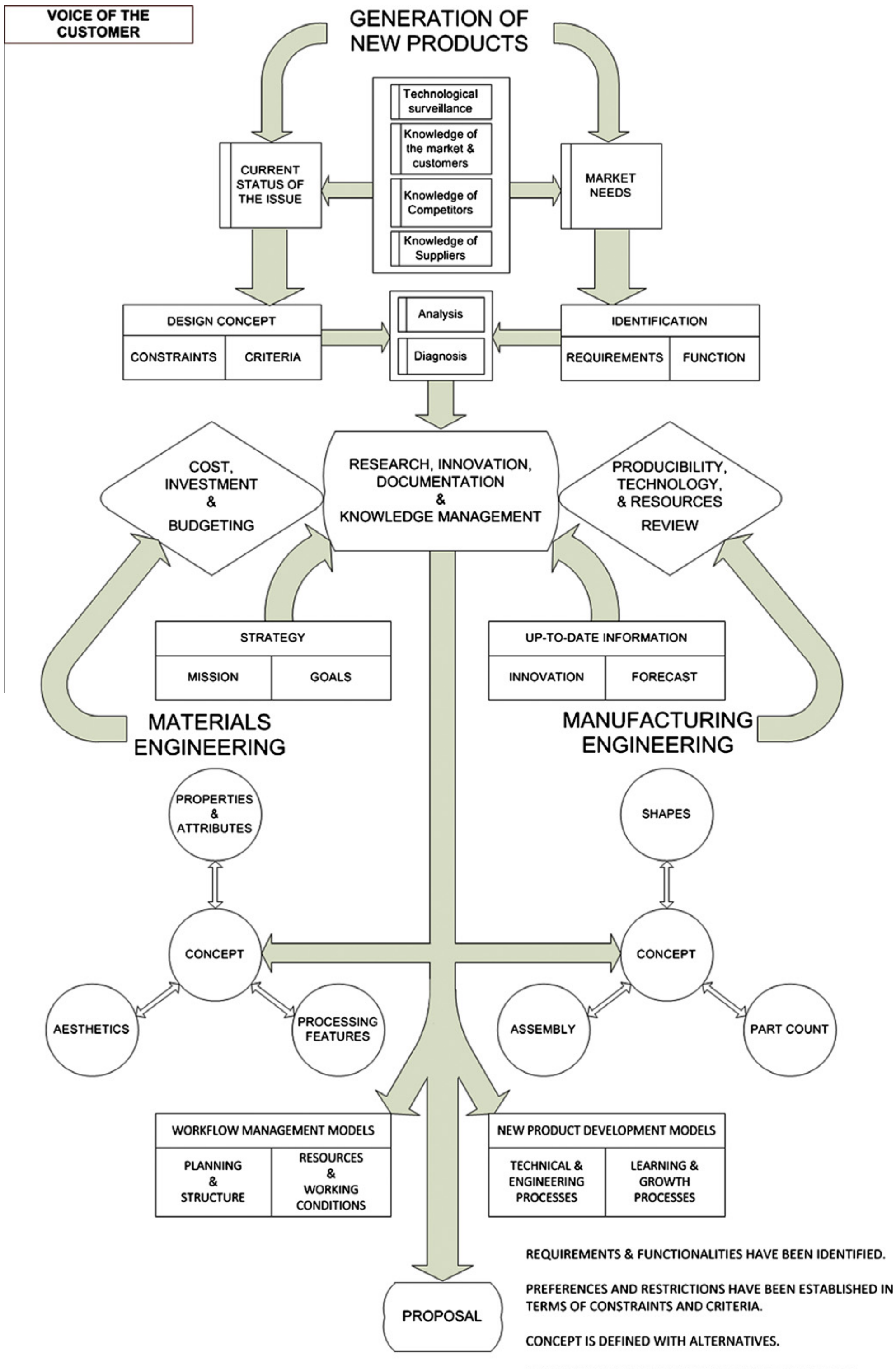

Fig. 5. The preliminary process of selecting materials and manufacturing processes.

   a. Properties and attributes, processing features and aesthetics of materials.
   b. Shapes (geometries), part count (Producibility) and assembly.
5. Co-selection results.
   a. Initial screening of materials and manufacturing processes that are not technically or economically viable.
   b. Optimise configuration of the product.
      i. Strategic framework. Strategy: mission and goals.
      ii. Costs, investment and budgeting of the project.
      iii. Update information, innovation and forecast.
      iv. Producibility, review of the condition of technology and resources.
6. Proposal.

a. Establish workflow management model.
   i. Planning and structures. Work breakdown, mapping of the processes involved and approval of financial plan.
   ii. Resources and working conditions. Establish project plan and revision stages.
b. Establish new product development model.
   i. Technical engineering processes. Prepare alternative products and prototypes.
   ii. Learning and growth processes. Manage innovation and intellectual property.
c. Document final proposal.

The assessment of the concept must evaluate the impact of the product. The PESTEL methodology offers this evaluation in the following factors:

- Political factors.
- Economic factors.
- Sociocultural factors.
- Technological factors.
- Environmental factors.
- Legal factors.

A deeper analysis will take into account topics such as the usefulness of the product functionality, maintenance, reparability, consumable spare parts, aesthetics and ergonomics. At the strategic level, the following points must be taken into account:

- Accessibility and continuity in the supply of raw materials.
- The occupational framework and the availability of qualified employees.
- Energy resources and their availability.
- The means of production available and, if necessary, the acquisitions needed.

In sum, we can conclude that the best solution in design is part of an iterative process between the different areas of selection (Fig. 6). The first approach in selection can come from a cost-based point of view or from the actual operating behaviour of the final product.

The cost-based point of view aims at the use of commercial forms and the reduction of the total number of parts. This is where a decision is made as to whether to use simple or complex geometries and between modular or specific manufacturing. The requirements used in the individual selection of each part give rise to interactions and conflicts in the final product. All this leads to a narrowing of the margin in the limit conditions of the whole process. Product breakdown is in fact a design in its early stages that is mature enough to be able to apply certain validation tools, such as questionnaires, which evaluate the user's decision to purchase (Fig. 7).

To finish, it is important to bear in mind that:

- It is not always possible to identify all the requirements.
- Viability is conditioned by scientific and technical progress.
- If the technology, processes or materials are unknown, then training and experimentation should be carried out.
- If a project is excessively complex, the best strategy is to divide it into phases.

Many models have been developed for the product development process [38,42], but few of them have been fully or partially implemented and, moreover, the integrated selection of materials and processes are not generally considered. This could be because these models are mainly focused on management aspects.

Therefore, our proposed framework provides a systematic path from the early generation of ideas to the production of a new product proposal. It shows how the knowledge sources influence both the state of the art and the market needs so that they become opportunities for innovating products. The framework provides the milestones needed to fully define and document the product. The analysis of materials and manufacturing engineering supplies a feedback path to prepare the documents for project approval. This is, in our opinion, an innovation in comparison to existing models.

5. Case study

In this contribution we present a case study of a design for an outboard motor bracket, which has allowed us to validate and improve our proposal. Each of the activities carried out during the different stages of the proposed methodology (Fig. 5) are briefly explained in the following.

5.1. Generation of ideas for new products

During the design, development and manufacture of small recreational boats the aim is to achieve a more silent and comfortable product. Every element is important but minimising the noise and the transmission of vibrations from the engine to the ship's hull is sometimes critical. Therefore, a key element, the outboard motor bracket system, has to be designed bearing in mind added performance, as well as corrosion, weight and cost.

5.2. Current state of the issue. Product market analysis

Following our previous proposal, a market analysis revealed a huge number of light outboard motor models available for recreational boats. The study determined that there were few different outboard motor brackets that could satisfy the function outlined above. Therefore, a methodologically new product design and development process was initiated. The starting point was the study of the most recent solutions and patents and the most up-to-date one was identified as the patent US 2005/0260899 [47].

5.3. Market needs. Identify functionalities and requirements that provide value to the user

In order to identify the functionalities and user requirements, transverse knowledge methodologies were applied (see Fig. 4). With perceptual maps all the transverse knowledge involved in the entire product could be established, including data such as the dimensions of the motor boat, propeller speed, torque-speed characteristics and friction of the hull on water.

We have focused the case study on medium-sized recreational boats. To establish limitations and criteria for the product we considered the maximum weight of the motor, the maximum thickness of the stern, engine power and the aesthetics of boats.

From the user point of view, costumers demand low-noise motors that are also lighter and more resistant to corrosion. Moreover, they ask for more robustness when fixing the engine. The number of propeller tilt positions required is at least six. The difference between tilt positions must be four degrees at the most. Within the product life cycle, the overall operational time for the motor must be greater than five years or two thousand hours of navigation.

From the manufacturer's point of view, the requirements could be summarised as reducing cost, minimising machining operations, applying sustainable surface treatments and optimising assemblies.

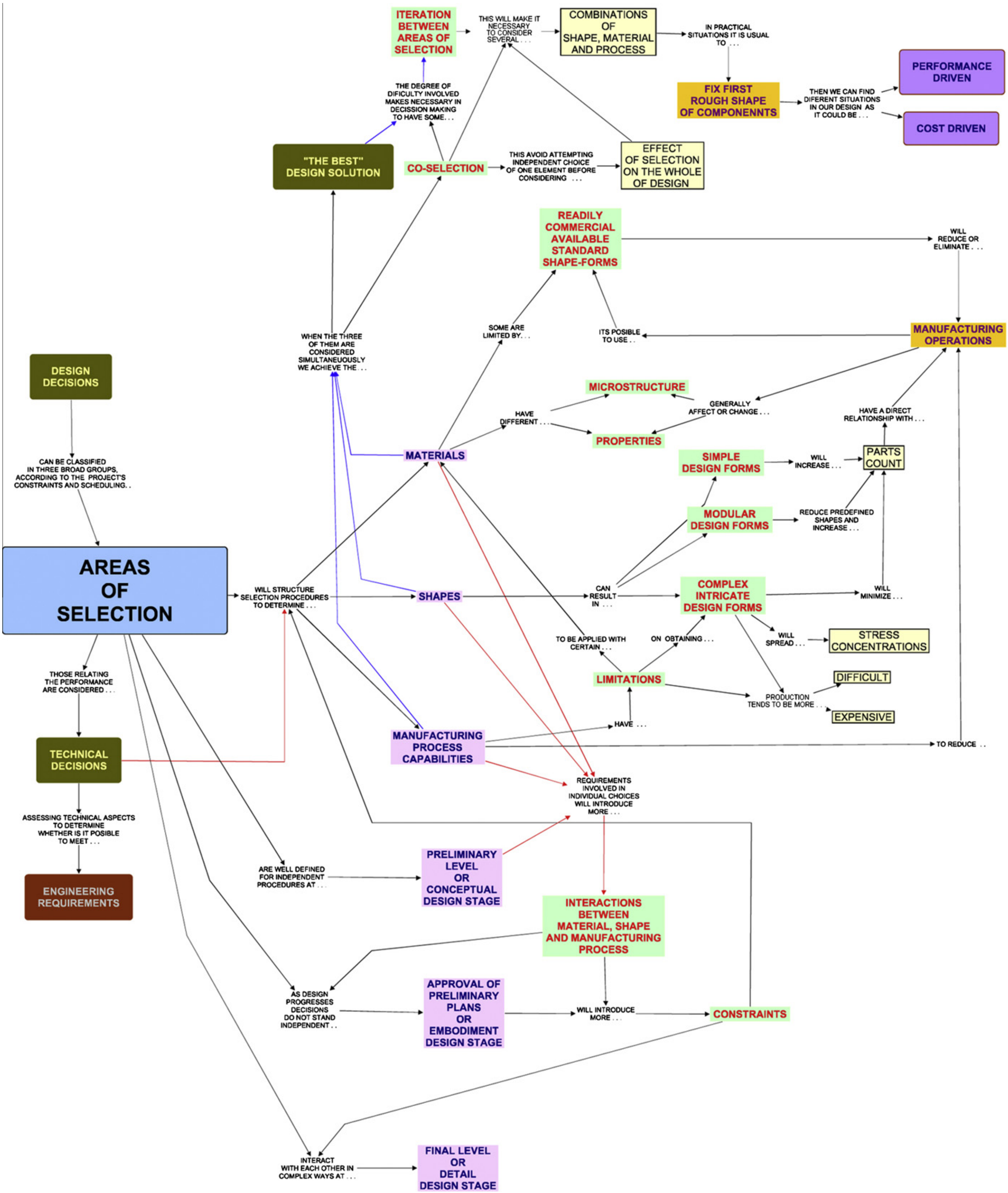

Fig. 6. The areas of selection in conceptual design.

5.4. Analyse and diagnose. Establish the final list of product attributes and functionalities

Once the functionalities and requirements had been defined, a deeper analysis was conducted. This analysis showed that there were different bracket solutions on the market, mainly made of a variety of metals. The most common bracket solution is composed of two lateral parts, linked together via two transversal axes. The superior axis, which has a greater diameter, supports the engine and the smaller one links the two lateral parts. A kinematic

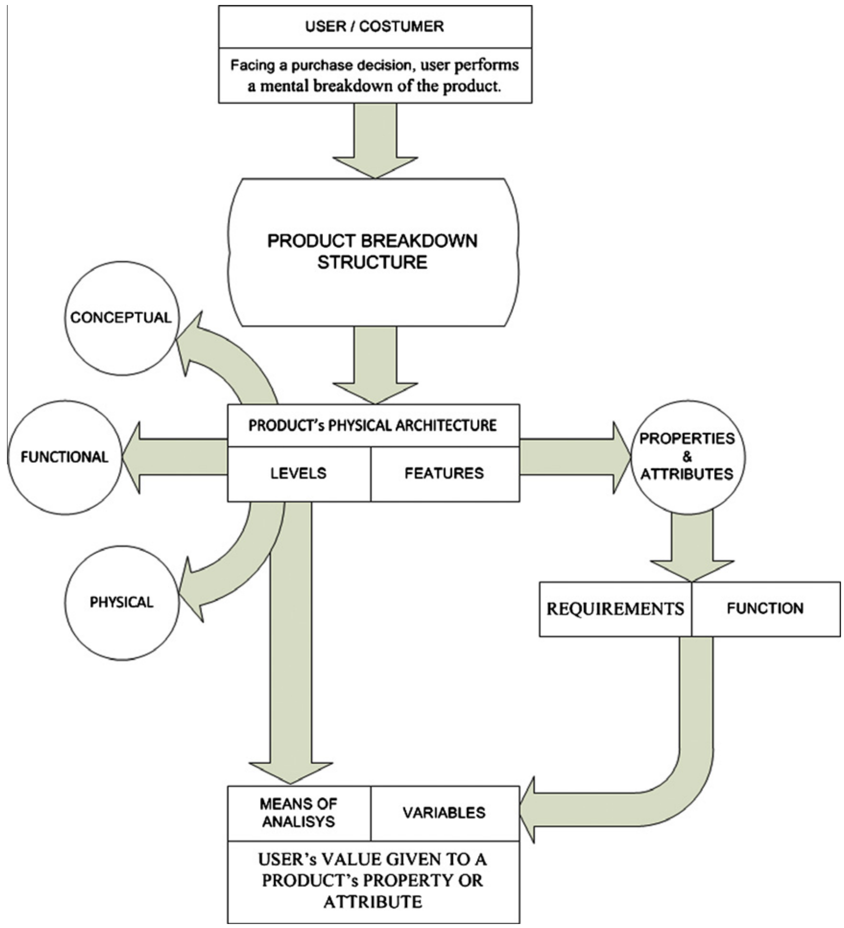

Fig. 7. Product breakdown structure.

Table 3
Final global requirements of the case study and specific requirements for the lateral part.

Geometry and appearance	Maximum motor weight 80 Kg. Maximum thickness of the stern 60 mm. Maximum engine power 25 HP Aesthetics in accordance with the motor/boat	
Mechanical requirements	Yield strength (elastic limit) Fracture toughness	>100 MPa KIC > 10 MPa $m^{1/2}$
Thermal properties	Minimum service temperature Maximum service temperature Flammability Resistant to fresh water	At most −40 °C At least 100 °C Non-flammable or self-extinguishing Good
Durability	Resistant to salt water Resistant to organic solvents Resistant to UV radiation (sunlight)	Good Good Good

analysis of the motor-bracket-boat system was performed with a Computer-Aided Engineering finite element analysis tool in order to determine a conceptual and preliminary design. This analysis allowed us to determine the key part of the assembly and led us to focus on the bracket part. Therefore, mechanical properties and functionalities were identified just for the key part.

5.5. Research, innovation, documentation and knowledge management

As we have just explained, the design of the lateral parts of the assembly is the scope of this case study. These parts were analysed in terms of their function, their purpose (which should be maximised or minimised), their constraints (what conditions must be met) and the design variables that can be modified. As they are symmetrical, we will focus and present the design/application for one of the parts.

Regarding candidate materials for this part, the mechanical requirements, thermal properties, terms of durability, aesthetics and geometry were all considered relevant factors. Calculations are performed with the data acquired in the transverse knowledge mentioned earlier. All the mechanical calculus is summarised in Table 3 with the main requirements that have driven the design.

Once all the product-related data, information and other related knowledge had been determined, the conceptual design phase was

Table 4
Materials, processes and cost metrics for concurrent selection.

Sales forecast		250,000 parts per year	
Batch size		10,000 units	
Material			
Cast aluminium alloy, ISO: Al–Si_{23}CuMgNi		PBT with 60% long glass fibre	
Manufacturing process	Cost p.u. (€)	Manufacturing process	Cost p.u.
Die pressing and sintering	3.16	Injection moulding (thermoplastics)	4.00 €
Green sand casting, automated	4.06		
High pressure die casting	9.32		
Powder metal forging	12.36		
Cosworth casting	12.60		

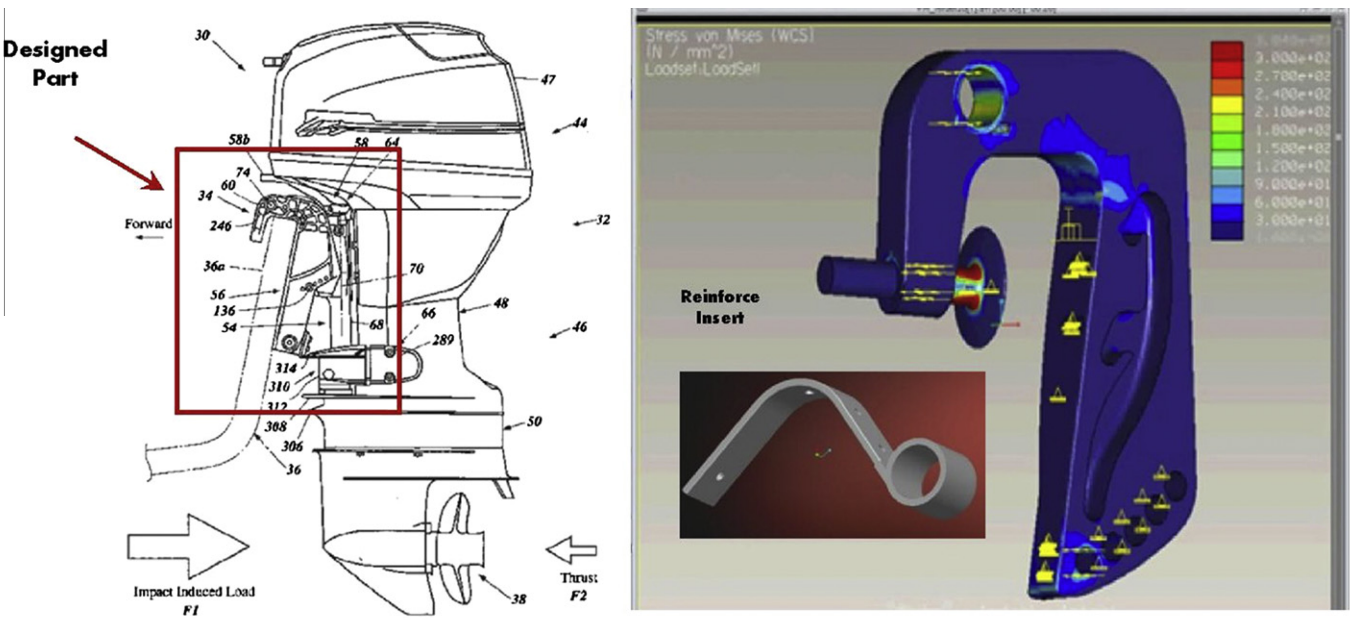

Fig. 8. Case study.

initiated in order to allow us to prepare diverse alternatives with different geometric designs and solutions.

5.6. Concurrent analysis of materials and manufacturing engineering

The main phase of our proposed methodology is the concurrent analysis. With the different alternatives achieved during the previous conceptual designs, we can now proceed to concurrently select candidate materials and manufacturing processes.

From the materials engineering point of view, a screening process was conducted in order to analyse the different sets of material limit values under working conditions. The research ruled out those sets of materials that do not pass this filter. We then established functions aimed at maximising or minimising the material parameters. These functions allowed us to methodologically rate the materials and the result was a greatly reduced list of candidate materials.

The use of material databases with functionalities, properties and attributes allowed the designers to consider two alternatives for manufacturing in terms of materials. One alternative involved a metal-based part and the other was based on a technical plastic part that satisfies a preliminary analysis of materials and manufacturing engineering.

On considering these materials, we can establish the part geometry that is capable of achieving the functionality and work requirements. The geometry of the part will allow us to simulate working conditions such as stress, modes of vibration and fatigue. The results of the analysis will optimise the selection of materials, part geometry and producibility by considering the costs involved.

With the engineering results, the design and development process can start with detailed attributes that guide the embodiment of the part and the preliminary assessment of the technology and resources. The assessment should ensure that producibility geometry and assemblies meet functionalities as well as both technical and economic viability. The engineering analysis includes an evaluation of compatibility between material and processes, and in order to assess the manufacturing production parameters, a database query was analysed. The results were sorted to show a list of processes from the economic viability point of view (cost-based).

The next step involves the core analysis of alternative previous weighted materials with limit values, mechanical properties and features. Therefore properties, attributes, processing features and aesthetics of materials are analysed. In this case study, finally we compare the following materials, which satisfy all the requirements: cast aluminium alloy (ISO: Al-Si23CuMgNi) [48], and polybutylene teraphthalate (PBT) with 60% long fibreglass (Table 4). In the following table, information about the sales forecast, part count, batch size and manufacturing process cost per unit is shown.

5.7. Co-selection results and final proposal

The final decision supposes a deeper analysis of the alternatives in an attempt to optimise the product configuration and the detailed geometry of the part. Co-selection will make it necessary to consider several combinations of shape, material and process instead of making an independent choice of one element before considering the effect on the design as a whole. In this case study we have attempted to establish a rough shape for the component. To do so, first, parts performances were considered, and then, the selection was cost-driven.

The final geometrical result of the part, which was based on the requirements taking into account not only the product but also the use of the outboard engine, is shown in Fig. 8. It can be seen in the figure that, for the solution using PBT with 60% long fibreglass, an insert was needed to reinforce the part.

The results of this case study helped to define the strategic framework (mission and goals) for this product development and the project costs (investment and budgeting). The information was updated and a new workflow management model was established to map all the processes involved, such as starting the production project plan, assigning resources, working conditions and revision stages. The process can then continue with the technical engineering processes to create product prototypes. One of the most important actions after the learning and growth processes is to manage innovation and intellectual property in order to write the final proposal document.

This case study has helped us to validate the proposal and to determine whether it is possible to meet the design goals. However, other cases with a different set of requirements are needed to improve our proposal.

6. Conclusions

The proposal attempts to cover some aspects of integrating management and the selection of technical materials and manufacturing processes. Although there are excellent computer-aided tool methodologies for selecting materials and processes, they are focused on embodiment and detailed product design. As we have stated earlier, design detects or creates needs in consumers and turns them into products or services. Manufacturers and engineers are constantly searching for new materials and manufacturing processes in order to maintain a competitive advantage. The definition of the concept offers a wide range of possibilities for exploring the selection of materials and manufacturing processes. A structured process of reasoning offers a framework that does not restrain novel materials and processes. This work has analysed the most notable contributions in the field of material and process selection and offers a framework for reasoning and a process for approving the selection of materials and manufacturing processes.

Technological surveillance and knowledge management have become essential elements for organisations that intend to innovate. This is the reason why materials and process selection has been related to business processes, the life cycle, workflow management and methodologies for the creation of new products.

Finally, it should be noted that the most appropriate choices in the conceptual design will result in greater effectiveness throughout the whole project. It is vital for all the knowledge obtained in the creation of a new product to be structured and made available for use in future developments.

7. Future work

We have presented a framework for the concurrent selection of materials and processes. However, we think that it should undergo continuous improvement and further aspects must be considered to enhance it. Therefore, as future work we should explore:

- Knowledge management, in order to incorporate it into intangible assets.
- Enrich current decision-support tools during conceptual design and improve product life cycle management with qualitative attribute scoring.
- Define workflows and causal connections between activities within preliminary process selection.
- Establish the different types of documents containing data, information and knowledge model for use in the stage-gate schema.
- Develop an application that will be able to integrate the interrelationships of the conceptual maps (Fig. 2 and 6).

Finally, we would like to emphasise a more ambitious objective to be included in future work, that is, to consider the sustainability of manufacturing processes in terms of eco-auditing throughout the whole product life cycle.

Acknowledgements

The authors would like to acknowledge financial support from the local government and the Universitat Jaume I of Castellón (Spain) through research project number P11B2009-37, entitled ''*Methodologies for Implementing Product lifecycle management tools for mechanical Small and Medium Enterprises*''.

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