INSTITUTO TECNOLOGICO Y DE ESTUDIOS SUPERIORES DE MONTERREY
CAMPUS MONTERREY

DIVISION DE INGENIERIA Y ARQUITECTURA
PROGRAMA DE GRADUADOS EN INGENIERIA

TECNOLÓGICO DE MONTERREY.

METHODOLOGY FOR RAPID MECHATRONIC PRODUCT DEVELOPMENT AND MANUFACTURING

TESIS

PRESENTADA COMO REQUISITO PARCIAL PARA OBTENER EL GRADO ACADEMICO DE:

MAESTRO EN CIENCIAS

ESPECIALIDAD EN SISTEMAS DE MANUFACTURA

POR

PAOLA FARIAS MORENO

DICIEMBRE DE 2003

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SUMMARY

In today competitive world, products need to be designed to satisfy all the customer requirements that it is possible with specifications that will fulfill their needs. The design of these mechatronic products requires different disciplines because they integrate mechanical, electronic and software components which allow them to be more customers oriented.

This thesis proposes an integrated methodology for Rapid Mechatronic Product Development and Manufacturing which includes the activities from product planning to prototyping and the engineering activities of the design process (Analysis, Synthesis and Evaluation). This methodology helps the designer in the product development process by specifying detailed activities, the flow of product information, methods that can be applied in each phase, and some other organizational issues.

This methodology sets the foundation to create a generic template in order to allow the integration of the design methodology to the company own design process and also to pursue and automation of the process. The results obtained with this research are: (1) A classification of many applicable design methods and techniques by design phase and type of activity: analysis, synthesis and evaluation. (2) A methodology for rapid mechatronic product development and manufacturing. (3) A reconfigurable methodology depending on the special characteristics of the product to be developed. (4) An evaluation of design methodologies. (5) An information organization chart of the product development process for the three disciplines.

A case of study of a mechatronic product was carried out in order to demonstrate the usefulness of the methodology.

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Chapter 1 . Introduction.

1.1 Background

Why use a methodology for Product Design?

Many authors give some reasons and experiences about dealing with product design processes.

Otto and Wood [2001] in their book "Product Design" talks about the Product Development Process:

> *Enumerating a product development process in a detailed set of activities would result in discrepancies in its application; nevertheless, it is instructive to consider a typical and effective sequence of activities that one can expect in a Product Development Process.*
>
> *A structured design process has many benefits. Modern product development involves the application of objectively formulated methods that are systematically configured to permit designers to develop functional products according to customer requirements.*

Pahl and Beitz [1988] refer to systematic procedures:

> *Additional use of systematic procedures can only serve to increase the output and inventiveness of talented designers.*

Ullman [1992] write about the design process:

> *There is a continuous need for new, cost-effective, high-quality products. It has been estimated that 85% of the problems with new products-not working as they should, taking to long to bring to market, costing too much-is the result of poor design process.*

For those statements, is author opinion that it is important to integrate high value added methods and tools into a design methodology to support designers in taking decisions to develop their products assuring their functionality and avoiding mistakes that make longer and costly the design process. Also, if mistakes are avoided, a designer feeling is: "going in the right way" /"free to design", thus, creativity is enhanced.

1.2 Research Justification

The need to fill the existing gaps in the mechatronic design.

The need for product designers to have a detailed methodology to support them in taking decisions to develop their products assuring their functionality and avoiding mistakes. Detailed methodologies are divided in mechanical, electronic and software products, it is required that those methodologies could be used concurrently and be adaptable to design Mechatronic systems. It is important to describe how to use those methodologies concurrently, the phases in the design process, the activities required in each phase, the flow of information, the methods used in each phase or activity and some other organizational issues.

1.3 Objectives

- To develop a Design Methodology for Mechanic, Electronic and Software products (Mechatronic Product).
- To demonstrate the use of the Methodology with a case of study to identify key issues in Mechatronic Design.
- The description of Activities or Functions, Product Information, Organizational Issues and Methods required in every design phase.

1.4 Scope

The areas of research addressed in this investigation are:

- Product Design Methodologies, specially the areas of Engineering design, Product design, and Mechanical Design.
- Specialized methods and tools that support the product design process, focusing in evaluation tools.
- The difficulties encountered by designers designing a product.
- Methodology Characteristics:
  - Methodology organized in a biaxial information transformation space. Axe 1 refers to activities in design phases. Axe 2 refers to design phase (Analysis, Synthesis and Evaluation).
  - A set of methods and tools are available to integrate in the design activity depending in the kind of product to be designed.
  - The methodology has to assure that less or no mistakes will pass to the next design activity because of constant reviews or evaluations.

1.5 Thesis organization

This research is organized in 6 chapters. Each chapter has a specific objective; these are mentioned at the beginning of the same.

The Literature Review presented in Chapter 2, refers to Product Design Methodologies, making a comparison between product design, mechanical design, electronic design, software design, and engineering design methodologies. Also describes the common problems encountered by designers through the design process. The last part of the chapter presents some theories and developments and a detailed explanation of a few methods.

Chapter 3 proposes the integration of some evaluation tools that have to be implemented in every design process to discard that mistakes pass to the next design activity. The integration of this evaluation tools in the model of the methodology is also described. You can also find a detailed description of the evaluation methods.

The chapter 4 is the center of this work. Here, a methodology for product design was developed. The concept model for the methodology in presented. The design activities are described completely. The methods and tools required are categorized for each design phase (analysis, synthesis, and evaluation).

Chapter 5 refers to a study case that validates the methodology. This study case refers to a electronic product. It shows the implementation of the methodology activity by activity.

Chapter 6 presents the results obtained from the application of the methodology, conclusions are written down and a proposal for further research in this area is defined.

Chapter 2 . Literature Review.

2.1 Introduction to Product Design.

In today's competitive world, products need to give the customer all the requirements that it is possible with specifications that will fulfill their needs. Products are made to carry out a function. Products that are competitive are products that carry out the function that they are intended to with the major benefit for the customer. These benefits could be adaptability, robustness, low price, etc. For a product to meet the customer expectatives, has to be designed in such manner that accomplishes all the requirements that will cause in the customer the feeling that he is getting more benefits than another products.
Design is the activity that could meet this goal.

There are a lot of methodologies for product design [Table 2.1].

Ullman [1992]	Ulrich [2000]	Pugh [1996]	Pahl & Beitz [1988]
1. Specification development 2. Conceptual Design 3. Product Design 4. Production 5. Service 6. Product retirement	1. Identifying customer needs 2. Establish product specifications 3. Concept Generation 4. Concept Selection 5. Product architecture 6. Industrial design 7. Effective prototyping	1. Marketing 2. Specifications 3. Concept Design 4. Detail Design 5. Manufacture 6. Sell	1. Clarify of task 2. Conceptual design 3. Embodiment design 4. Detail Design

Table 2-1 Methodologies for product design.

The design process is a combination of art and science. Yet scientific methods are required to assure the product makes effective use of materials, space, interactions among the parts, and accomplishes this at a cost attractive to potential buyers. This aspect of design routinely requires mathematical analysis to determine the size and shape of parts to carry the required loads, operate for the prescribed life, withstand the environmental conditions, etc. in the course of fulfilling its intended functions.

When emanate an idea of a product to satisfy some need, there needs to be an embodiment of the idea. Transform this idea in to a product needs manufacturing.

Whit the passage of time the civilizations engineering drawings became a common language for communication between engineers. Also, improves were made to manufacturing processes [Srinivasan, 1994]. As the products became more complex and the users more diverse, a problem between design and manufacturing was inevitable. Drafting standards and conventions have emerged to streamline this communication. The designs have become more sophisticated, so, the requirements are stricter. The average designers use a systematic approach to generate a design satisfying the specifications [Srinivasan, 1994].

This design is the base for the manufacturer, who fabricates the part. Some times the product fail to perform as desired. One of the reason for this failure leads into *tolerances* [Srinivasan, 1994].

2.2.1 Comparison of disciplines in design.

In the previous section were mentioned many methodologies for product design, many try to be general, and others apply only for one discipline.
It is possible to categorize the kind of product that we will develop. For this research the author categorize the products in three kinds:

- Mechanical Products
- Electrical Products
- Software Products

Many products are conformed by mechanical, electrical (especially electronic), and software components, because of that many disciplines appear, like Mechatronics.

Ullman in 1992 made a comparison of design disciplines. He uses seven measures: type of objects, type of problem, form-function relation, decomposition potential, language complexity, graphic complexity and design methods.

	Mechanical	**Electrical**	**Software**	**Industrial**
Type of Objects	Many types across many disciplines	Standard components	Structures of text strings	Shape, texture, and color
Type of problem	All types	Primarily selection and configuration	Selection and configuration	All types
Form-function relation	Overlapping	Most forms have specific functions	Form specifies function	Form dominates function
Decomposition potential	Often strongly coupled	Along circuit and component boundaries	Into subroutines or procedures	Usually not a problem
Language complexity	All types mixed	All types mixed	Primarily textual	Usually graphic or physical
Graphic complexity	2D, 3D, and shaded images	2D	If any, 2D flowcharts and trees	2D, 3D, and shaded images
Design methods	Partially developed	Some available	Methods exist	Some available

Table 2-2 Comparison of mechanical design with other disciplines. [Ullman, 1992]

2.2 Problems in design

The designer has the great responsibility of ensuring that the product will conform to customer requirements, comply to specification, meet cost targets and ensure quality and reliability in every aspect of the product's use, all within compressed time scales.

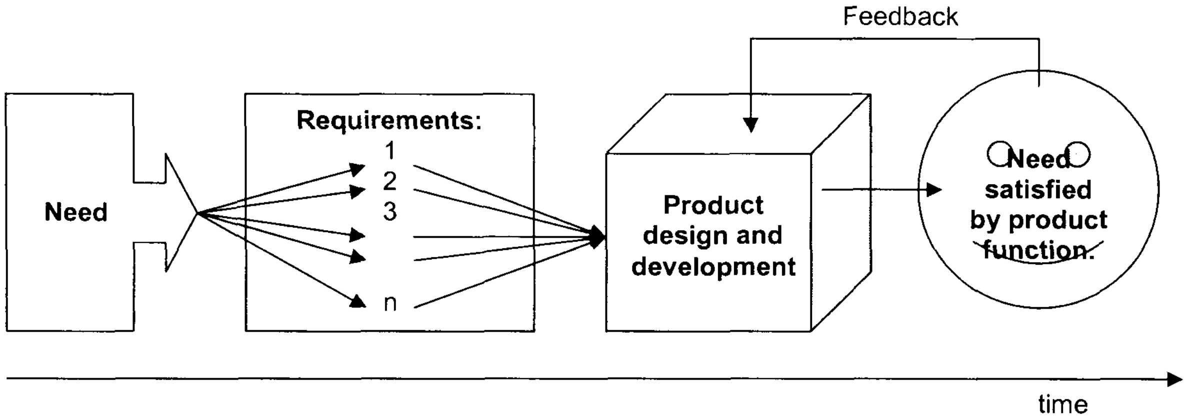


Figure 2-1 Cycle of product development

Shetty and Kolk [1997] define several important life cycle factors:

- Delivery: Time, cost, and medium.
- Reliability: Failure rate, materials, and tolerances.
- Maintainability: Modular Design.
- Serviceability: On board diagnostics, prognostics, and modular deign.
- Upgradeability: Future compatibility with current designs.
- Disposability: Recycling and disposal of hazardous materials.

So it is important to consider that in the mechatronic design approach, life cycle factors have to be included during the product design stages.

Each product is derived from individual pieces of material, individual components and individual assembly processes. The properties of these individual elements have a probability of deviating from the ideal or target value. In turn, the designer defines allowable tolerances on component characteristics in anticipation of the manufacturing variations, but more often than not, with limited knowledge of the cost implication or manufacturing capability in order to meet the specifications [Craig 1992, Korde 1997].

Also, when complex products, as mechatronic products, include elements from many disciplines (mechanics, electronics and software) the integration of components becomes the major challenge. Design teams have to work concurrently to avoid integration mistakes due to the lack of information.

When design processes are not clearly defined and activities relating many areas correctly settled, the spread of information is not good enough to develop individual components that will be integrated to give form to one entire system.

Another problem refers to the optimization of the whole system. That is because changes in one subsystem sometimes implies changes in other subsystems, and interactions between these elements are complex to simulate and analyze.

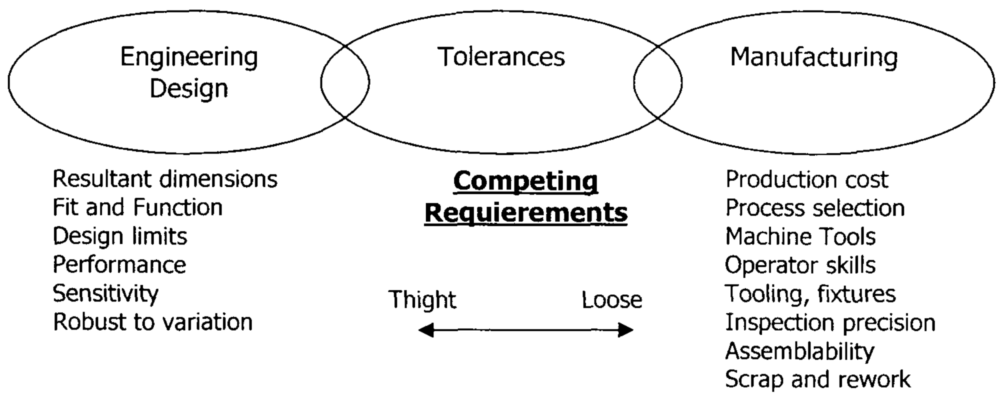


Figure 2-2 Tolerances – the critical link between design and manufacture [Chase and Parkinson, 1991]

The traditional electromechanical system design approach attempted to inject more reliability and performance into the mechanical part of the system during the development stage. The control part (electronics-software) system was then designed and added to provide additional performance or reliability and also to correct undetected errors in the design. Because the design activities occur sequentially, the traditional approach is a *sequential engineering approach*. The undetected errors were costly to repair using control software.

Many product failures are cause by a lack of scientific knowledge; a majority of these problems arise because of poor design of the product, process, software, and systems. One reason so many design mistakes are being made today is that design is being done empirically on a trial-and-error basis [Nam Su, 2001].

A significant proportion of the problems of product quality can directly result from variability in manufacturing and assembly [Craig, 1992]. However the difficulties associated with identifying variability at the design stage mean that these problems are detected too late in many cases [Swift et al 1997].

The first concern in designing process capable products is to guarantee the proper functioning of the product, and therefore to satisfy technical constraints. Dimensional characteristics reflect the spatial configuration of the product and the interaction with other components or assemblies.

2.3 Methodologies-Theories for Product Design.

2.3.1 Ullman, Pugh, Ulrich, Pahl & Beitz, Methodology for the Development and Design of Technical Systems and Products: VDI 2221/2222.

Design Process from Ullman.

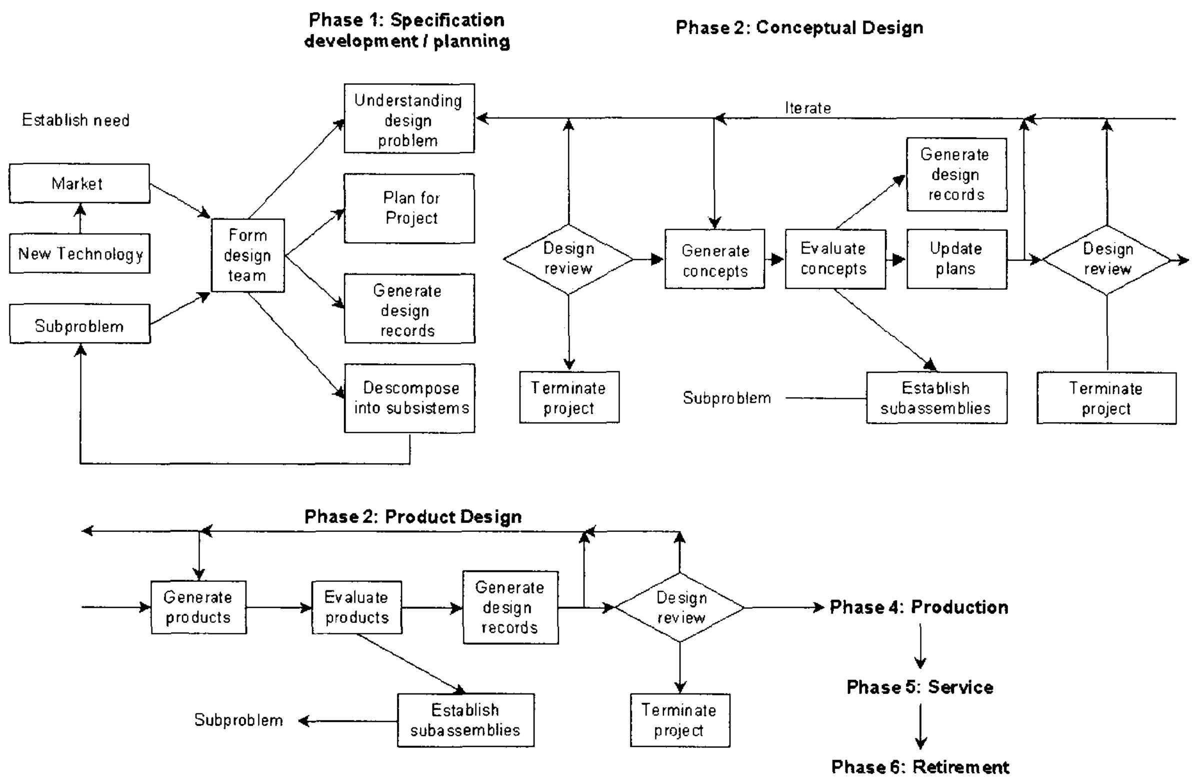


Figure 2-3 Design Process from Ullman. [1992]

Design Process Pugh.

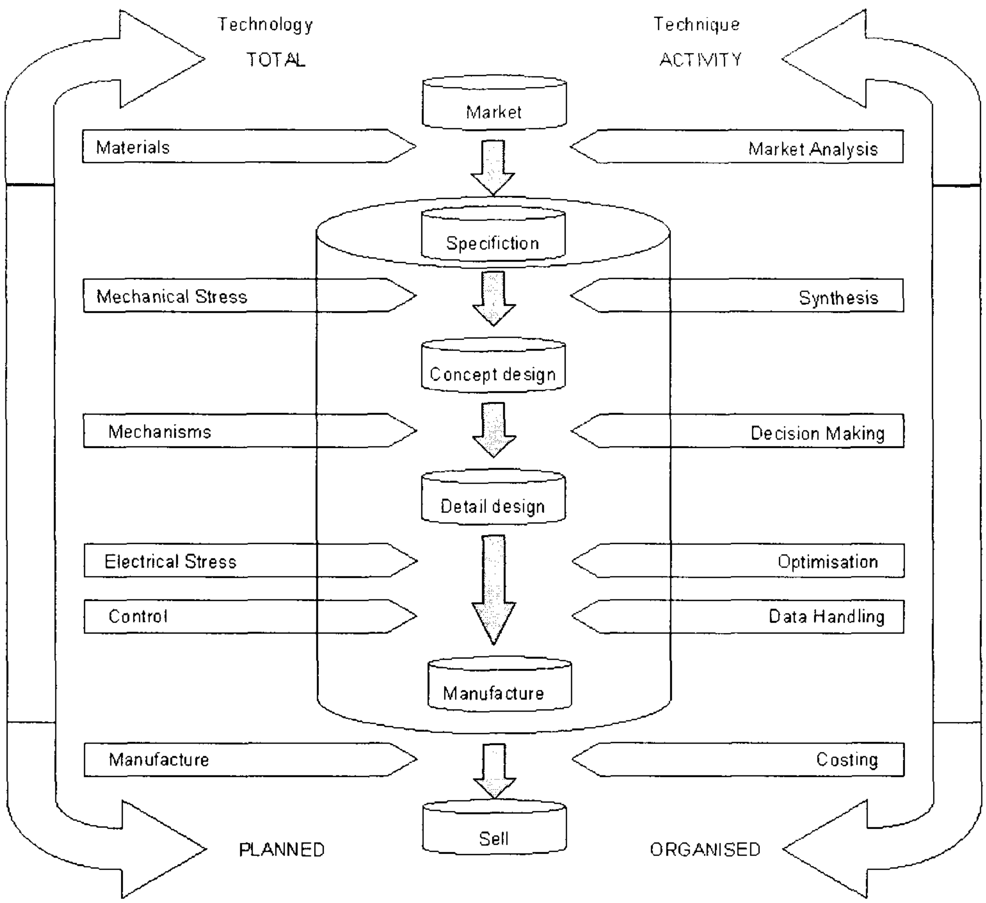


Figure 2-4 Design Process from Pugh.[1991]

Design Process Ulrich.

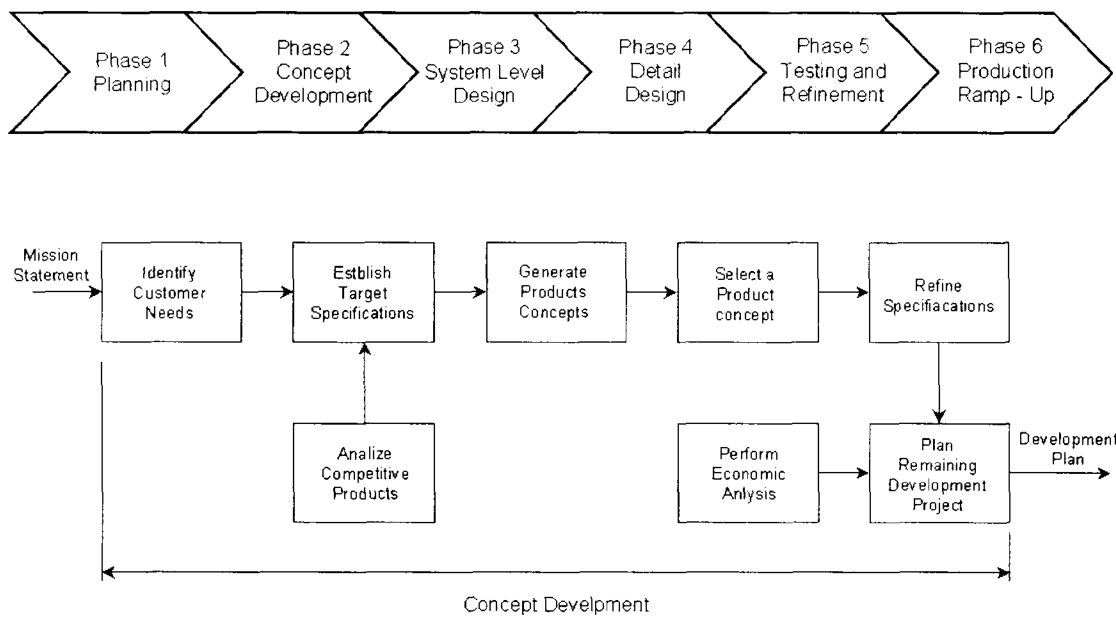


Figure 2-5 Design Process from Ulrich. [2000]

Design Process Pahl & Beitz.

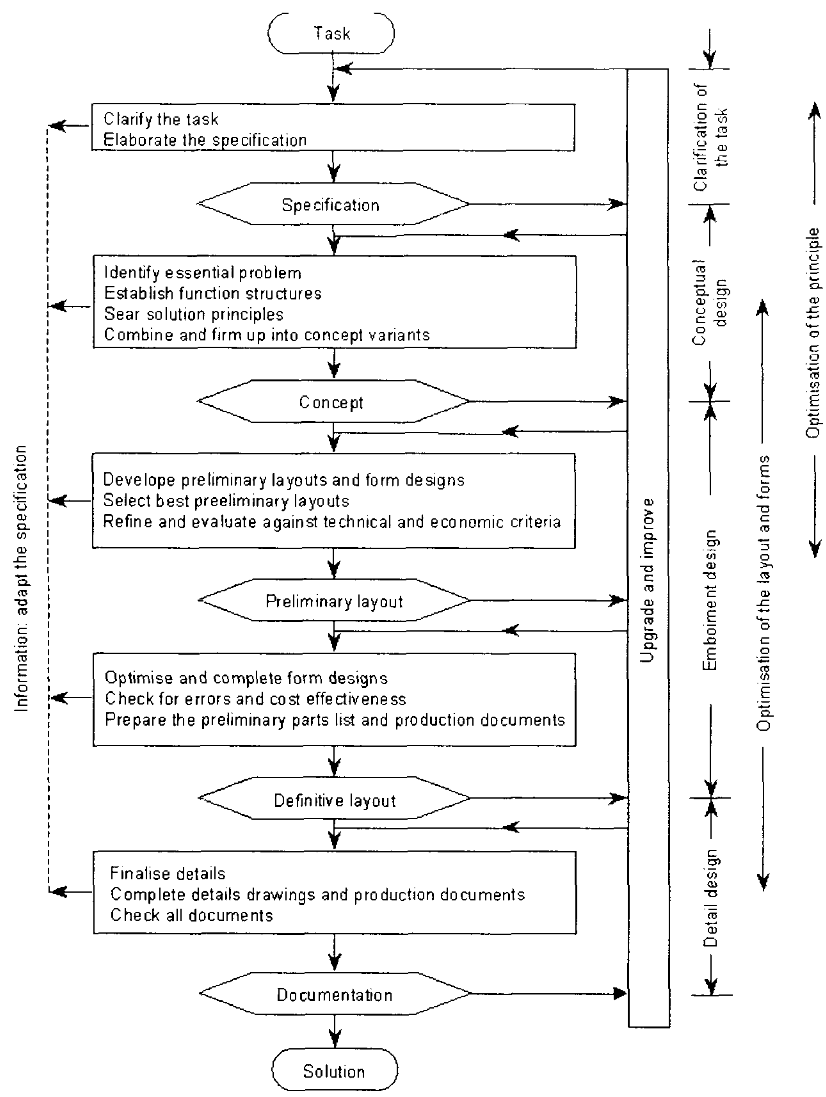


Figure 2-6 Design Process from Pahl and Beitz. [1988]

Methodology for the Development and Design of Technical Systems and Products: VDI 2221/2222.

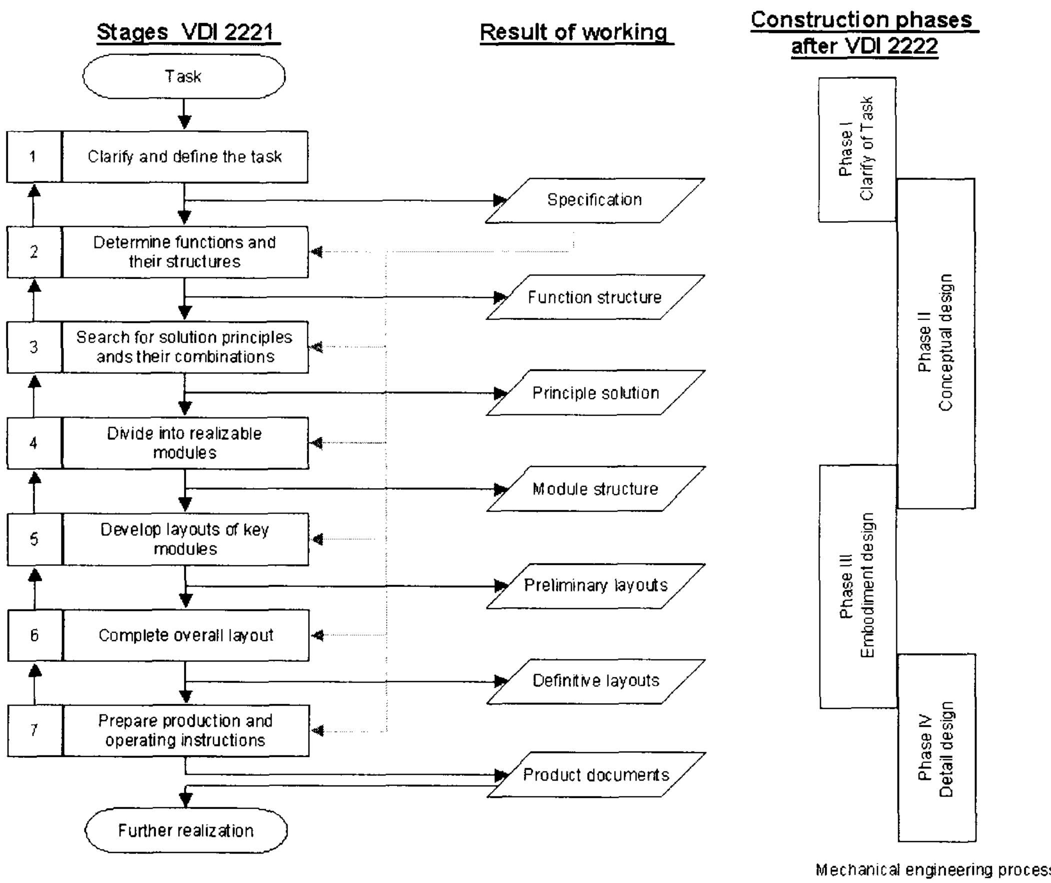


Figure 2-7 Methodology for the Development and Design of Technical Systems and Products [VDI Richtlinie 2221/2222, 1993]

2.3.2 CONDENSE, Concurrent Design Evaluation System [Chen, 2001].

CONDENSE consists of two subsystems, namely both the qualitative and the quantitative aspect evaluation models. The qualitative aspect evaluation model assists the product designer in searching the initial product design space to determine the appropriate design specifications or solution principles. The quantitative aspect evaluation model assists the product designer in the evaluation of different design/concept alternatives in terms of certain criteria to facilitate design selection during the conceptual design stage. These two subsystems can be developed independently. Each model consists of four modules.

(1)Qualitative aspect evaluation model:

- NEEDS: used to determine the design objective and requirements for the specific design project;
- MATLS: used to determine the material to be used and the basic shape of the product;
- SPECS: used to determine the product specifications;
- SUGTS: used to determine the design suggestions and organize the results obtained from previous subsystems to form the functional results;

(2)Quantitative aspect evaluation model:

- FUNTN: used to analyze the performance of the design/concept alternatives and provides warning messages if required;
- ASMAB: used to evaluate the assemblability of the design/concept alternatives in terms of the number of assembly directions, the number of assembly operations needed, and reducible components;
- MAFAB: used to judge the manufacturability of the design/concept alternatives in terms of some manufacturing rules and the number of certain operations needed;
- COSTS: used to estimate the manufacturing costs of design/concept alternatives on a comparison basis and organize the results obtained from previous modules (subsystems) to form the functional results.

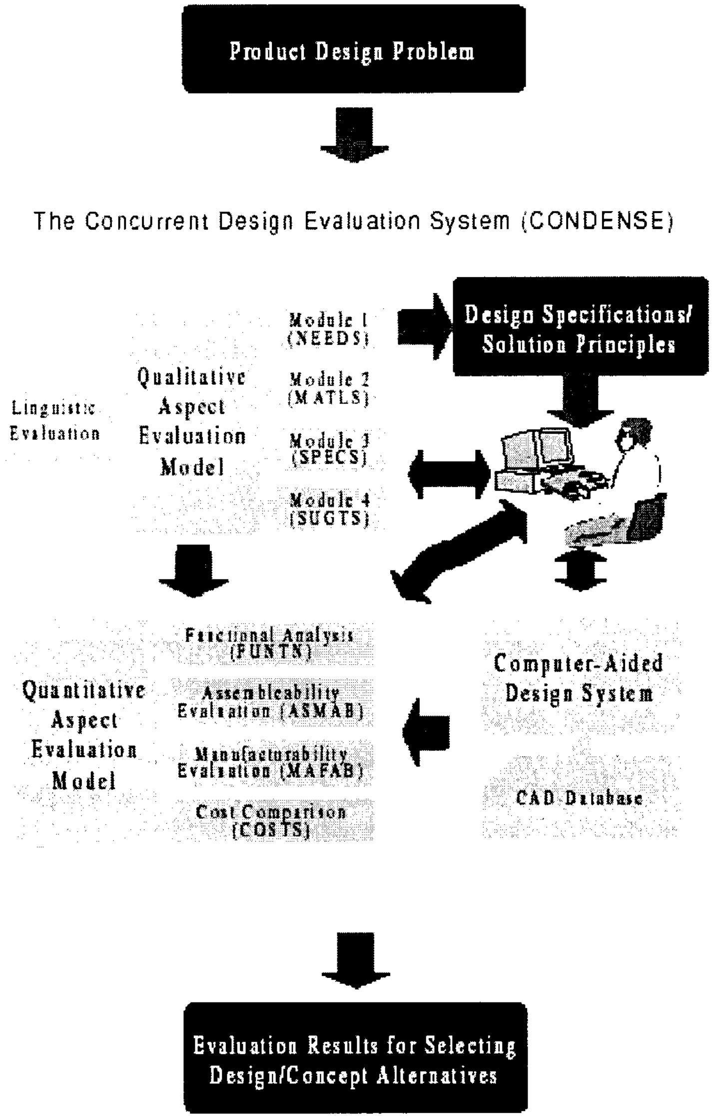


Figure 2-8. Framework of the concurrent design evaluation system (CONDENSE).
[Chen et. Al., 2001]

2.3.3 Design For Manufacturing-Producibility (DFM).

Design for manufacture (DFM) definitions:

- Is the practice of designing products with manufacturing in mind. Its goal is to reduce costs required to manufacture a product and improve the ease with which that product can be made [Bralla; Korngold 2000].
- Producibility is a discipline directed toward achieving design requirements that are compatible with a variable capabilities and realities of manufacturing. Other terms used interchangeably with Producibility are manufacturability, DFM, DFA, DFAutomation, DFRobotics, DFProduction, and Design for "x" [Priest, Sánchez, 2001].

- The ability to define and characterize the various product and process elements that exert a large influence on the key product response parameters, and then optimize those parameters in such a manner that the critical product quality, reliability, and performance characteristics display:
  - Robustness to random and systematic variations in the central tendency (μ) and variance (σ2) of their physical elements,
  - Maximize tolerances related to the "trivial many" elements and optimize tolerances for the vital few,
  - Minimize complexity in terms of product and process element count, and,
  - Optimize processing and assembly characteristics as measured by such indices as cost, lead time, etc. [Harry, 1991]. [Harry, Lawson, 1987]

The concept of DFM is not new, it dates back as early as 1788 when LeBlanc, a Frenchman, devised the concept of interchangeable parts in the manufacture of muskets which previously were individually handmade [Bralla]. By implementing limited tolerances on the components and developing basic manufacturing processes for repeatability, the muskets could be made far more quickly, cheaply and reliably than hitherto by craftsmen. However, it was not until the late 20th century that the term DFM became a household name [Bralla].
Producibility requirements and performance can be measured by the relative ease of manufacturing a product in terms of cost, lead-time, quality and technical risk. Some examples of Producibility measures that are often used in design requirements and Producibility analyses include [Priest, Sánchez, 2001]:

1. Cost.
   b. Total manufacturing cost.
   c. Part and vendor cost.
   d. Direct labor cost to build a product.
   e. Complexity.
      i. Number of parts, parameters, features, etc.
      ii. Level of precision required (i.e. tolerances/manufacturing requirements).
      iii. Number of fasteners (assembly).
2. Schedule or lead time.
   a. Manufacturing and/or purchased part lead time.
   b. Total product lead time including ordering and shipping.
3. Quality.
   a. Projected number of defects or yields, cp and cpk.
   b. Cost of quality [pretension, measurement and warranties).
   c. Variance of critical parameters.
4. Technical risk.
   a. Number of new technologies, parts, vendors and processes.
   b. New or never before achieved levels of requirements.

The key Producibility recommendations for design and manufacture are [Priest, Sánchez, 2001]:

- Concentrate on key design parameters (i.e. key characteristics)
- Develop design parameters that are "robust" to variation
- Loosen tolerances on "trivial many" non-critical parameters and develop optimum tolerances for the "vital few" critical parameters
- Minimize design complexity
- Optimize design parameters for manufacturing processes and assembly.

One of the best practices for Producibility is Process capability information.

Producibility's goal is to:

- Reduce or minimize all requirements on non-critical areas
- Standardize requirements within the design and with other products on non-critical areas
- Optimized balance of design and manufacturing requirements on critical requirements
- Minimize the number of defects caused by variation and
- Compensate for variability by reducing its effects on a product.

Producibility also considers the variability of the process when determining design requirements. Variability is often referred to as "process, vendor or part tolerance". The cause of variability can come from the process such as purchased part, machine, environment, or operator, or can occur overtime such as aging and drift. Variability cannot be eliminated. The overall design of a product should compensate for and be *tolerant* to ever-present variations in the manufacturing processes and the parts used. When the product is placed into production, the design makes allowances for the anticipated "shifts and drifts" in the process and parts occurring over time. This can require the designer to use large design margins that reduce performance and often increase cost. The design team finds the optimum level of design requirements and manufacturing requirements. Some Producibility techniques that effectively compensate for manufacturing variability include tolerance analysis, mistake proofing, Taguchi robust design, and six sigma quality methods.

Computer simulations are used to evaluate product manufacturing. Assembly tolerances, methods and time standards, simplification analysis process requirements, production problems, and other information can also be gathered.

2.3.4 Design For Assembly (DFA).

DFA was formally recognized back in the late 1970's when G. Boothroyd and P. Dewhurst (University of Rhode Island) developed a systematized and quantified methodology to evaluate the ease of assembly. This was the first time the "common sense" rules about designing a part to make it easy to assemble had been collected for use [Boothroyd and Dewhurst, 1983; Ishii and Kmenta, 2000].

In the 1980's people such as R. Sturges at Westinghouse and a group of individuals at Hitachi's Production Engineering Research Laboratory (PERL) began developing other design for assembly tools. Hitachi Assembly Evaluation Method (AEM), Westinghouse assembly method, and the Boothroyd-Dewhurst DFA method are examples of the work done during the 1980's.

All of these tools breakdown the assembly into discrete operations by which the handling, insertion, and processing activities are evaluated according to stability, directionality, manipulability and other difficulties [Redford and Chal, 1994].

These tools became widespread throughout industry during the 1980's and early 1990's [Sturges and Kilani, 1992]. After this success in industry, it became apparent that further development was needed. M. Hinckley, hypothesized that there was a correlation between product complexity and the number of defects one could expect. Whereas the previous methods focused on reducing cycle-time by use of time studies, Hinckley's work provided a new way to look at a product's assemblability— through the complexity of the entire product. Although it is not terribly shocking that as complexity of a product increases the expected defect rate should also increase Hinckley was one of the first to document these findings [Barkan and Hinckley 1993].

Name of Tool	Organization – Author
Westinghouse (DFA)	R. Sturges
Design for Assembly	Boothroyd-Dewhurst
Sony Standard Time Assembly Method	Sony Electronics
Modified Westinghouse (DFA)	GE Aircraft Engines
Assembly Evaluation Method	Hitachi
Hinckley Assembly Complexity Factor	Standford

Table 2-3 Related Tools [Beiter, 2000]

The base for Hinckley's work was a modified approach of that developed by Sturges at Westinghouse. He adopted the Westinghouse method as the way to obtain cycle-time information for further evaluation. His complexity factor is calculated from several of the outputs of the Westinghouse spreadsheet— the total number of parts and the total assembly factor.

Pahl and Beitz [1988] define assembly as the combination of components into a product and to the auxiliary work needed during and after production. The cost and quality of a product depend on the type and number of assembly operations and on their execution. The type and number, in the run, depend on the layout design of the product and on the type of production (one-off or batch production).

They define the essential operations that are involved in the assembly process:

- Storing of parts to be assembled
- Handling of components
- Positioning and aligning
- Joining
- Adjusting
- Securing
- Inspecting

These operations are involved in every assembly process, their importance, sequence and frequency depending on the number of units and the degree of automation (manual, part automatic or fully automatic assembly).

The general guidelines established by them are:

- Decrease the number of identical components, for instance, by replacing a large number of small bolts with a smaller number of larger ones;
- Combine several components into one larger component (integral construction);
- Use pre-assembled (bought-out) assemblies; and
- Facilitate the combination of several operations by appropriate arrangement of locating surfaces and connectors, to ensure for instance, the simultaneous tightening of several bolts.

They proposed that designers should consider each assembly operation separately.

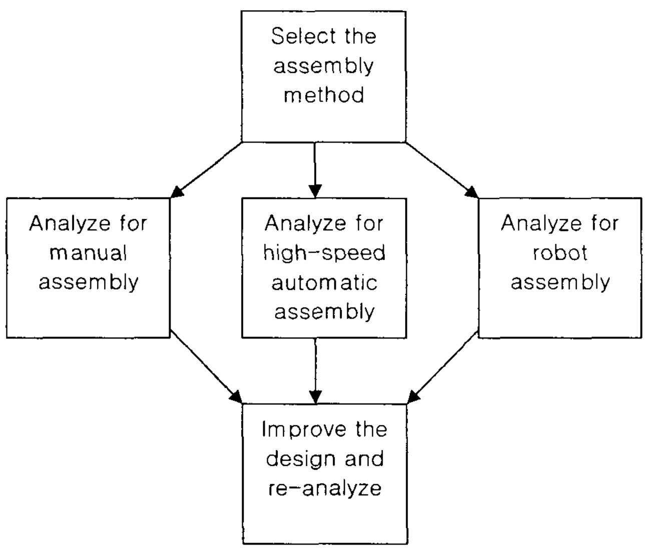


Figure 2-9 Stages in Design for Assembly Analysis.
[Boothroyd & Dewhurst, 1989]

The design for assembly process defined by Boothroyd and Dewhurst 1989 is concerning with reducing the cost of a product through simplification of its design. The best way to achieve this cost reduction is first to reduce the number or individual parts that must be assembled and then to ensure that the remaining parts are easy to manufacture and assemble. The analysis technique is systematic in its approach and is formalized step-by-step process.

The cost of assembling a product is related to both the design of the product and the assembly method used for its production. The lowest assembly cost can be achieved by designing the product so that it can be economically assembled by the most appropriate assembly method. The three basic methods are:

(1) Manual Assembly.
   - Bench or transfer-line assembly using only simple tools.

(2) Special-purpose transfer machine assembly.
   - Assemblies are transferred by an indexing transfer device (rotary or in-line).
   - Assemblies are transferred by a tree-transfer device (non-synchronous).

(3) Robot Assembly.
   - One general-purpose robot arm operates at a single work station.
   - Two general-purpose robot arms work hand-in-hand at a single station.
   - A multi-station free-transfer machine with general-purpose robot arms.

Assembly systems can be a combination of more that one of these methods.

DFA theory presented before is a common tool to evaluate designs. Many other authors as Hinckley have been modified the concept and made a more detailed tool that can be used not only to analyze or reduce assembly time, also to analyze product complexity and try to define the number of defects that could be expected.

2.3.5 Tolerance analysis.

Tolerancing methodology [Srinivasan, 1994]

This methodology provides the designer whit a viable set of parameters to estimate the effects of manufacturing variability on the design, early in the design process. Has a mathematical and physical foundation. Includes a methodology for the computation of error parameters. The error parameters abstract the structure of the manufacturing profile, this aspect provides a prospective foundation for the development of "math-based" standards for automated tolerancing.

The tolerancing methodology has three main stages: problem identification, error analysis and representation, and synthesis and validation [Figure 2.11]. These stages are divided in twelve steps that reflects the interaction between the design and manufacturing domains:

1. Identify and clarify the problem
2. Isolate tolerance sub-problem
3. Establish precision of manufacturing processes
4. Data acquisition
5. Identification of deterministic structures
6. De-trending (intercept, slope)
7. De-periodizing (offset, amplitude, frequency)
8. Outlier correction
9. Wavelet analysis (fractal dimension, magnitude factor)
10. Synthesis of realistic part models
11. Comparison
12. Performance evaluation

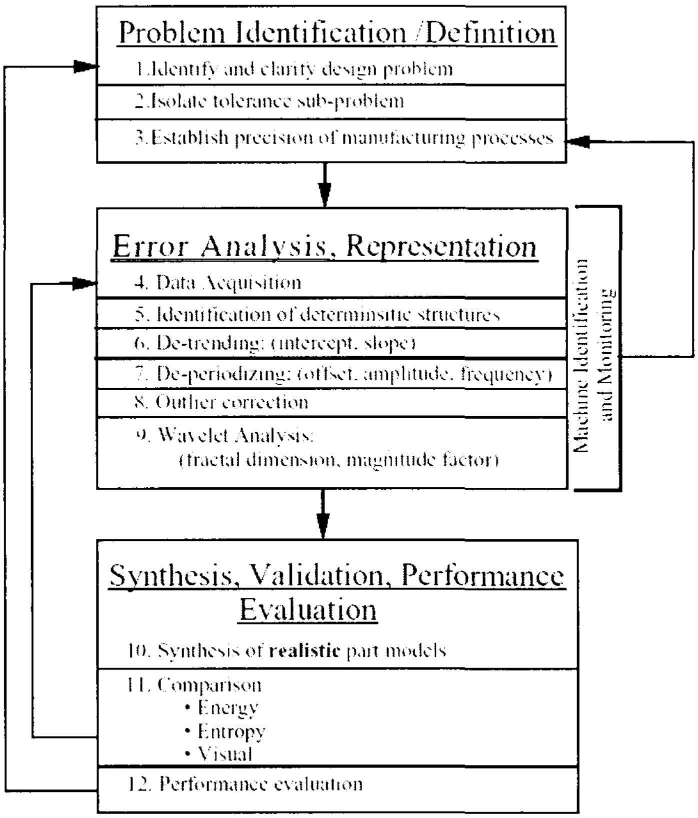


Figure 2-10 Steps in proposed tolerancing methodology for DFM.
[R.S. Srinivasan, 1994]

2.3.6 Trade-off studies.

Design trade-off studies examine alternative designs with the purpose of optimizing the overall performance of the system and reducing technical risk. Trade-off studies are therefore directed at finding a proper balance between the many demands on a design. A balance between performance, technical risk, cost, schedule, producibility, reliability, and other parameters should be established.

Appropriate attention to reliability and producibility considerations is necessary to assure that any alternatives that could provide improvement are examined. All trade-off studies need to address the possible impacts in design decisions on all aspects at the appropriate level of detail. To be most effective, design analyses must be an integral, timely part of the detailed design process. Otherwise, the analyses merely record information about the design after the fact. Changes made later in a program are more costly and less likely to be incorporated [Priest, 1988].

Relationship of design elements in trade-off studies [Priest, 1988].

Environmental analysis		Design policy/criteria
Mechanical stress analysis		FMEA and criticality analysis
Thermal analysis		Worst-case analysis
Design requirements and analysis	Design Trade offs	Packaging analysis
Reliability allocations		Sneak circuit analysis
Testability analysis		Bit+ate analysis
Producibility analysis		Breadboarding results
Facility requirements		Human factors
Supportability and maintainability analysis		Safety

2.3.7 Worst-case and parameter variation analyses.

A part's parameter change with time (i.e. aging) and environmental conditions (i.e. stress). These effects can be characterized and described by statistical distributions. A given parameter has a mean value and a variance (i.e. tolerance) that vary depending on the manufacturing techniques, testing, environmental conditions, and aging. Two methods are often applied in design analyses to compensate for the effects of variations caused by stress and time. These methods are worst-case analysis and parameter variation analysis. These methods determine whether the various part distributions can combine in such a way as to cause the product's performances to be out of specification [Priest 1988].

A worst-case analysis is a rigorous evaluation of the ability of a design to meet operational requirements under the worst possible combination of circumstances. This is accomplished by determining the worst-case values of critical design parameters –high and low- that could affect performance, producibility and so on. Design parameters are then evaluated for both high and low conditions. If the overall performance under these conditions remains within specified limits, then the design has been shown to be reliable over the worst possible conditions. If the output performance is not within acceptable ranges, probability of failures occurrence is more even the individual parts are within their specifications.

The parameter variation analysis method is a less rigorous methodology that determines allowable parameter variation before a design fails to function.

Parameters, either one at time or two at time, are varied in steps from their maximum to their minimum limits, or vice versa, while all other inputs parameters are held at their nominal value. Data are thus generated to develop safe operating envelopes for the various parameters. These parameters envelopes are often plotted and are called Schomoo plots. If each parameter or plot is kept within the safe operating limits, the design will perform satisfactorily [Priest 1988].

Another tool that had been more used in recent years and can be comparable to parameter variation is Design of Experiments (DOE).

2.3.8 Functional Analysis.

The importance of simulation is because:

- Increase the level of knowledge of how the product interacts with the environment; assess the benefits, costs, and attributes of each requirement.
- Perform design trade-off studies to optimize various design elements, such as performance, producibility, and reliability.
- Verify that the design ensures that it can meet all requirements.

The following are some analysis areas that help designers test his models:

- Structural Analysis (Linear and non-linear).
- Motion Analysis (Interference, Dynamics and Kinematics).
- Modal (Normal Mode Dynamics, Modal Response).
- Thermal (Thermal response to specified heat loads and transient thermal analysis).
- Electromagnetic Analysis (Magneto-static, Electro-static problems etc).
- Mold Flow Analysis.
- Computational Fluid Dynamics.
- Stress Analysis.
- Dynamics.
- Vibration.
- Seismic.
- Shock.
- Drop Test.

Examples of CAE Software are:

- Pro/Mechanica
- Ansys.
- Nastran.
- Patran.
- Adams.
- Working Model
- StarC

2.4 Methodologies in Mechatronics Design.

2.4.1 Defining Mechatronics.

Some definitions of mechatronics are:

- Is the synergetic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and processes [Bradley, Dawson, Burd, Loader, 1993].
- Mechatronics is used to denote a rapidly developing, interdisciplinary field of engineering dealing with the design of products whose function relies on the integration of mechanical and electronic components coordinated by a control architecture [Alciatore, Histand, 2003].

In May 1997 edition of the Mechanical Engineering Magazine, the author Ashley gave some definitions about mechatronics.

> For Takashi Yamaguchi, mechatronics is "a methodology for designing products that exhibit fast, precise performance. These characteristics can be achieved by considering not only the mechanical design but also the use of servo controls, sensors, and electronics. For Giorgio Rizzoni, mechatronics is "the confluence of traditional design methods with sensors and instrumentation technology, drive and actuator technology, embedded real-time microprocessor systems, and real-time software." Mechatronic (electromechanical) products, he said, exhibit certain distinguishing features, including the replacement of many mechanical functions with electronic ones, which results in much greater flexibility and easy redesign or reprogramming; the ability to implement distributed control in complex systems; and the ability to conduct automated data collection and reporting.
>
> For Masayoshi Tomizuka, "Mechatronics is really nothing but good design practice". "The basic idea is to apply new controls to extract new levels of performance from a mechanical device." It means using modern, cost-effective technology to improve product and process performance and flexibility.
>
> The journal IEEE/ASME Transactions on Mechatronics, first published in March 1996, is another indication that the importance of this interdisciplinary area is being recognized. Transactions covers a range of related technical areas, including modeling and design, system integration, actuators and sensors, intelligent control, robotics, manufacturing, motion control, vibration and noise control, microdevices and optoelectronic systems, and automotive systems.

The next diagram illustrates that mechatronics is where mechanics, electronics, computers, and controls intersect.

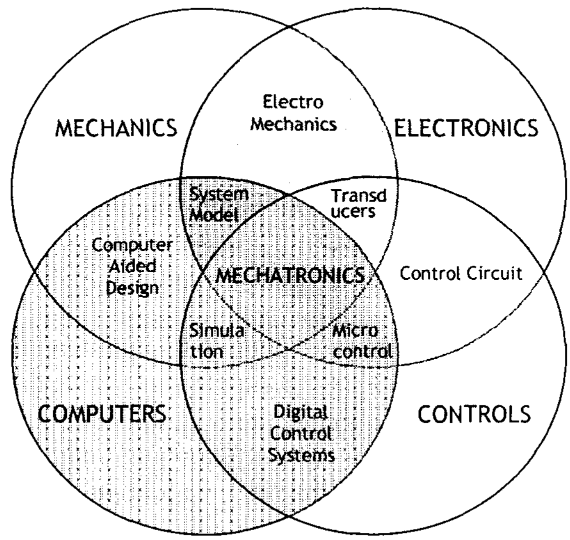


Figure 2.11. Interaction of disciplines in Mechatronic Design [Ashley, 1997]

For the author, mechatronics is the integration of mechanical, electronic and software design, controls are an integration of electronic and software design.

2.4.2 The Roots of Mechatronics

Mechatronics was first used in terms of the computer control of electric motors by an engineer at Japan's Yaskawa Electric Co. in the late 1960s. The word has remained popular in Japan, and has been in general use in Europe for many years. Although mechatronics has been slow to gain industrial and academic acceptance as a field of study and practice in Great Britain and the United States, its increasingly prominent place worldwide is shown by the growing number of undergraduate and postgraduate mechatronics courses now being offered.

In the 1970s, mechatronics was concerned mostly with servo technology used in products such as automatic door openers, vending machines, and autofocus cameras. Simple in implementation, the approach encompassed the early use of advanced control methods, according to Transactions editors.

In the 1980s, as information technology was introduced, engineers began to embed microprocessors in mechanical systems to improve their performance. Numerically controlled machines and robots became more compact, while automotive applications such as electronic engine controls and antilock-braking systems became widespread.

By the 1990s, communications technology was added to the mix, yielding products that could be connected in large networks. This development made functions such as the remote operation of robotic manipulator arms possible. At the same time, new, smaller -even microscale- sensor and actuator technologies are being used increasingly in new products. Microelectromechanical systems, such as the tiny silicon accelerometers that trigger automotive air bags, are examples of the latter use.

The view of Belgian robotics researcher Hendrik M. J. Van Brussel, published in Transactions [June 1996]: "In the past, machine and product design has, almost exclusively, been the preoccupation of mechanical engineers,". Solutions to control and programming problems were added by control and software engineers, after the machine had been designed by mechanical engineers.

Van Brussel [2001] wrote:

- "Recently, machine design has been profoundly influenced by the evolution of microelectronics, control engineering, and computer science,".
- **"What is needed, as a solid basis for designing high-performance machines, is a synergistic cross-fertilization between the different engineering disciplines.** This is exactly what mechatronics is aiming at; it is a concurrent-engineering view of machine design."
- "Mechatronics encompasses the knowledge base and the technologies required for the flexible generation of controlled motion."
- An essential feature in the behavior of a machine is the occurrence of controlled and/or coordinated motion of one or more machine elements. "The generation and coordination of the required motions, such that the increasingly growing performance and accuracy requirements are satisfied, is the raison d'etre of mechatronics."

Van Brussel idea is that traditional mechanisms are limited in their flexibility in generating a wide variety of motions. Also restricted is their potential for creating complex functional relationships between the motion of the actuator and that of the driven element. Yet another limitation of purely mechanical drive systems is their inherent lack of accuracy, caused by friction, backlash, wind-up errors, resonances, dimensional errors, and so forth.

2.4.3 Gausemeier, 2002 – From mechatronics to Self Optimization

It starts from the idea of a product or business and leads to the successful product launch and incorporates the areas of product planning responding product marketing, R&D and manufacturing process planning. The product innovation process can be viewed as a phase model. A phase model describes the fundamental work flow, which does not mean, however, that one phase must be finished before the next one can be started or that an iterative approach is not possible. In practice, the product innovation process comprises a number of cycles.

The first cycle characterizes the steps from finding the success potentials of the future to creating the promising product design, what we call the principle solution.

There are four major tasks in this cycle:

- foresight,
- product discovering,
- business planning and
- conceptual design.

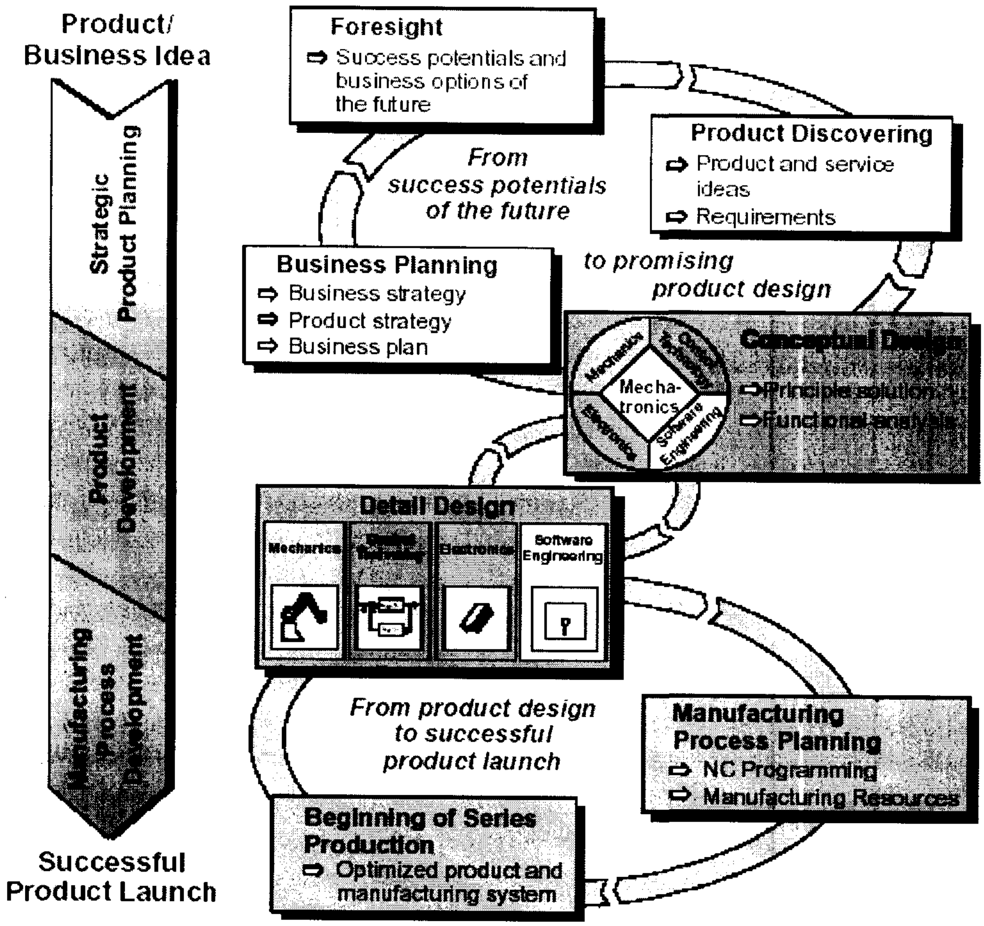


Figure 2.12. The product Innovation Process [Gausemeier, 2002]

The aim of foresight is to recognize the potentials for future success, as well as the relevant business options. We use methods such as the scenario technique, Delphi studies and trend analyses. But the smartest approach is the scenario technique, it helps us to think ahead the future as distinct from predict the future. Sometimes it encourages us to expect the unexpected. That could be the way to be ahead of the race. Be that as it may, the scenario technique gives an impression how the future could be and what opportunities and threats are coming up.

The objective of product discovering is to find new product ideas. We apply in this phase creativity techniques such as Lateral Thinking of de Bono or the well-known TRIZ.

Business planning initially deals with the business strategy, i.e. answering the questions as which market segments should be covered, when and how. The product strategy is then elaborated on this basis. This contains information on:
• setting out the product program,
• cost-effective handling the variety of variants required by the market,
• the technologies used (that can be expressed by technology road maps) and
• updating the program over the product lifecycle etc.

In addition a business plan must be worked out to make sure whether an attractive return on investment can be achieved or not.

This first cycle is concerned with the conceptual design, although this area of activity is actually assigned to product development in the narrower sense. The result of the conceptual design is the principle solution. It is e.g. required to determine the manufacturing costs needed in the business plan. That is the reason why there is a close interaction between strategic product planning and conceptual design.

The second cycle corresponds to the actual understanding of product development. The essential point here is the refinement of the cross-domain principle solution by the experts from domains involved, such as mechanical engineering, control technology, electronics and software engineering. As a matter of course there must be a close interaction of conceptual design and domain specific design.

The third cycle focuses on manufacturing process development and the optimization of the product design. In principle, the seven activities listed in the figure are worked through from top to bottom, as indicated also by the arrow to the left in the diagram. Our approach should underline that the product development should be processed in an integrative way.

Specialists from the departments of product planning, R&D and manufacturing process planning but also from domains, such as mechanical engineering and informatics, must cooperate closely in order to create a successful product. Obviously, the ability of people to cooperate single-mindedly is the most important success factor on the way to creating products for the markets of tomorrow.

2.4.4 Guideline VDI 2206 "Design Methodology for Mechatronic Systems"

The new VDI Guideline 2206, with the title "Design methodology for mechatronic systems", has been worked out. It is intended to consolidate the substantial knowledge, that has been gathered in recent years from research projects and practical applications, and make this available to practitioners.

The metaphor to represent the design process is the "V-model", which has been adopted from the field of software development [Figure 2.17]. It describes the generic approach to the development of mechatronic systems. The starting point here is the list of requirements. The system design specifies the cross-domain principle solution, and the domain-specific design further concretizes the principle solution, in general this will be done separately for each of the domains involved.

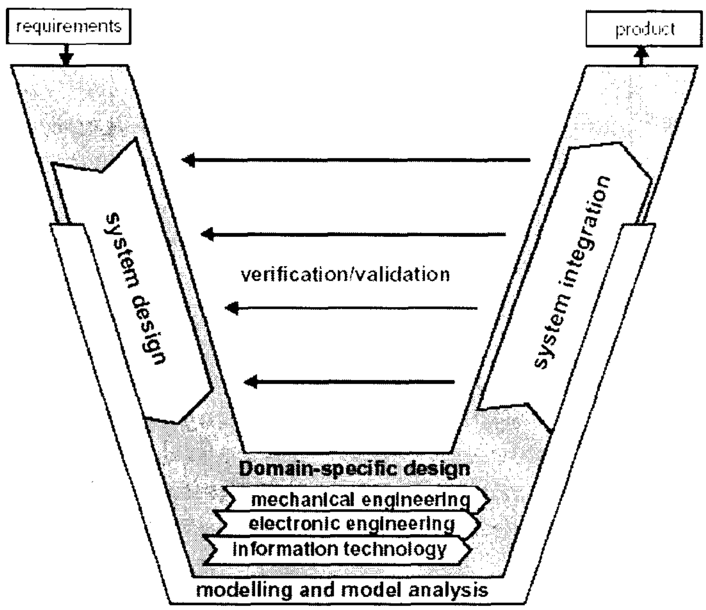


Figure 2.13. The design process based on the V-Model [Gausemeier, 2002]

At the system integration stage, the results from the individual domains are then integrated to constitute a complete system. This is done in particular, so that the interactions can be investigated. This stage includes verifying and validating the properties, i.e. checking that the actual system properties correspond to the required ones.

The development process described so far is supported by computer models to map and investigate the system properties.

The end result of a macrocycle, based on the V-model, is a product with a certain degree of maturity, for example, a laboratory sample, prototype, pre-series product, and so on. The development of a complex mechatronic product will generally require a number of macrocycles as shown in the figure 2.17.

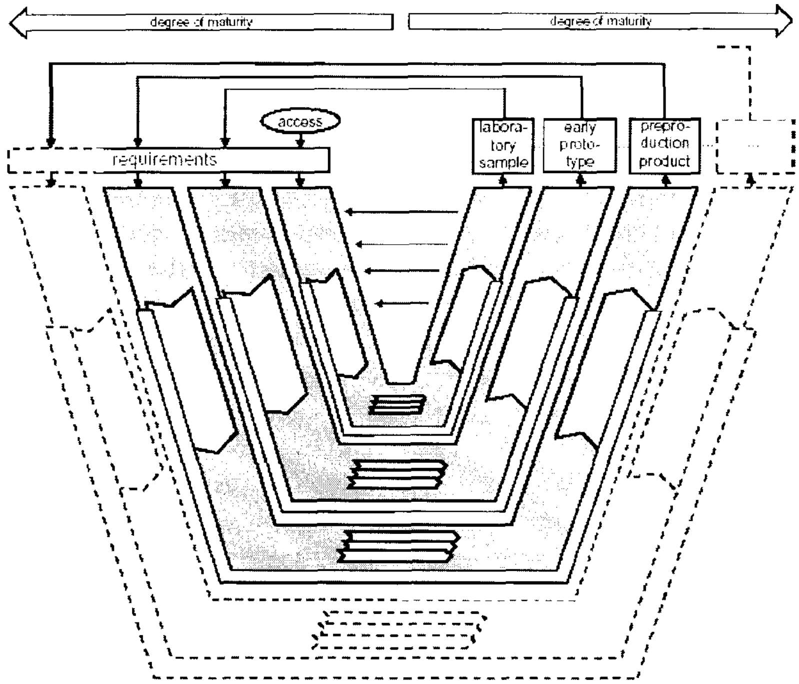


Figure 2.14. Quite a number of macrocycles must be applied to obtain a final design of a complex mechatronic product [Gausemeier, 2002]

2.5 Comparison of Design Methodologies.

Detailed methodologies are divided in mechanical, electronic and software products. It is required that those methodologies could be used concurrently to design Mechatronic systems. It is important to describe how to use those methodologies concurrently, the phases in the design process, the activities required in each phase, the flow of information, the methods used in each phase or activity and some other organizational issues.

Many problems in the use of methodologies are because the best methodologies and design processes lose impact when they are not used effectively and efficiently. This insufficiency is generally a result of the usage of too many, wrong or not embedded and adjusted means.

There are a lot of different solutions, practices, methods, and tools that have been developed to overcome problems and to enhance effectively and efficiency in product development. The difficult thing is to select and implement the right mix of solutions and means that fit in to a particular problem of product development with it specific problems, constraints, goals, processes, organization, products, and environment.

Many reason because people are reluctant to many design activities or methods/tools are:

- Wrong methods and tools: Methods and tools are not universal remedies. They can serve as a support to better carry out the right processes in the proper environment.
- No user-oriented: Supporting methods often are developed without closely involving the later uses of these means. Therefore, they tend to be too theoretical, sophisticated, or difficult to learn and use.
- Not accepted: Methods and tools which are not accepted will not be used. They need to be promoted by management but adjusted by the user and included in a framework such a process or rules.
- Adjusting: Methods should be learned by doing, consequently they should be adjusted to the specific situation and environment of the company.
- Wrong environment: the introduction of new methods and tools is seen as a major threat to people who will have to change some of their habits.
- Too many: A few well known and utilized are certainly better than a lot of unused.

Analyzing the methodologies presented before, the next table presents the results of evaluating them in three aspects about the description of the activities and information offered to the reader:

- *Product Design Cycle Coverage.* It is about if the methodology includes the four design stages defined by the author: Product Planning, Conceptual Design, Embodiment Design, Launching/Production. The qualification symbols used are: (blank) If the methodology doesn't include that phase, (-★) If the methodology include that phase but is described poorly, (★) If it is included and explained widely.

- *Engineering tasks coverage.* Qualify if the methodology has Analysis, Synthesis and Evaluation activities. The qualification symbols used are: (blank) If the methodology does not include that activity, (★) If it is included.

- *Detailed Description of:* Functions or Activities, the flow of Product Information, Organizational Issues and the Methods used in each phase. The qualification symbols used are: (blank) If the methodology doesn't include that issue, (-★) If the methodology include that issue but is described poorly, (★) If it is included and explained, and (★★) If it is included and explained widely.

Methodology	Application Area	Phases	Product Design Cycle Coverage		Engineering tasks coverage.			Description of:			
					Analysis	Synthesis	Evaluation	Functions / activities	Product Information	Organization issues	Methods
PAHL AND BEITZ 1988	Engineering Design	4	Product Planning	★	★	★		★	★	★	★
			Conceptual Design	★	★	★	★	★	★	★	★
			Embodiment Design	★	★	★	★	★	★	-★	★
			Launching/production								
ULLMAN 1992	Mechanical Design	3	Product Planning	★	★	★	★	★	★	★	★
			Conceptual Design	★		★	★	★	★	★	★
			Embodiment Design	★		★	★	★	★	★	★
			Launching/production								
PRIEST 1988	Engineering Design	5	Product Planning	-★	★				★	★★	
			Conceptual Design	★	★				★	★	
			Embodiment Design	★	★		★		★	★	★
			Launching/production								
KMETOVICZ 1992	Product Development	5	Product Planning	★	★				★	★	
			Conceptual Design	★	★	★	★	★	★	★	
			Embodiment Design	★	★	★	★	★	★	★	
			Launching/production								
ICHIDA, Design Review 1996	Product Development	-	Product Planning	★					★	★★	
			Conceptual Design	★					★	★	
			Embodiment Design	★					★	★	
			Launching/production								
KUSIAK A 1999	Engineering Design	5	Product Planning							★★	★
			Conceptual Design	★	★	★				★	★
			Embodiment Design	★	★	★	★		★	★	
			Launching/production								
OTTO AND WOOD 2001	Generic Design Process	3	Product Planning	★	★	★	★	★	★	-★	★★
			Conceptual Design	★	★	★	★	★	★	-★	★★
			Embodiment Design	★	★	★	★	★	★		★★
			Launching/production	★	★	★	★	★	★		★★
YANG, EL-HAIK 2003	Product Development	4	Product Planning	★	★	★	★	★	★	★	★
			Conceptual Design	★	★	★	★	★	★		★
			Embodiment Design	★	★	★	★	★	★	★	★
			Launching/production	★	★	★	★	★	★		★
FARIAS 2003	Generic Design Process	4	Product Planning	★	★	★	★	★	★	★	★★
			Conceptual Design	★	★	★	★	★	★	★	★★
			Embodiment Design	★	★	★	★	★	★	★	★★
			Launching/production	★	★	★	★	★	★	★	★★

Figure 2.15. Comparison of Design Methodologies.

Chapter 3 . Integration of Evaluation Methods and Techniques.

3.1 Introduction.

The design process is regularly an extensive process depending on the product complexity. Following a methodology this process can be shortened in time and compile information in a more organized way. The methodology for rapid mechatronic product development and manufacturing is organized in four phases for the product development process.

	Phase
1	Product Planning
2	Conceptual Design
3	Embodiment Design
4	Prototyping

Figure 3.1 Design phases for the methodology.

Important information is gathered through the product development process, and some conclusions or definitions have to be obtained from that information. The designer has the responsibility to clearly define the correct parameters, features, attributes and other information that will intervene in the product definition process. At the early stages of the product development process, all the features of the product that is going to be designed have to be clearly established and understood by all the members of the design team.

Many decisions have to be made during the product development process, this decisions can be:

- Selection of design parameters (QFD).
- Selection of design concepts (Morphological matrix).
- Selection of layout, component shapes, materials, dimensions.
- Selection between few final alternatives.

3.2 Review Algorithm.

Design is an iterative process. After each new step, it may become necessary to upgrade or improve the result of the last; that is, to repeat it at a higher information level, and to reiterate until the necessary improvement has been made, when possible. A Review Algorithm is being proposed to identify when it is necessary to iterate and when the result is enough good to pass to the next design activity. This algorithm is an evolution from many authors, first Krick [1969] and Penny [1970]; this algorithm was later modified by Yang [2003] in his DFSS approach of product development.

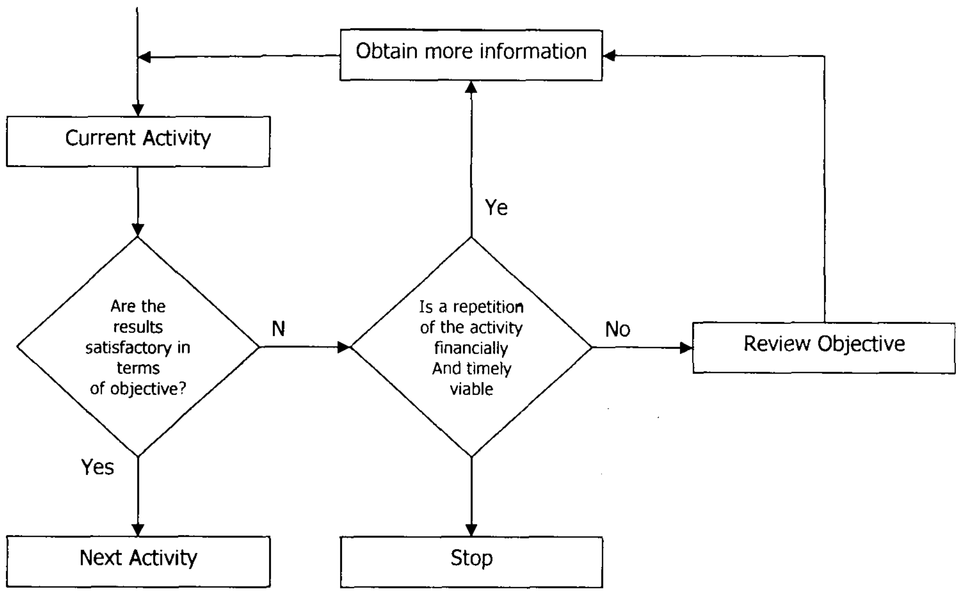


Figure 3.2 Review Activities Algorithm [Yang, El-Haik, 2003]

To explain how it works, an example is shown next.

Activity: Market Requirements Analysis
Objective: Identify and define all the customer information about an analog/new product categorized by:

- Typical uses
- Likes
- Dislikes
- Suggested Improvements

Define the customer statement, the interpreted need and the importance for each one of the last three.
Technique: Customer Interview.

The Record obtained from that interview show the information that was gathered. The information is compared with the objective and a decision is made. The interview is shown next.

Customer Data: SAC (Sistema de Aprendizaje y Conocimiento)
Customer: Myrna Sánchez García — Interviewers: Joaquín Aca, David, Paola FM, Amir P
Adress: Lázaro Garza Ayala No. 1000 Pte
San Pedro Garza García, Nuevo León — Date: August 15, 2003
Willing to do follow up? Y — Currently uses: Communication media
Type of user: Teacher

Question	Customer Statement	Interpreted Need	Importance
Typical uses	Answer questions		
	Make questions		
	Transmit feelings		
	Inform about needs		
	Call for help		
Likes	Easy to use	Simple	Must
	Small	Small	Must
	Cheap	Cheap	Must
	Not damaged when falling	Resistant material	Must
	Nontoxic	Non toxic	Must
	Independent	No computer needed	Must
	Dual system	batteries-connector	Nice
	Manageable	With handle	Nice
	Light	With light	Nice
	Easy to clean	Flat surface	Nice
	Reconfigurable	Recordable	Good
	Resistant to the liquids	No holes	Should
	Space for user information		Should
	A lot of information available	As much as possible figures	Should
			Good
Dislikes	Few information available	Few figures	Must
	Computer needed	Computer needed	Must
	Inadequate size of the product	Big products	Good
	Inadequate size of the figures	Small figures	Good
	Heavy product	Heavy product	Good
Suggested Improvements	2000 messages and figures available Resistant to: cold, hot, rain,		

Figure 3.3 Example of Interview Record.

This methodology will help designers to ensure that they are doing correct decisions during the design process and as a result, the product will perform correctly its function.

The evaluation and review methods used are organized, a set of them are defined for every design phase accordingly to the necessities of designers at each activity. The next table shows the classification.

Phase	Evaluation Tools
Product Planning	■ Product Selection/Evaluation [Pugh] ■ QFD ■ Parametric Analysis ■ Review of Technical Requirements ■ Product Competitiveness
Conceptual Design	■ Idea Selection ■ Concept Selection/Variants Evaluation ■ Attacking the Negatives
Embodiment Design	Mechanical Design: ■ Checklist ■ FMEA ■ DFM-DFA ■ Value Engineering ■ Design Test (CAE) ■ Tolerance Analysis Electronic Design: ■ Simulation Software Software Design: ■ UML Language
Prototyping	■ Materials/process Selection [Pugh] ■ Prototype Evaluation

Table 3.1. Evaluation Tools in the Methodology.

Also, because of the variety of problems that can be encountered in a design process, the methodology includes a Tool Box, where the designers should select the best tool for their problem and adapt it. As was mentioned before, the set of activities including the tools and methods should be learned by doing and it is better if the designer adjust them to their specific situation and environment of the company.

Research in the design area demonstrated that design is a problem solving process. There is a three-phase problem solving approach to design, for example, Analysis, Synthesis and Evaluation that has been widely accepted by many researchers [Coyne et. Al. 1990, 2002]. The first stage is to diagnose, define and prepare, the second is to synthesize solutions and the final stage is to test those solutions against the goals and requirements.

Analysis is the resolution of anything complex into its elements and the study of these elements and of their interrelationships. It calls for identification, definitions, structuring and arrangement.

Synthesis is the putting together of parts or elements to produce new effects and to demonstrate that these effects create an overall order. It involves search and discovery, and also composition and combination. An essential feature of all design work is the combination of individual findings or sub-solutions into an overall working system, that is, the association of components to form a whole. During the process of synthesis the information discovered by analyses is processed as well. In general, it is advisable to base synthesis on a global or system approach; in other words, to bear in mind the general task or course of events while working on sub-tasks or individual steps.

Evaluation is the defining phase in the problem solving or design process. These compositions and combinations have to be evaluated to choose the one that fulfill more requirements. Also define which the best design is, or propose corrections, through the use of some techniques.

I propose a bi-axial information transformation space. The axes are the Design Phase and Activity for the product design process. This methodology will be explained in detail in Chapter 4.

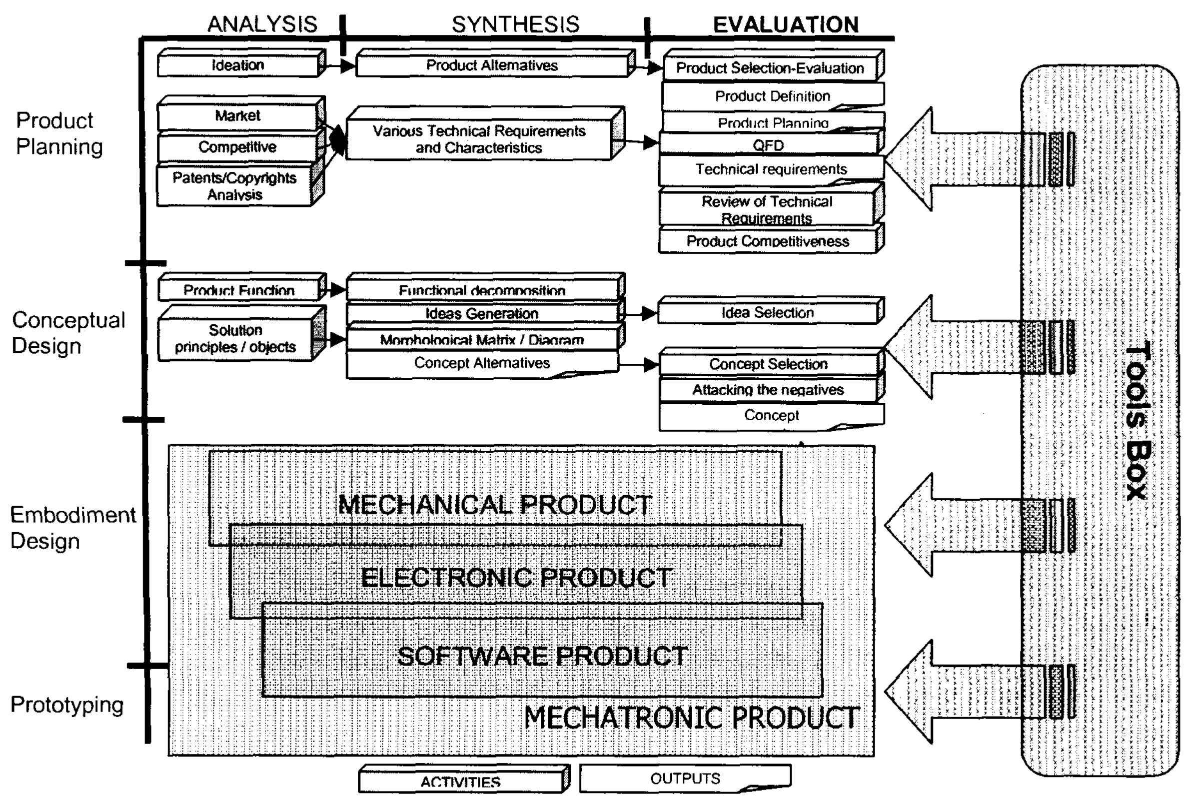


Figure 3.4 Product Design Methodology Model.

Chapter 4. Methodology for Rapid Mechatronic Product Development and Manufacturing.

4.1 Methodology Description.

In the present chapter, the author will propose a methodology for Mechatronic Product Design. The concept refers to a bi axial information-transformation space. Axe 1 refers to the activities in the design process. It begins whit the product planning and the final result is a functional prototype. Axe 2 refers to the phases in the design process (Analysis, Synthesis, and Evaluation). Figure 4.1 presents Methodology Model.

This methodology is a proposal that will help designer in the art of design. Although design is something that involves creativity and flowing of ideas (freedom of thinking), there is the need to have a detailed methodology to help designers choose the good ones and get the knowledge required to design. Also this methodology should be viewed and used as a generic template, a design algorithm with ample flexibility for customization to fit companies' specific needs.

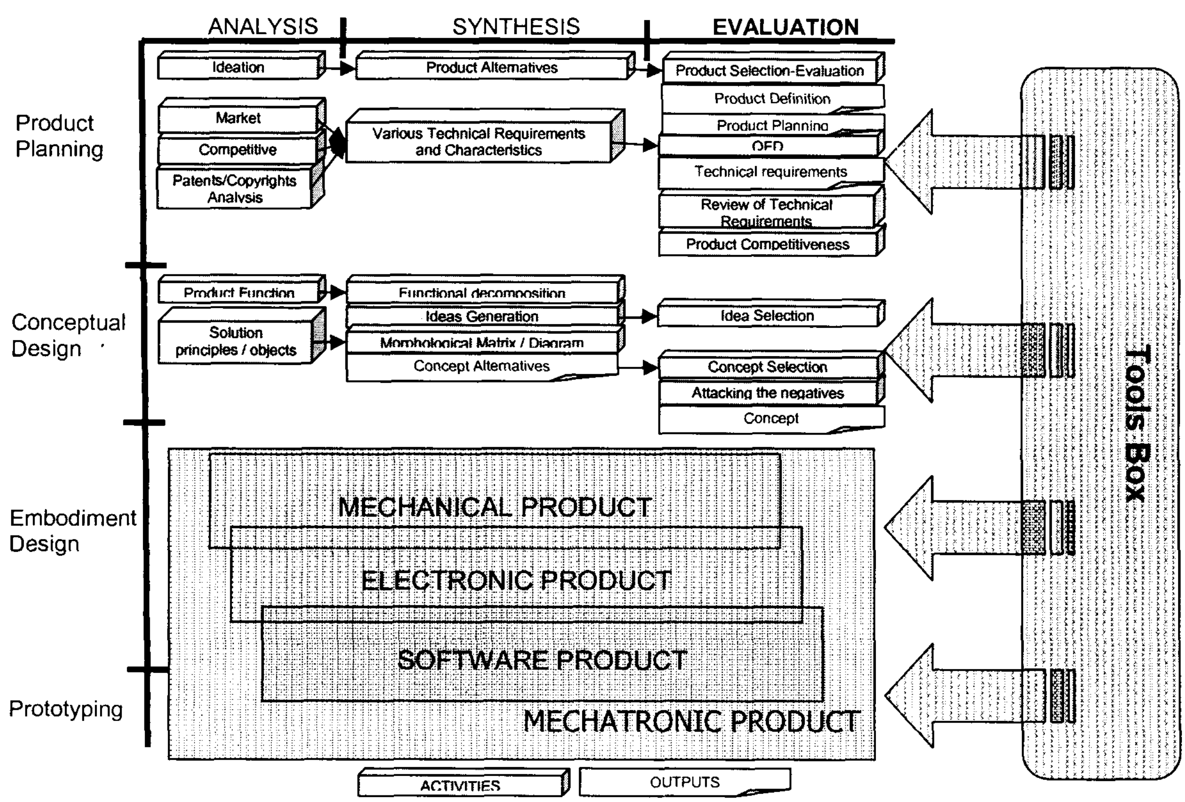


Figure 4.1 Methodology for Rapid Mechatronic Product Development and Manufacturing.

The methodology is focused in the conceptual and embodiment design phases because:

- A lot of decisions have to be made.
- These are the most difficult areas for designers; they need a high level of concretization.
- Especially embodiment design phase is like a "big black box" where lot aspects of the product (technical, safety, ergonomics and economic requirements, among others) have to be considered and shaped.

The activities defined in the Product Planning and Conceptual Design phases are the same without concerning the type of product (mechanical, electrical or software). Different activities are defined in the Embodiment Design and Prototyping phases.

In conceptual design are analogous activities for Mechanical, Electronic and Software. Although the general activity is the same, the tools and techniques are different in some cases. Software design process is the most differentiated.

General Activity	Mechanical (Method)	Electronic (Method)	Software (Method)
Product Function	Description.	Description.	1. Description 2. Domain Modeling (Class Diagram)
Functional Decomposition	Functional Decomposition Diagram	Functional Decomposition Diagram	Case Modeling (Use Cases)
Ideas generation/selection	Ideas Generation Session	Ideas Generation Session	Ideas Generation Session
Solution principles to fulfill the function	Research of Solution Principles	Research of components	1. Identify boundary, entity and control objects. 2. Make case packages.
Morphological Matrix	Morphological Matrix	Morphological Matrix for components	Robustness Diagram
Concept Alternatives	Various combinations from Morphological Matrix.	Various combinations from Morphological Matrix.	Various Robustness Diagrams
Concept Selection/Variants Evaluation	Pugh Charts, Variants Evaluation	Pugh Charts, Variants Evaluation	Pugh Selection with UML criteria.
Concept	Sketch.	List Function-Component	1. Robustness Diagram 2. Domain (static) model updated.

Table 4.1. Analogous Activities in the Conceptual Design Phase.

The Methodology concept for Mechanical Design is represented in Figure 4.2. The embodiment design activities include identify embodiment requirements, scale drawings, preliminary layouts and definitive layouts. A set of supporting/evaluation tools are proposed to help designers make correct decision, do not forget important design aspects, and evaluate functionality, manufacturing, etc. These activities will be described in detail in next sections.

Analysis activities for embodiment design include embodiment requirements, and identify the function carriers. Synthesis activities include scale drawings and preliminary layouts where the designer synthesizes all the knowledge gathered in the analysis activities. Evaluation activities, as was mentioned in chapter 3, are developed during or to support the synthesis activity. Examples of that are shown in Chapter 5.

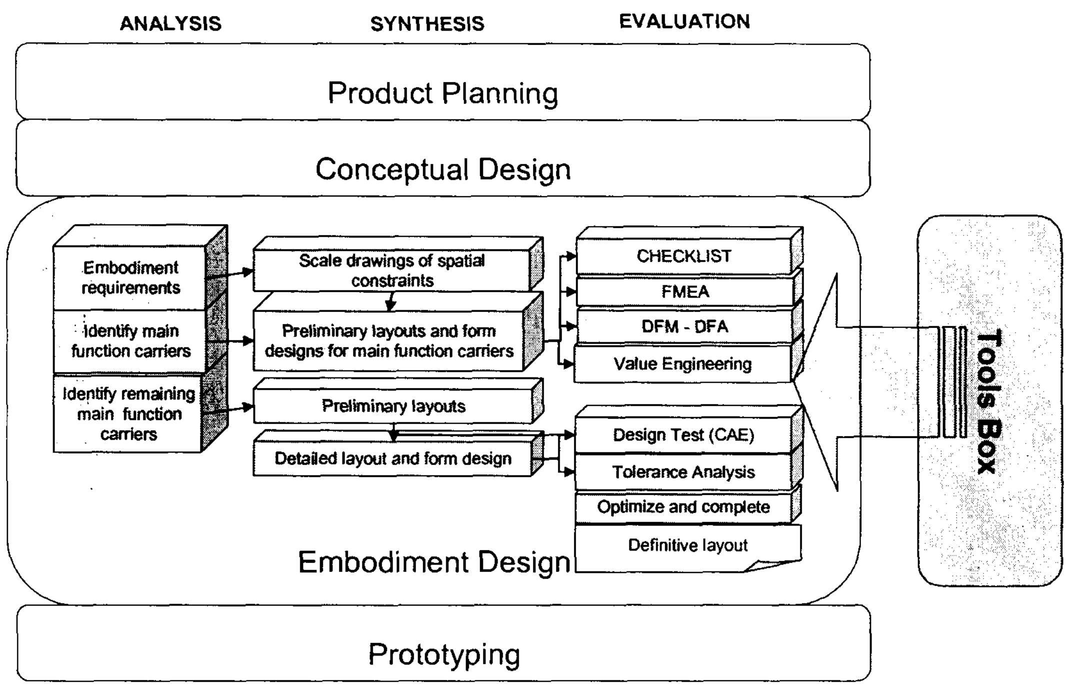


Figure 4.2 Methodology for Rapid Mechatronic Product Development and Manufacturing for MECHANICAL DESIGN.

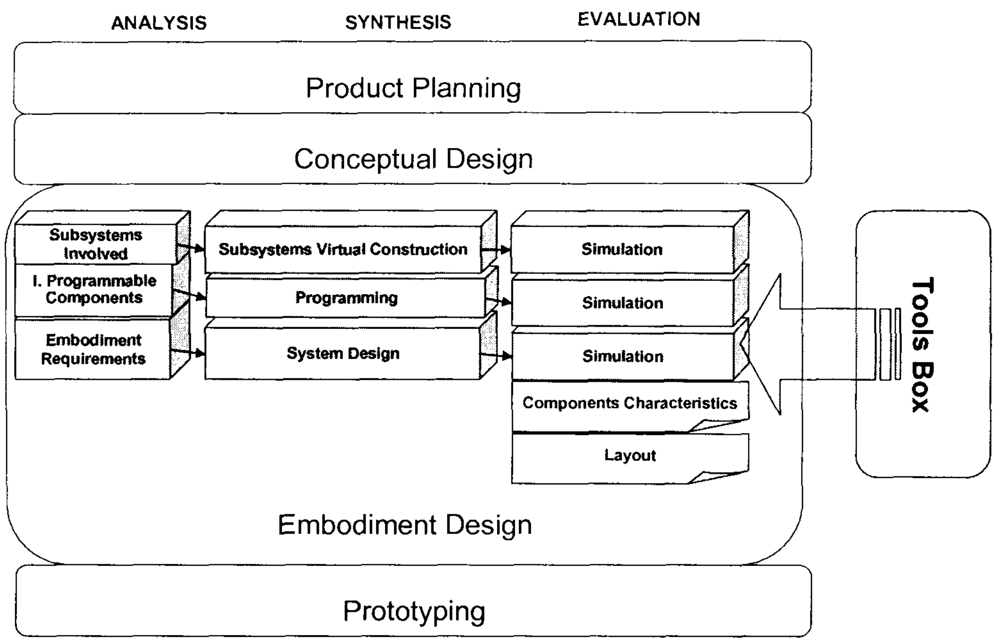


Figure 4.3 Methodology for Rapid Mechatronic Product Development and Manufacturing for ELECTRONIC DESIGN.

The Methodology concept for Electronic Design in represented in Figure 4.3. The embodiment design activities include identify subsystems involved, virtual construction, programming (if necessary) and simulation.

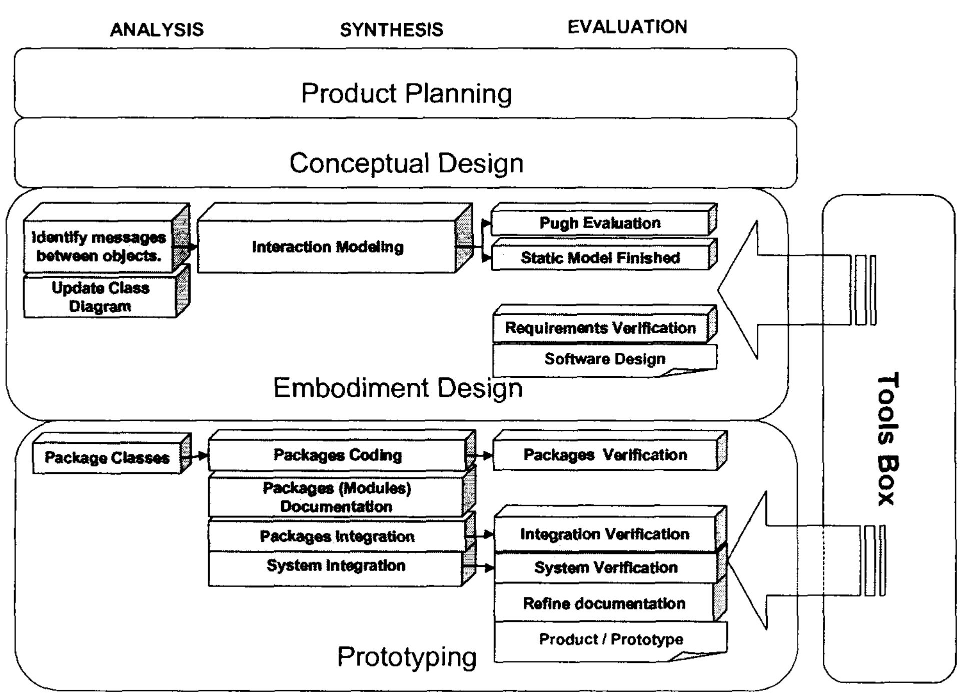


Figure 4.4 Methodology for Rapid Mechatronic Product Development and Manufacturing for SOFTWARE DESIGN.

A detailed description of each activity is presented in this chapter.

Before the methodology is explained in detail, there are some organizational aspects that have to be considered.

Creativity vs. procedures.
When ever possible, separate the critical from the creative activities. That is, let designers realize technical activities and define a business team to business activities. It is more possible that these two teams interact in product planning and conceptual design phases because many decisions include cost analysis and some other administrative criteria.
Embodiment design phase has to be leader by design team because the necessity of detailed knowledge about technical aspects and almost all evaluation activities have to be developed by this leader team.

Team.
Team may be defined as two ore more persons engaged in a common goal, who are dependent on one another for results, and who have joint accountability for the outcomes. The pride principles must be followed in any product development project: Purpose, Respect, Individuals, Discussions, and Excellence. Working in team is common to define team roles. Exist a variety of ways to describe and present team roles. One approach is to distinguish important roles according to titles and brief distinguishing features. They are simply meant to provide guidance and assist in understanding how a design team should function.

Design Team.
An interdisciplinary design team is preferable to have all the knowledge required. Engineers and designers interactions are daily activities to develop the product concurrently. But engineers and designers **do not have to work together all the time** because they often find frustrated, feeling like the other party could care less for their concerns. Design team should include additional areas of expertise that reflect the nature of the product. The core team should be relatively small and should stay together throughout the process with expertise added and subtracted as needed.

Business team.
Business team has to contain people that know the business of the company: marketing, research, etc.

The roles that have to be considered are: [Wilde, 1993: Wild et al, 1998]

- Administrator/Reviewer.
- Troubleshooter/Inspector.
- Producer/Test Pilot
- Manager/Cordinator
- Conserver/Critic
- Expediter/Investigator
- Conciliator/Performer
- Mockup maker/Prototyper/Modelmaker
- Visionary

- Strategist
- Needfinder
- Entrepreneur/Facilitator
- Diplomat/Orador
- Simulator/Theoretician
- Innovator
- Director/Programmer
- Organizer
- Motivator
- Pusher
- Soldier
- Gatherer
- Listener
- Completer
- Specialist
- Evaluator

To understand how human personalities can be made to work effectively together as a team the Myer-Briggs Type Indicator (MBTI) is used. The MBTI is a simple measurement indicator of how people behave and contribute in a work environment. MTBI is based on the work of Carl Jung [1875-1961]. Jung's model of psychological types describe four categories to distinguish personality: how a person is energized (Extroversion vs. Introversion), what a person pays attention to (Sensory vs. Intuition), how a person decides (Thinking vs. feeling), and what kind of outlook on life a person adopts (Judgement vs. Perception).

Tailoring.
The methodology is adaptable. Some times, the designer will start with a project that is already defined by the market, so he will use only the conceptual, embodiment and prototyping phases of design. You can start at any phase depending in the information available. Some methods and techniques are categorized and mentioned in the methodology in case the design problem requires additional ones.

Design Documentation.
A good design should include documentation. Although it may be impossible to document every conceptual thought, reason, calculation, or decision during the design stage, it is possible for engineers to provide better documentation during the design process. The purpose of design documentation is to provide a path of communication between the design engineer and those who must direct, review, and manufacture the design. Drawings that are well thought out, concise and articulate help all members of the project team.

One reason good documentation is difficult to produce is that the areas of responsibility for generating it tend to overlap between the different design disciplines.

The benefits of good design documentation are both immediate and long term. In addition to documentation's helping other team members, as discussed earlier, accurate and readable design notes benefit the individual engineer in successive iterations along the path to a finished design. Once completed, a properly documented design can survive long after its concept and serve as a data base of ideas to ensure continued profitability for the company.

For design documentation to be effective, it must have the following characteristics:

- Accuracy
- Clarity
- Conform to policy, convention and standards
- Completeness
- Integrity
- Brevity
- High Quality
- Retrievability
- Proper Format

Methods of complying with these requirements vary from one project to another since each organization has its own set of documentation requirements.

Design activities are divided in analysis, synthesis and evaluation activities. A tools box supports the development of each activity depending in the kind of product that is being designed. See figure 4.1. The four stages of product design activities are described below.

4.2 Activities in the Design Phases.

Each design phase (product planning, conceptual design, etc) is formed by design activities. Each activity needs an input and usually at the end of the phase has to be an output. Some phases have many outputs. Activities are divided in analysis activities, synthesis activities and evaluation activities according with the design phase that refers about. See figure 4.1.

- Product Planning, before a commercial product can be designed there has to be a product idea; that is, one that promises to lead to technically and economically viable applications. The scope of the project is defined and the project plan is defined. This phase also involves the collection of the information about the customer requirements to be embodied in the solution. The customer requirements are traduced in technical requirements. This phase will be described in detail in section 4.2.1.

- Conceptual Design, in this phase is the identification of essential problems by the establishment of function structures and by the search for appropriate solution principles. The basic solution path is laid down through the elaboration of a solution concept. Evaluation of solution concepts based on defined criteria needs to be done. This phase will be described in detail in section 4.2.2.

- Embodiment Design, this is the phase of the design process in which the arrangement, form, dimensions and surface properties of all individual parts are finally laid down, the materials specified (mechanical products), the technical and economic feasibility rechecked and all the drawings and other production documents are produced. This phase will be described in detail in section 4.2.3.

- Prototyping, the purpose is work out any remaining problems in the prototype construction and test it in order to check the functionality and potential design modifications. This phase will be described in detail in section 4.2.4.

In each design activity will be proposed a format to facilitate the flow of information and the documentation. This format, when filled, will be converted in a Record. The group of records will contain all the information obtained through the design process.

4.2.1 Product Planning Phase for Mechatronic Design.

In this phase, as was mention before, the idea of the product that is going to be developed is established depending in market opportunities. In synthesis activity, many alternatives of this new product or family of products are defined, the evaluation stage will decide which product is going to be produced depending in the technical and economical criteria selected by the design team.

The product planning phase activities are made once, that is, viewing the product as a whole. Ideation activities to product planning are activities that are best performed by business people because they know the market.

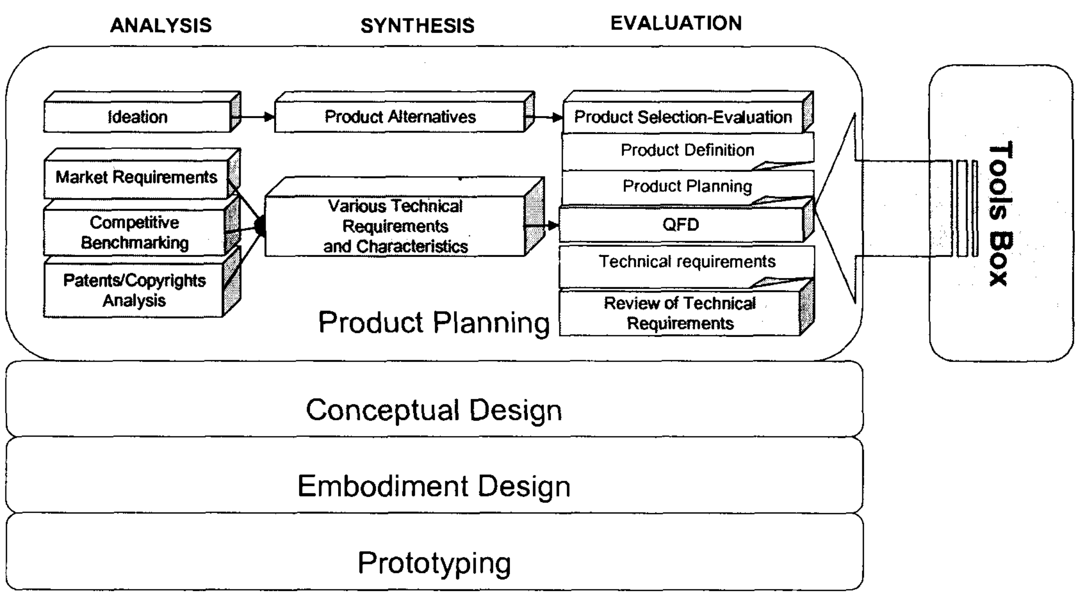


Figure 4.5 Product Planning Phase.

According to the design documentation issues, a set of formats is proposed. These formats have a classification. This classification consists of six digits. Digit one refers to the type of document. F refers to Format and R refers to Record. The second two digits refer to the design phase that refers about, and the last three digits to the activity number. For example, R-BD-009, defines a record document, for the product planning phase (basic development) and it refers to the activity number nine.

The general objective for this phase is to obtain the *product definition* that is going to be designed, a *schedule* for the project and the *technical requirements* depending on the customers wants. Each activity is going to be explained in detail through this chapter.

1. Ideation.

Objective: Clearly define the characteristics and capabilities of the project partners (knowledge competences, equipment and software, market technologies) and define the responsible.

This activity is the analysis of the project partners involved. The information required to the Ideation activity is:

- Project partners name
- Knowledge competences
- Technology capacities (equipment and software descriptions)
- Market opportunities (geographical location, sector with higher grow, commercial agreements, potential customers)

The output for this activity is a document containing all the characteristics and capabilities by the project partners.

To format proposed for this activity is shown next.

TECNOLÓGICO DE MONTERREY	**Ideation**	***F-PD-001***
Instituto Tecnológico y de Estudios Superiores de Monterrey		

Date	

1. Project partners

Ref.	Partner Name	Responsible
P1		
P2		

2. Knowledge Competences

Ref.	Partner	Knowledge competence
P1		•
P2		•

3. Technology Capacities

a. Equipment description

Ref.	Partner	Equipment Description
P1		•
P2		•

b. Software description

Ref.	Partner	Software Description
P1		•
P2		•

4. Market opportunities

Geographical Location	•
Sector with higher grow	•
Commercial Agreements	•
Potential customer	•

Figure 4.6. Format for Ideation Activity.

2. Product Alternatives.

Objective: Define at least three product alternatives that could be develop depending in the characteristics of the project partners defined in the previous activity.

Many product ideas are defined in a general form depending on the capabilities defined in the ideation activity. The output for this activity is the kind of product or family of products that could be produced by the project partners.

Information required in this activity is:

- Kind of product name.
- Image of product (if there is an analog product could be shown here).
- General description of the product.

The format proposed for this activity is shown next.

TECNOLÓGICO DE MONTERREY	**Product Alternatives**	***F-PD-002***
Instituto Tecnológico y de Estudios Superiores de Monterrey		

1. **Product Ideas**

SECTOR		
Product Name	**Product Description**	
	Image	**Description**
	Image	**Description**
	Image	**Description**

Figure 4.7. Format for Product Alternatives Activity.

2. Product Selection.

Objective: Evaluate the product alternatives to select the economically and technically viable one. At least five evaluation criteria should be used.

Pugh charts are a specialized tool in evaluation of concepts. In this activity this chart will be used to select the product idea. Detailed information of Pugh charts is presented in Appendix D.

The product ideas have to be evaluated considering technical and economical criteria, examples of these criteria are:

- Knowledge
- Market
- Technology
- Price
- Feasibility

The format for this activity is shown next.

TECNOLÓGICO DE MONTERREY	Project Selection	F-BD-003

		PRODUCT IDEAS		
CRITERIA	Importance			
Knowledge				
Market				
Technology				
Price				
Feassibility				
	Total +			
	Total -			
	Sum			
	TOTAL			

Figure 4.8. Format for Product Selection.

Results in the middle of this phase are:

- Product Definition. After de product selection activity, a more detailed definition of the product is required including the key business goals of the project, the primary and secondary markets, and many assumptions about the product.

The information that has to be defined in this activity is:

- Product Description
- Key Business Goals
- Primary Market
- Secondary Market
- Assumptions
- Stakeholders

To present the information about product definition the proposed format is:

TECNOLÓGICO DE MONTERREY	*Project Definition*	*F-BD-003*
Instituto Tecnológico y de Estudios Superiores de Monterrey		

Product: Project: Responsible:

Date	

Name of the Product	
Product Description	
Key Business Goals	
Primary Market	
Secondary Market	
Assumptions	
Stakeholders	

Figure 4.9. Format for Product Definition.

- Product Planning. A schedule for the project is defined considering the market necessities and the product competitors. The most used tool is Gant diagram.

4. Market Requirements.

Objective: Know and define all the customer information about an analog/new product categorized by:

- Typical uses
- Likes
- Dislikes
- Suggested Improvements

Define the customer statement, the interpreted need and the importance for each one of the last three.

Technique: Customer Interview. Detailed information about the technique is available in Appendix D.

TECNOLÓGICO DE MONTERREY	**Customer Interview Data**	***F-BD-004***
Instituto Tecnológico y de Estudios Superiores de Monterrey		

<table>
<tr><td colspan="3">Customer Data:
Adress:

Willing to do follow up?
Type of user:</td><td colspan="1">Customer:
Interviewers:
Date:
Currently uses:</td></tr>
<tr><td>Question</td><td>Customer Statement</td><td>Interpreted Need</td><td>Importance</td></tr>
<tr><td>Typical uses</td><td></td><td></td><td></td></tr>
<tr><td>Likes</td><td></td><td></td><td></td></tr>
<tr><td>Dislikes</td><td></td><td></td><td></td></tr>
<tr><td>Suggested Improvements</td><td></td><td></td><td></td></tr>
</table>

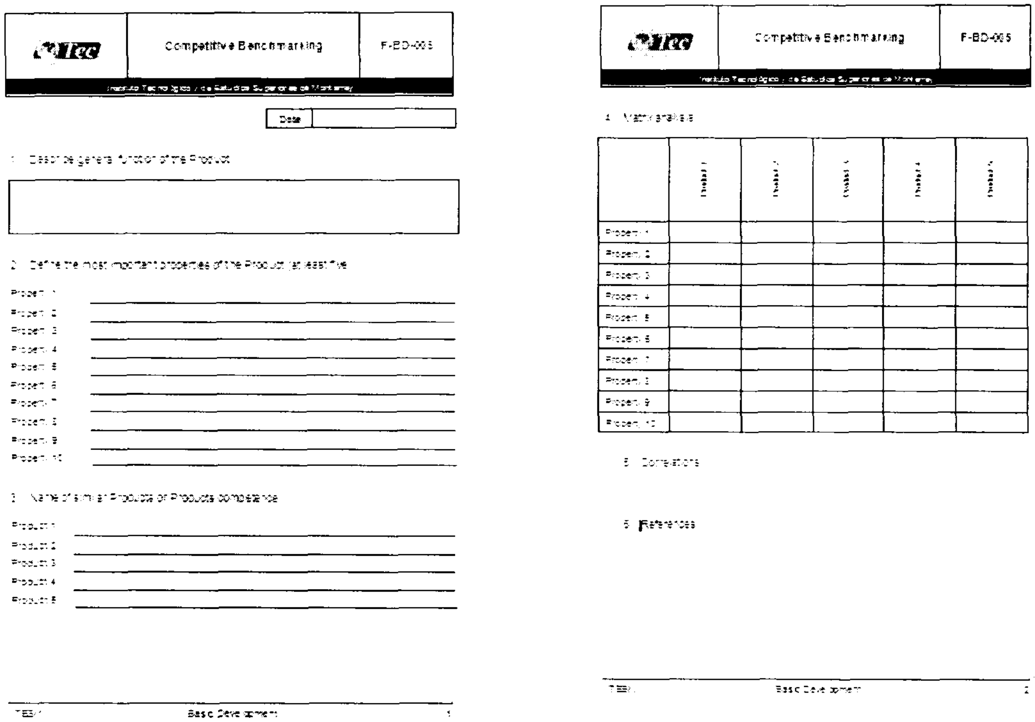
Figure 4.10. Format for Customer Interview

5. Competitive Benchmarking.

Objective: Search and present all the information that is possible about analog products. The information refers to parameters or properties about the product. Information must be organized in six steps:

- General function of the Product.
- Most important parameters of the Product (at least five).
- Similar Products or Product competences.
- Matrix analysis.
- Correlations
- References

Technique: Parametric Analysis. Detailed information about the tool is included in Appendix D.


Competitive Benchmarking F-BD-005

Competitive Benchmarking F-BD-005

Figure 4.11. Format for Competitive Benchmarking.

6. Patent Analysis.

Objective: Find patents about analogous products to avoid law problems and to find new ideas that could be integrated to your product.

One useful tool for this search is the web page www.uspto.gov. The web page for the United States of America patents. Patents images from 1790 and full text patents from 1976 to 2003 are available.

Altshuller in the 1960s and 1970s, categorized patents into five levels:

• Level one. Routine design problems solved by methods well known within the specialty.
No invention needed. About 32% of the solutions fell into this level.
•Level two. Minor improvements to an existing system, by methods known within the industry.
Usually with some compromise. About 45% of the solutions fell into this level.
•Level three. Fundamental improvement to an existing system, by methods known outside
the industry. Contradictions resolved. About 18% of the solutions fell into this category.
•Level four. A new generation that uses a new principle to perform the primary functions of the system. Solution found more in science than in technology.

About 4% of the solutions fell into this category.
•Level five. A rare scientific discovery or pioneering invention of essentially a new system.
About 1% of the solutions fell into this category.

He also noted that with each succeeding level, the source of the solution required broader knowledge and more solutions to consider before an ideal one could be found.

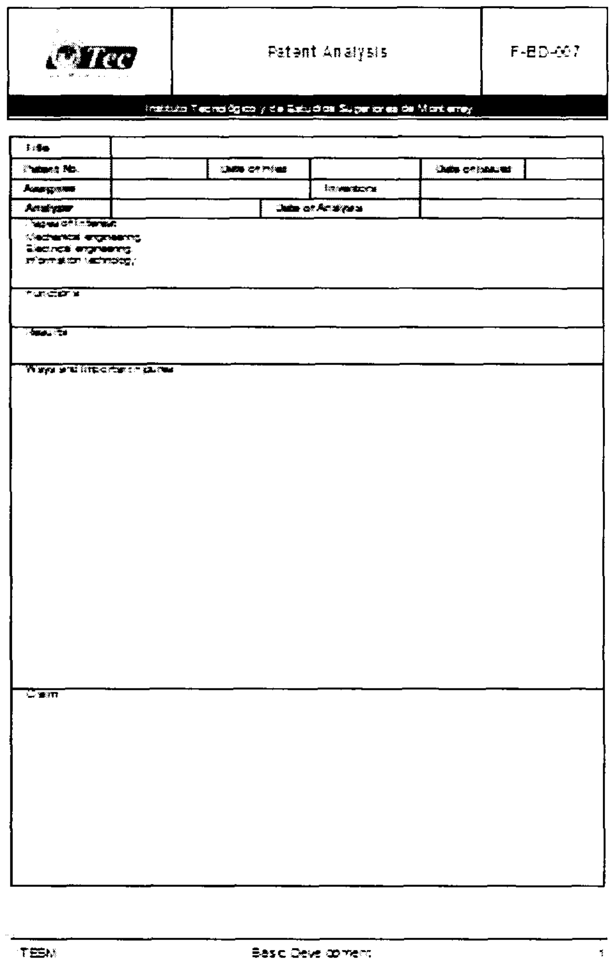


Figure 4.12. Format for Patent Analysis.

7. Various Technical Requirements and Characteristics.

Objective: List as much as possible characteristics, interpreted needs, and technical requirements from the information gathered in the Customer Interview, Competitive Benchmarking and Patent Analysis.

At this step, lot of information about analogous products is available for the design team. Information that is very useful to define what major characteristics can not be forget in the new design. Also, depending in the information gathered in the competitive benchmarking could be established some technical requirements.

8. QFD.

Objective: Make the match between customer needs and characteristics wanted in the product and the technical requirements. Obtain a importance value for each one of the technical requirements.

QFD should be viewed as a evaluation tool for the technical requirements, from it we will obtain a importance value for each of the technical requirements. Also this method is a condensed and organized form that will help design team to product information flow and for the documentation.

It is possible to define more technical requirements than those listed in the previous activity to satisfy some characteristics wanted in the product for the user.

Detailed information about how to make a QFD is presented in Chapter 3.

Design team should be conscientious about the more important technical requirements that have to be satisfied for the customer in the product that is going to design. The whole team must collaborate to make the QFD, it is important that experience and knowledge about every issue in the product be present to give the correct answers for the technical parameters.

Today in market there are available some computational tools like Qualisoft. Qualisoft facilitates only to organize the information, no to evaluate that some requirements are missed or defined in a wrong manner. To avoid that kind of mistake it is important to check in Chapter 3 the information about how to make a QFD.

A simple view to the QFD obtained from Qualisoft is presented in the next figure.

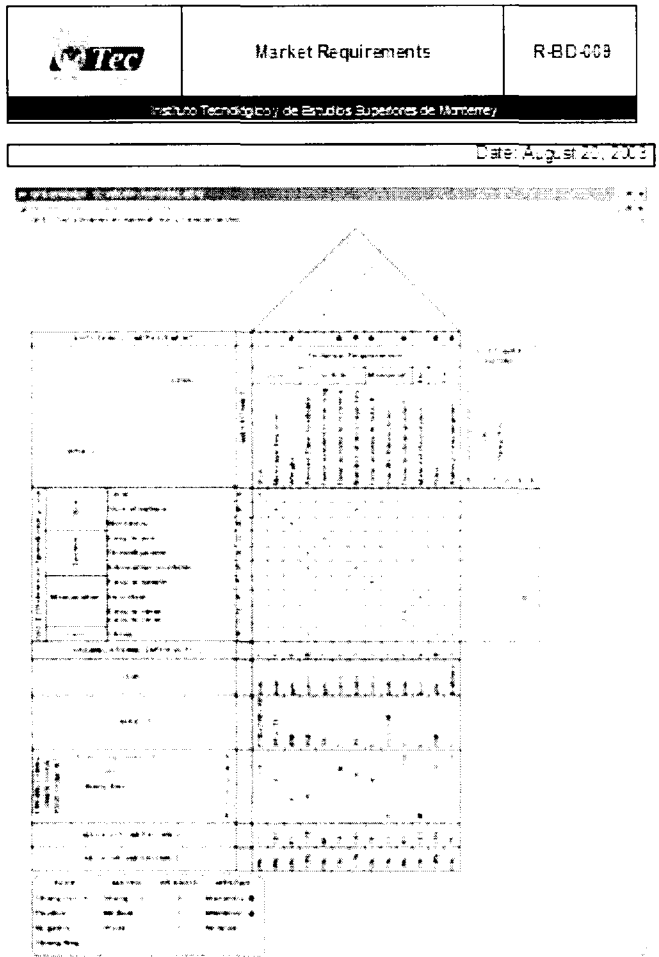


Figure 4.13. Format example for the QFD technique.

Previous figure, represents only the aspect of the QFD method realized in the QualiSoft tool, in chapter 5 is going to be presented in detail.

9. Parametric Analysis.

Objective: Identify possible relations between two parameters.

To make a parametric analysis, it is necessary to have a lot of information about analogous products in the market. This information required was defined before, in the competitive benchmarking. Now it is time to make graphs relating two parameters to identify possible relations.

Once relations are identified, the design team can make assumptions like which parameters increase the price of the product or which parameter give a better performance in the system.

Detailed information about how to make the Parametric Analysis is presented in chapter 3.

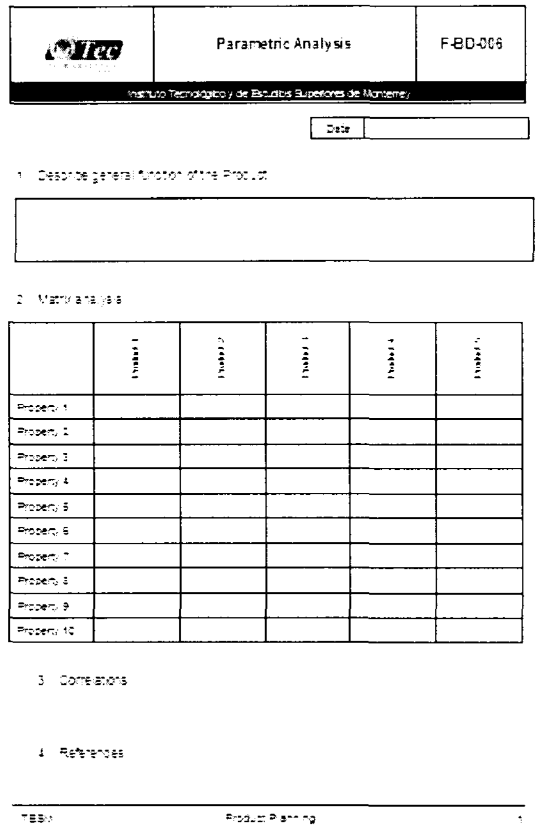


Figure 4.14. Format for Parametric Analysis.

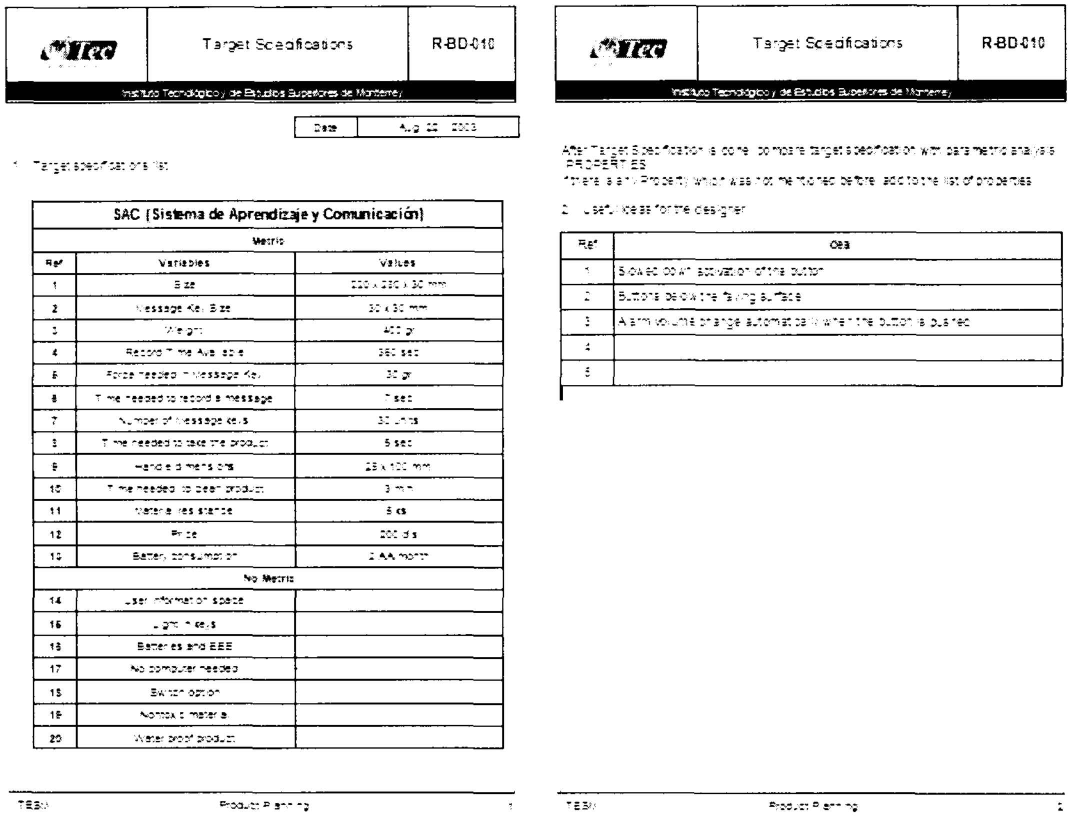
Results of this phase are:

- Technical Requirements

After the conversion of customer needs to technical requirements and the evaluation of these, it is necessary to have a document with all that target specifications that will be the basis for the next design activities. This document will help to take decisions in the conceptual and embodiment design phase.

It is important to compare this list with the properties defined in the parametric analysis and complete both.

An example of a target specification list is shown next. This is the most important document that will be developed to support designers.



	Target Specifications	R-BD-010
Instituto Tecnológico y de Estudios Superiores de Monterrey		

Date	Aug 22 2003

1. Target specifications list

SAC (Sistema de Aprendizaje y Comunicación)		
Metric		
Ref	Variables	Values
1	Size	[illegible] mm
2	Message Key Size	30 x 30 mm
3	Weight	400 gr
4	Record Time Available	360 sec
5	Force needed in Message Key	30 gr
6	Time needed to record a message	7 sec
7	Number of Message Keys	30 units
8	Time needed to take the product	5 sec
9	Handle dimensions	25 x 100 mm
10	Time needed to clean product	3 min
11	Material resistance	[illegible]
12	Price	200 dls
13	Battery consumption	2 AA month
No Metric		
14	User information space	
15	Light in keys	
16	Batteries and [illegible]	
17	No computer needed	
18	Switch option	
19	Nontoxic material	
20	Water proof product	

ITESM Product Planning 1

	Target Specifications	R-BD-010
Instituto Tecnológico y de Estudios Superiores de Monterrey		

After Target Specification is done, compare target specification with parametric analysis PROPERTIES.
If there is any Property which was not mentioned before, add to the list of properties.

2. Useful ideas for the designer

Ref	Idea
1	Slowed down activation of the button
2	Buttons below the facing surface
3	Alarm volume change automatically when the button is pushed
4	
5	

ITESM Product Planning 2

Figure 4.15. Format for Target Specifications.

10. Review of technical requirements.
Objective: Review that all the customer needs and all the parameters defined in the parametric analysis are reflected in the technical requirements defined in the Target Specification document.

11. Product Competitiveness.
Objective: Decide if the product designing is going to be successful with those parameters defined. Compare it in the parametric analysis and make a radar diagram

At this point, the team should review the general objective of the phase and decide if the work is complete and the results satisfy the objective.

4.2.2 Conceptual Design Phase for Mechatronic Design.

The general objective for this phase is to obtain a sketch that represents all the solution principles/structures/carriers for all the product's functions in the case of a mechanical product design. For electronics products the output is a list of components related to each function, and for software products, a robustness diagram that shows the relation between objects and is considered as a sanity check.

General Activity	Mechanical (Method)	Electronic (Method)	Software (Method)
Product Function	*Description.*	*Description.*	*Description.*
Functional Decomposition	Functional Decomposition Diagram	Functional Decomposition Diagram	Case Modeling (Use Cases)
Ideas generation/selection	Ideas Generation Session	Ideas Generation Session	Ideas Generation Session
Solution principles to fulfill the function	Research of Solution Principles	Research of components	Identify boundary, entity and control objects.
Morphological Matrix	Morphological Matrix	Morphological Matrix for components	Robustness Diagram
Concept Alternatives	Various combinations from Morphological Matrix.	Various combinations from Morphological Matrix.	Various Robustness Diagrams
Concept Selection/Variants Evaluation	Pugh Charts, Variants Evaluation	Pugh Charts, Variants Evaluation	Pugh Selection with UML criteria.
Concept	Sketch.	List Function-Component	1. Robustness Diagram 2. Domain (static) model.

Table 4.1. Analogous Activities in the Conceptual Design Phase.

In this phase the proposed activities are:

1. Product Function

Objective: Make a description that defines the general function of the product and the sub functions that it could realize.

This description should be as detailed as possible. This description will be the basis for the functional decomposition.

2. Functional Decomposition

Objective: Functional model that shows the relations between functional elements.

Functional modeling provides a basis for organizing the design team, tasks, and process. To the extent that functions of the product are independent, design-process activities may be chosen according to the independent product "piece". The interactions between the functional elements provide the required key communication needed among the concurrent design activities. Interfacing specifications can be readily developed.

Creativity is enhanced by the ability to decompose problems and manipulate partial solutions. By first decomposing a design task in to its functional elements, solutions to each element are more apparent due to the reduction of complexity and extraneous information.

There are a lot of useful methods to product function modeling:

- FAST. Function Analysis System Technique.
- Subtract and operate procedure.
- Function structures

Detailed information about these methods is available in Appendix D.

Between the FAST and Subtract and Operate methods, a reasonable function tree can be developed for a product. One should apply both methods independently and then compare the results to merge into an acceptable functional model, one that captures overall high-level intent as well as the functions of important subsystems and components[Otto & Wood, 2001].

To organize the information obtained in the functional modeling activity a format is proposed. The designer could adequate the format depending in the method choose.

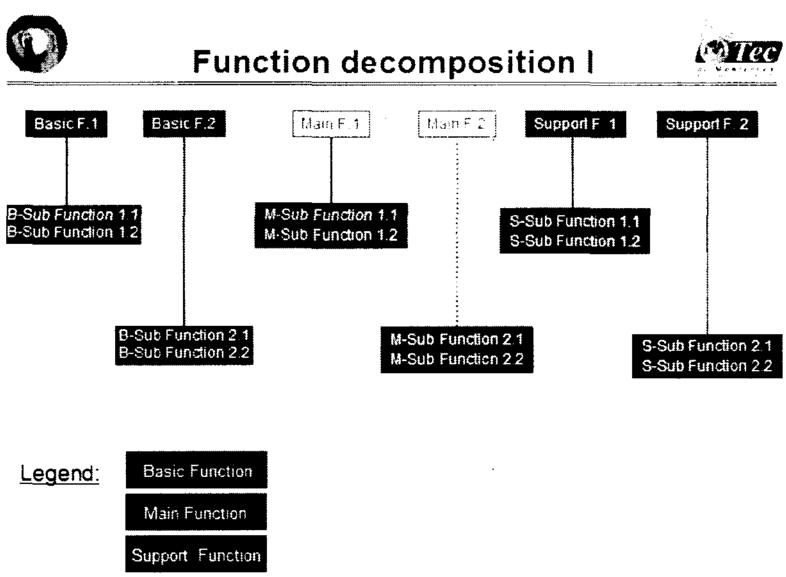
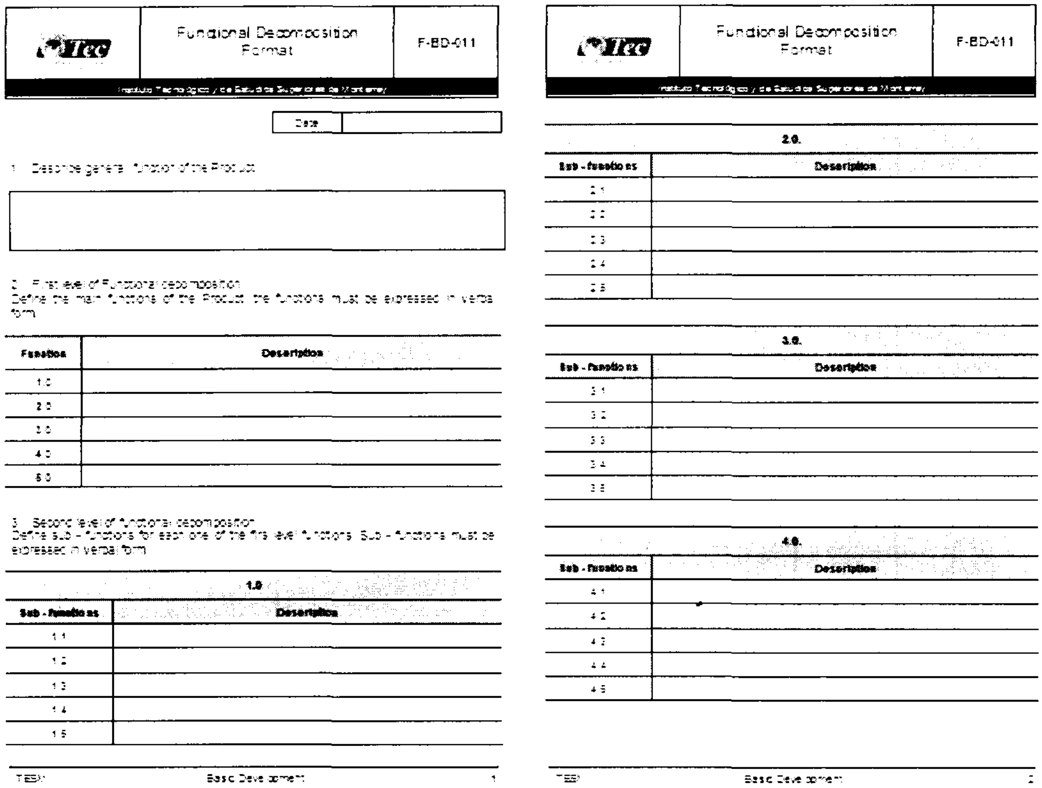


Figure 4.16. Functional Modeling

Next, it is preferable to have a list for the functions divided by levels to give them to independent teams or people to develop that "piece" of the product.



	Functional Decomposition Format	F-BD-011

Date

1. Describe general function of the Product

2. First level of Functional decomposition
Define the main functions of the Product. The functions must be expressed in verbal form

Function	Description
1.0	
2.0	
3.0	
4.0	
5.0	

3. Second level of functional decomposition
Define sub-functions for each one of the first level functions. Sub-functions must be expressed in verbal form

1.0

Sub-functions	Description
1.1	
1.2	
1.3	
1.4	
1.5	

TESM Basic Development 1

	Functional Decomposition Format	F-BD-011

2.0

Sub-functions	Description
2.1	
2.2	
2.3	
2.4	
2.5	

3.0

Sub-functions	Description
3.1	
3.2	
3.3	
3.4	
3.5	

4.0

Sub-functions	Description
4.1	
4.2	
4.3	
4.4	
4.5	

TESM Basic Development 2

Figure 4.17. Format for Functions Format.

For the case of Software products, the functional decomposition is defining the use cases of the product based in the UML (Unified Model Language).

3. Ideas Generation

Objective: Get new ideas for the product concept. At least six new ideas should be obtained from the Creativity Session.

Depending on the functions defined in the previous activity, a Creativity session is needed to think about the configuration, the level of technology, etc of the product. Another document that has to be present in this creativity session is the market interview. With this document the ideas can be generated from the market requirements.

The idea in this activity is to make a brainstorming that will result in many product idea alternatives. The steps for this activity can follow the proposed activities shown next:

- Overview.

The moderator tells to the team about what the meeting is all about. A review of the Agenda and a small introduction about what to expect is given.

- Objectives

Describe that the objective is for: "New product ideas" or "New feature ideas". Also the top requirements or restrictions should be presented to the group.

- Rules

The basics rules for the session are: - no idea is a bad idea, - be creative, - take risks, - no criticism allowed.

- Creativity Activities

Begin the process of generating new ideas. Use games and exercises to "warm up" the creative thinking. When ideas slow down, try another exercise to generate fresh ideas. Breaking into smaller groups may be helpful. Use a paper and a computer to capture every comment and idea.

- Summarize

Review the ideas generated. Vote on top candidates and consolidate. Check requirements and descriptions. Trim list to top 5-10 ideas.

- Next steps

The moderator has to describe what happens next. The ideas should be evaluated in criteria like technology level, cost, needs satisfied by project partners, etc.

At the end, all the team should have a general idea for all the product alternatives. And all members express their product proposals depending in their knowledge.

4. Idea Selection

Objective: Select the best idea from the creativity session depending on the criteria.

The criteria could be the same as those used in the first product selection activity. For example, knowledge, market, technology, price, feasibility, etc. This will help the team to decide which product is feasible to develop depending in the competences defined for the project partners.

Detailed information of Pugh charts is presented in Appendix D. The format used for this evaluation is shown in figure 4.8 (Product selection-Evaluation activity).

5. Solution Principles to Fulfill the Function

Objective: Search and define alternative solution principles (or components) that could realize each function. In the case of software products, define the kind of objects involved to realize each function.

6. Morphological Matrix

Objective: Define one or as much two configurations for the product. Selection of shapes-forms that satisfy the functions (components or structures). Select the shapes or components based in evaluation criteria like price, desirable size, availability, etc

Tec	Morphologic Matrix Format	F-BD-013

Instituto Tecnológico y de Estudios Superiores de Monterrey

Date	

PRODUCT:
REFERENCE: Functional Decomposition (R-BD-011)

1. **Morphologic matrix.**

Note.

- Use one matrix for each function
- Select the criteria for evaluation.
- Give a qualification between 1 and 5 for each part in the criteria
- Bigger numbers refer to better solutions

		Possible Solutions				
Function	**Sub functions**	**1**	**2**	**3**	**4**	**5**
1	1.1					
	Qualification Criteria 1 Criteria 2					
	1.2					
	Qualification Criteria 1 Criteria 2					

ITESM Basic Development 1

Tec	Morphologic Matrix Format	F-BD-013

Instituto Tecnológico y de Estudios Superiores de Monterrey

Note
For reference of Patents writes down the number of patent and annexes first page patent using format MM1
For reference of Products writes down the name product and annexes reference documents using format MM1
For own ideas use the format MM1

Function or Sub function		**Solution Number**		**Format MM1**
Source		**Date**		
Description of solution				
Sketch				

ITESM Basic Development 2

Figure 4.18. Format for Morphological Matrix Format.

Result in the middle of this phase is:

- Concept Alternatives

Concept alternatives refers to different morphologies about how the components can be assembled, also, if in the morphological matrix were defined more than one configuration, this other morphology should be also defined. Next all those configurations should be evaluated to choose the best one.

7. Concept Selection

Objective: Select the best configuration of the product evaluating the options with the appropriate criteria.

Useful methods for this selection are:

- Pugh charts (The method used for this activity is the same used before in the activities product selection and idea selection)
- Variants Evaluation

Criteria used to evaluate those configurations is different depending on the kind of product. The most important criteria should be those that accord with the market requirements.

For software products, criteria should be as:

- Sanity
- Completeness

Additional information about the software design process can be found in Rosenberg and Scott, 1999.

The Result of this phase is:

- Conceptual Design

A concept is an idea that can be represented in a rough sketch or with notes, in other words an abstraction, of what might someday be a product. Some product ideas are naturally generated during the product planning phase, since in order to understand the problem, we need to associate it with things we already know. There is a great tendency for designers to take their favorite idea and start to refine it toward a product design. This is a very weak methodology, best expressed by the adage: *"If you generate one idea it will probably be a poor idea; if you generate twenty ideas then you might have one good idea."*

At this point, a review of the general objective of the phase has to be done. Check for completeness of documentation. All the team should know which is the concept defined and all have to understand the idea.

4.2.3 Embodiment Design Phase for Mechatronic Design.

4.2.3.1 Embodiment Design Phase – Mechanical Design.

The general objective for this phase is obtaining a detailed layout for the product.

In this phase a detailed layout for the whole product has to be developed. The designer has to define the components shapes and materials. This concretization is obtained through preliminary layouts. These layouts need to be critically reviewed. In some cases many layouts (embodiment designs) are needed before the definitive layout, because it has to be checked for function and refined. This process involves thousands and thousands of decisions. This process is complex because many actions have to be performed simultaneously, some steps have to de repeated at a higher level of information, and changes in one area have repercussions on the existing design in other areas. The activities proposed in this phase are described below, the distinction of each for analysis, synthesis or evaluation could be checked in the methodology concept model. The activities described below refer to a mechanical design. The Figure 4.20 shows the concept model.

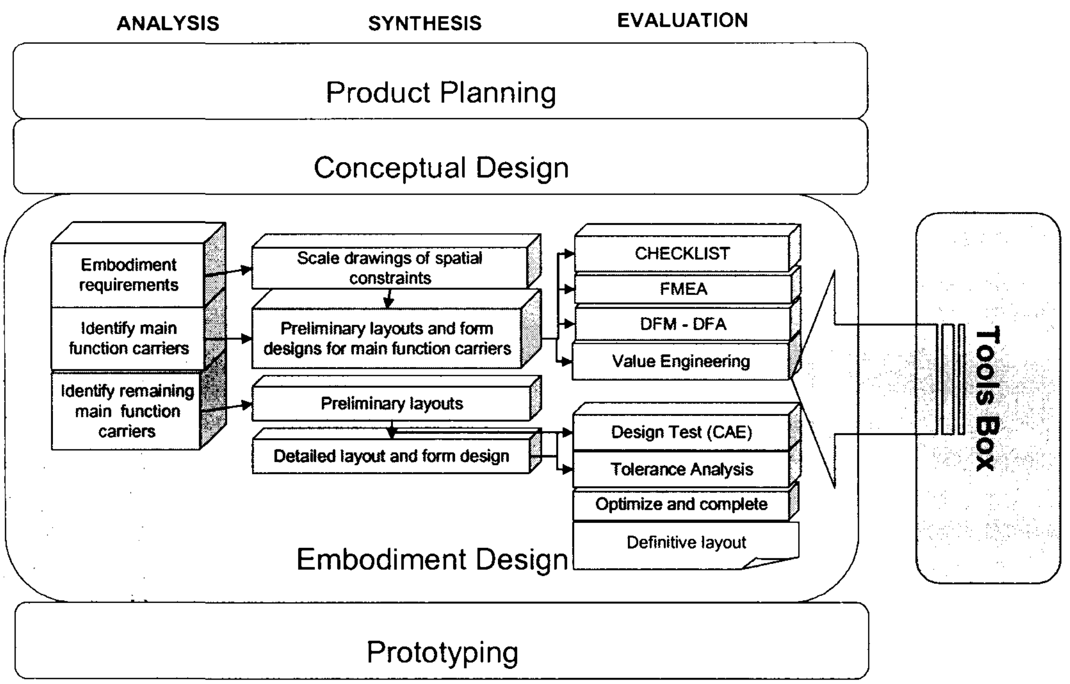


Figure 4.19 Mechanical Design Methodology Model.

1. Embodiment requirements.

Objective: Definition of restrictions and requirements for the concept that will be the basis for the next activities of design. Check that those requirements agree with the customer requirements.

Here the crucial requirements are identified: size, arrangement, materials. The output for this activity is a list with the characteristics of components.

2. Scale drawings of spatial constraints.

Objective: Obtain a sketch defining the spatial restrictions for the product based on the list defined in the previous activity for the whole product and for the components involved.

Define the determining or restricting spatial constraints, like, clearances, axle positions, installation requirements, etc. The output for this activity is a set of sketches.

3. Identify main function carriers.

Objective: Identify the main structures and/or components that determine the size of the product. Define them and make a classification.

To define them, use a rough layout from concept development and answer two questions: (1) Which main functions carries determine the size, arrangement and component shapes of the overall layout? (2) What main functions must be fulfilled by which function carriers jointly or separately? The output for this activity is a list with the main function carriers and some parameters for them.

To accomplish the next activities, some tools are classified in the column "evaluation activities". These will help to accomplish the objective of two activities: (1) Preliminary layouts and form designs for function carriers, and (2) Detailed layout and form design. These "evaluation activities" are methods that are described in detail in Appendix D.

In this Chapter we will describe the product information flow and some organizational issues for these evaluation methods.

- Checklist
- FMEA
- DFM- DFA
- Value Engineering/Axiomatic Design

Checklist is a tool that has to be accomplished through the execution of all activities in the embodiment design phase. The objective here is to evaluate that the layout of the product has considered all aspects for the functionality of the products. Some of those aspects are: safety, ergonomics, production, etc.

FMEA is another tool that "fights" with the lacks of historical information. It helps the design team to get that historical information. FMEA is information documentation also.

FMEA is actually used in many companies. Whirpool is one of these companies. They have been used this tool for many years and they give important opinions about this tool:

- FMEA should be viewed as a serious tool.
- The key is "know the product". Experience is a powerful necessity to develop a FMEA.

Other premises that the design team should consider are:

- "Don not let the user to interact in the "correct" way with the product". That is, do not let open, to the user, the possibility to interact in an incorrect way with the product.
- "Who generates an engineering change do not be the one who approves it". This is called "double check".

Referring to the administration of the process, all team members should have defined their role in the team. Also, a worksheet has to be developed with the time required to complete the FMEA.

The general approach to the FMEA process is:

1. Show system failures. Define fails and mode fails. A useful tool for this activity is brainstorming.
2. Know the product. Functions definition for the whole product or components.
3. Know particular failures. Define failures in mode of no-functions.
4. Analyze and make recommendations. Causes of failure establishment. And complete the table.

FMEA refers to "how" am I validating the design, it is not only to see the failures. That validation is the "design controls".

FMEA has to be done after all components preliminary layouts and before the detailed layouts, that will save time in case something has to be changed in the design.

DFA and DFM also have to be accomplish during the through the execution of all activities in the embodiment design phase. The objective here is to evaluate that the layout of the product has considered all aspects for the manufacturing process and assembly facilities.

Value Engineering or Axiomatic Design is the method used to evaluate the design. This method is applied when detailed preliminary layouts are already constructed to evaluate the functionality of the design.

4. Preliminary layouts and form designs.

Objective: The general arrangement, component shapes and materials must be determined provisionally. Result must meet the overall spatial constraints and completed so that all relevant main functions are fulfilled. DFA and DFM guidelines should be considered, also, Some headings of the checklist can be used to review the functionality of the product.

The output for this activity is the preliminary layout. One of the evaluation tools used here is the checklist. Note that this tool is going to be useful through all the embodiment design activities. At this stage, the checklist first three headings could be checked. It is important to keep in mind the guidelines DFM and DFA, so the product form, shapes and dimensions do not require later modifications.

5. Select suitable preliminary layout.

Objective: Evaluate preliminary layouts (if many) or evaluate the preliminary layout making a FMEA.

FMEA is an analytical technique used by a product design team as a means to identify, define and eliminate, to the extent possible, known or potential failure modes of a product system. The technique should be used cooperatively with systems modeling to investigate and determine good choices for variables defining a product.

FMEA focuses on the entire product layout, not just on each subassembly, component, and interfacing system of a product. Must also be understood as a process. It entails the continuous application of design team tasks during a product's development. It also seeks to identify potential failure modes before a failure can occur in a product, not as a forensic tool for investigation a failure once it has occurred.

6. Detailed layout and form design.

Objective: The detailed layout in accordance with the evaluation tools feedback and with due attention to standards, regulations, detailed calculations and experimental findings. Evaluation of the integration of components.

To this activity DFA and DFM guidelines are reviewed again. Information gathered in the FMEA technique is used to improve the design if possible.

Once the detailed layout is completed, we can continue with the next "evaluation methods".

- CAE

CAE are computer systems that analyze engineering designs. Most CAD systems have a CAE component, but there are also independent CAE systems that can analyze designs produced by various CAD systems. CAE systems are able to simulate a design under a variety of conditions to see if it actually works.

Some tests include:

- Stress Analysis
- Dynamics
- Vibration
- Seismic
- Shock
- Drop Test
- Nonlinear materials
- Fatigue
- Heat Transfer
- FEA
- Electromagnetics
- Parametric Models
- Computational Fluid Dynamics
- CAM

Products available in market:

- ANSYS
- Adams
- Working Model
- Catia
- Patran/Nastran
- Design Space
- ICEM CFD Engineering
- Model Checker. ANSYS productivity tool designed to evaluate and document finite element models for errors through a rigorous set of standardized checks.

7. Optimize and Complete (Tolerance Analysis).

Objective: Define product tolerances according with manufacturing cost limit and product functionality.

In general, three categories of tolerancing schemes have been developed for industry use: parametric tolerancing, geometric tolerancing, and operational tolerancing. For product design are used primarily the first two categories, while the third category is used primarily in process design.
The schemes worst-case limit tolerancing, statistical tolerancing, and vectorial tolerancing are called parametric tolerancing because dimensions can be regarded as control parameters for an underlying mathematical representation.
Geometric tolerancing applies tolerances directly to attributes to features. Attributes characterized by the feature include size, position, form and spatial relation. The semantics of tolerances are established primarily by a set of rules for implementing datum systems from physical part features and another set of rules for constructing spatial zones. The datum system is used essentially for traditional machine drawings, but it becomes the rule of thumb in selecting the setup position for machining parts.
Operational tolerancing is different from both parametric tolerancing and geometric tolerancing in being used primarily in process design. A conventional tool used for operational tolerancing is dimension and tolerancing charting, also referred to as dimension chain, dimension chart, or dimension and tolerance chain.

The methodology proposes the statistical tolerancing scheme proposed by for parametric tolerances.

8. Check for errors and disturbing Factors.

Objective: Elimination of weak points identified in the evaluation activities. Review that all the points in the checklist are reviewed.

To continue to the next activity a review of the general objective is realized to verify that those objectives were reached.

4.2.3.2 Embodiment Design Phase – Electronic Design.

In this phase, a detailed layout for the electronic systems has to be developed. Also a list of electronic components with their characteristics is completed.

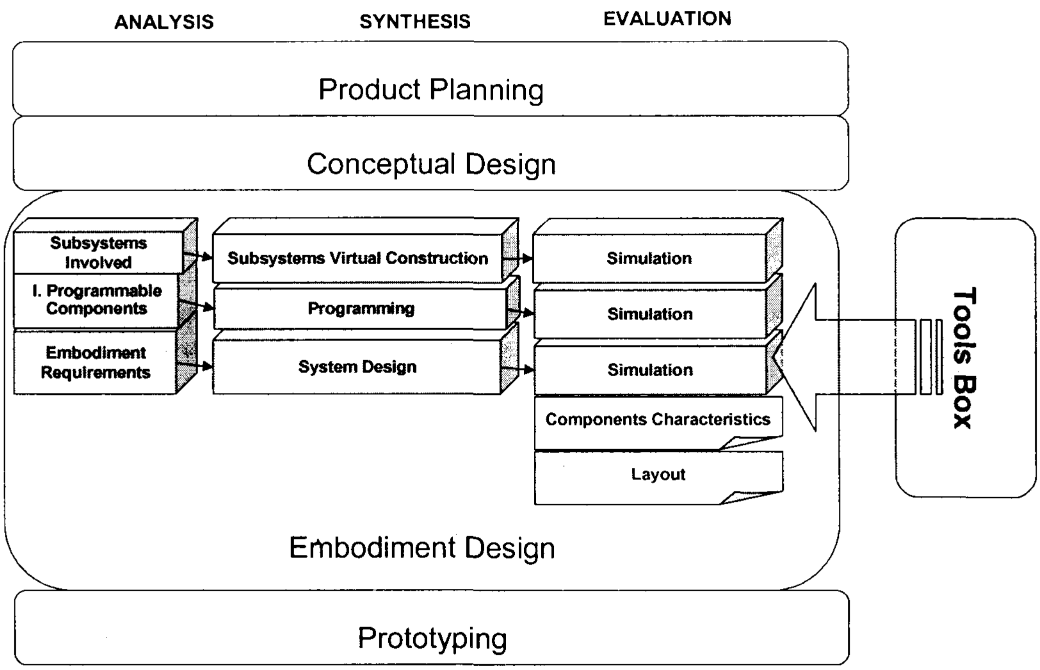


Figure 4.20 Embodiment Design Phase for Electronic Products.

1. Subsystems Involved

For complex products it is necessary to divide the electronic systems in many subsystems to divide the work to many engineers.

2. Subsystems virtual Construction

After the subsystems identification, they have to be constructed to make a functionality evaluation. There are many tools used for this activity, for example, eWorkbench and Spice software.

3. Simulation

After the subsystem is built it is easy to run a simulation for the product with the tools proposed (eWorkbench, Spice, etc). Maybe the designers run many simulations during the construction of the subsystems to probe the functionality of the prototype.

4. Identify programmable components

In this activity a list of the programmable components is required. This list must include how the interaction of the components is and which functions must realize.

5. Programming

The methodology includes a module for software design and this module is going to be used to program the components. Software design is presented in next section. An Object Oriented approach is proposed to define and model the functions of the product that will be the basis for code construction.

6. Simulation

Simulation of software for electronic programmable components is also shown in the next section.

7. Embodiment Requirements

Some embodiment restrictions and requirements for the electronic components have to be already defined in the preliminary layouts of mechanical design. For these activities the teams should work concurrently to develop adequate geometries that will fit in the assembly of the product.

8. Systems design

In this activity all the subsystems are integrated. The embodiment requirements define the space to make the layout for the components in the electronic card. Software like Protel is used to define the layout.

9. Simulation

Once the system is designed, the software (Protel) can run a simulation to check connection between components.

The outputs for this phase are:

- Components characteristics
- Layout

At this step, we can obtain a detailed bill of materials for the components involved in the electronic part, also, a detailed layout for the card is defined.

4.2.3.3 Embodiment Design Phase – Software Design.

The general objective for this phase is to obtain a detailed Sequence Diagram, also refine and complete the Domain Model and the Class Diagram that will serve as a base for the coding activity.

In this phase a detailed layout for the whole product has to be developed. The designer has to define the relations between objects in time. The methodology is based in the ICONIX Unified Object Modeling, and it is not intended to give a deep understanding of this activities because the literature available in the market for the reader [Rosenberg and Scott, Use Case Driven Object Modeling with UML, 1999].

The goals that have to be achieved in this phase are:

1. Allocate behavior among boundary, entity and control objects.
2. Show the detailed interactions that occur over time among the objects associated with each use case.
3. Finalize the distribution of operations among classes.

The Figure 4.22 shows the embodiment design phase for software Products.

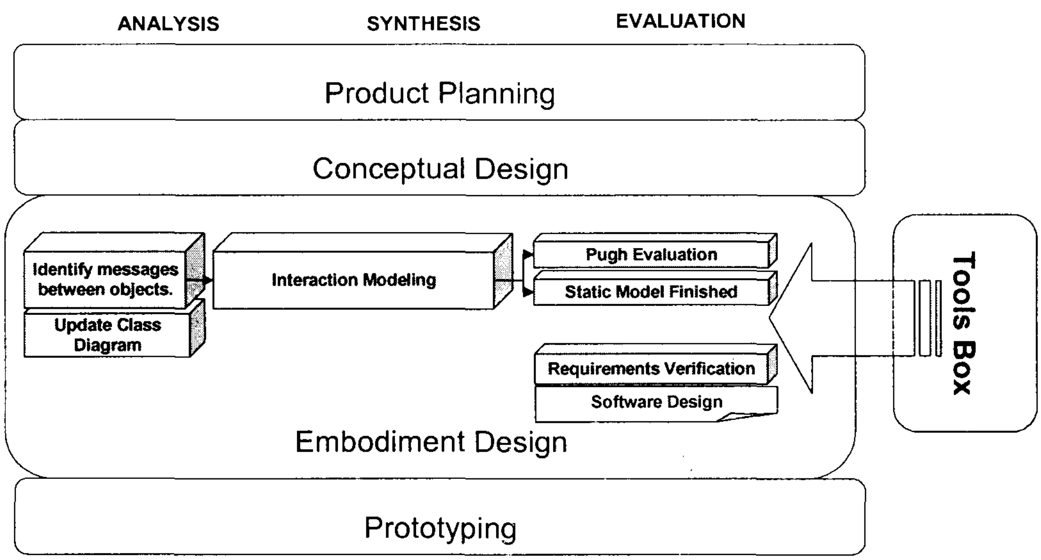


Figure 4.21. Software Design Methodology Model.

The activities defined for this phase are:

1. Identify messages between objects.

Objective: Define which objects are responsible for which bits of behavior.

Based in the Robustness Analysis and the set of objects identified that together could accomplish the desired behavior of the use cases, and the "broke down" of that behavior into discrete units, and then the creation of placeholders control objects for each unit of behavior the definition of which objects are responsible for which bits of behavior could be determined.

2. Sequence Diagram.

Objectives:

- Validate and Flesh out the logic of a usage scenario.
- Provide a way to visually step through invocation of the operations defined by the classes.
- Detect bottlenecks within an object-oriented design.

- Give you a feel for which classes in your application are going to be complex.

3. Pugh Evaluation.

Objective: Qualify the created classes with the criteria:

- Coupling. Measures the strength of a connection between two classes. You can improve the modularity of a system by designing it with *loose coupling* wherever possible. Classes that are highly independent are preferable.
- Cohesion. Measures how tightly connected the attributes and operations of a class are. It is desirable to strive for high functional cohesion, which occurs when the elements of each class are all working together to provide a clearly defined behavior.
- Sufficiency. Is the condition in which a class encapsulates enough of the abstractions of the model so that it offers something meaningful and efficient, with which other parts of the system can interact. The key question is whether the class covers all the relevant cases.
- Completeness. Is the condition in which a given class's interface captures all the relevant abstractions. So a complete class is one that is theoretically reusable in any number of contexts.
- Primitiveness. Is the condition in which an operation can be efficiently built only if it has access to the material on which your models are built. The idea here is that you can design certain operations that you can use as building blocks for other operations as your design evolves.

4. Update Class Diagram.

It is common that while creating a sequence diagram, new classes appear that have not been considered before, so, that classes have to be integrated in the class diagram. Check your sequence diagram and make a match with the class diagram.

5. Collaboration Diagram (Optional activity).

Objective:

Collaboration diagrams are use to model additional aspects of the dynamic behavior of the system. Typically are most useful in the design of real-time systems, or when you need to explain the real-time aspects of client/server or other distributed systems. This is a optional activity, you use it, when you have a genuine need to capture complex object behavior.

A collaboration diagram shows how objects associated with a use case collaborate to perform critical pieces of the behavior the use case calls for. Show detailed interactions among objects in the form of message passing and focuses the view on only the key transactions within a scenario, the emphasis is on the time ordering.

Specifically, collaboration diagrams add extra detail related to the timing of the messages. They should come in to play when you need to show additional detail about timing for the key transactions within your scenario. We usually do not need them the rest of the time.

Types of messages:

- A synchronous message corresponds with a method within a receiving object starting to execute only when the sending object has sent a message and the receiver is ready to accept that message.
- A balking message is equivalent to a synchronous message, except the sending object gives up on the message if the receiving object is no ready to accept it.
- A timeout message is equivalent to a synchronous message, except the sending object waits only for a specified period for the receiving object to get ready to accept the message.
- An asynchronous message involves the sending object being able to send the message regardless of whether the receiving object is ready to accept it.

6. Finish Static Model.

Once the sequence or collaboration diagram is finished, it is time to update the static model with the items discovered while doing it.

7. Requirements Verification.

In this activity the user requirements have to be matched with the Static Model obtained to look for completeness. All the user requirements have to have a defined operation in the static model.

The output for this activity is:

- Software Design.

Software design, refers to the static model defined by the dynamic model. This static model is going to be the basis for the coding activities.

4.2.4 Prototyping

The general objective for this phase is to evaluate the functionality of the product.

For mechanical Design we have alternatives in prototyping. The decision that has to be made is, use a Mathematical Model o a Physical Prototyping. But it is important to remember that even with analytic models, we have to build a physical one and carry out experiments.

With engineering models, at some point, sets of experiments have to be carried out. Sooner or later, we have to measure the inputs to a product definition, and we have to verify the output performance of a product. Because of this necessity we should consider the trade-offs between analytical and physical models.

Analytical	Physical
Simulations	Hardware
"Virtual" prototyping	Material and physical property correlation
Computer animations	Prototyping of manufacturing techniques
Optimization	Experimental Setups
	Fully functional mock-ups (alpha and beta prototypes)

Table 4.2. Analytical versus Physical Models

Focused	Comprehensive
Testing limited performance	Full-scale, fully functional dimensions version of product
Just representative enough to answer the question, and no more	As representative as possible
As cheap as possible	As true to real product as possible

Table 4.3. Focused versus Comprehensive Models

It is smart to make detailed engineering models when prototyping is expensive and when we have reasonable expectations in obtaining an accurate model. This is depicted in Table 4.4, adapted from Ulrich and Eppinger [1995].

Model Accuracy / **Prototype Accuracy**	**High**	Model It	Model It	Difficult Problem
	Medium	Model It	Doesn't matter	Prototype It
	Low	Difficult Problem	Prototype It	Prototype It
		Low	**Medium**	**High**
		Model Expense / **Prototype Expense**		

Table 4.4. Decision Trade-Off between Analytical and Physical Models

Instead of assuming that physical prototypes always increase cycle time and cost, teams can exploit recent advances to both reduce time-to-market and positively impact product quality. Physical and virtual models are seen now as competing technologies with clear decision criteria. Depending on the questions to be answered, studies to be conducted, and decisions to be made, the valid development choice may be a physical model, a virtual model, or some combination.

1. Type of Prototype.

Objective: Define the type of prototype that is going to be built.

Based on the considerations mentioned above, it is time to define the type of prototype that is going to be built.

2. Materials-Process Definition

Objective: Define alternative process for making the prototype.

Some new technologies for Rapid Prototyping are:

In daily commercial use:

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Laminated Object Modeling (LOM)
- Fused Deposition Modeling (FDM)

More at the research and development stage:

- 3-D printing in cornstarch, plastic or ceramic
- 3-D printing with plastics followed by planarization using machining
- Solid ground curing (similar to SLA)
- Shape deposition modeling (a combination of addition and subtraction)

Traditional:

- Machining
- Casting

Materials used to fabrication of prototypes are:

Rapid Prototyping	Liquid photocurable polymers	Sintered metal powder and waxes	Sheet material	Polymer spool	Viscous solidifying polymers
Stereolithography	X				
SLA		X			
LOM			X		
FDM				X	
Solid ground curing	X				
3-D printing followed by machining					X

Table 4.5. Materials for different prototyping processes. [Wright, 2001]

In Molinas work group some tools were develop to define and evaluate the process for prototype building. The next figure represents the activities realized to define the process.

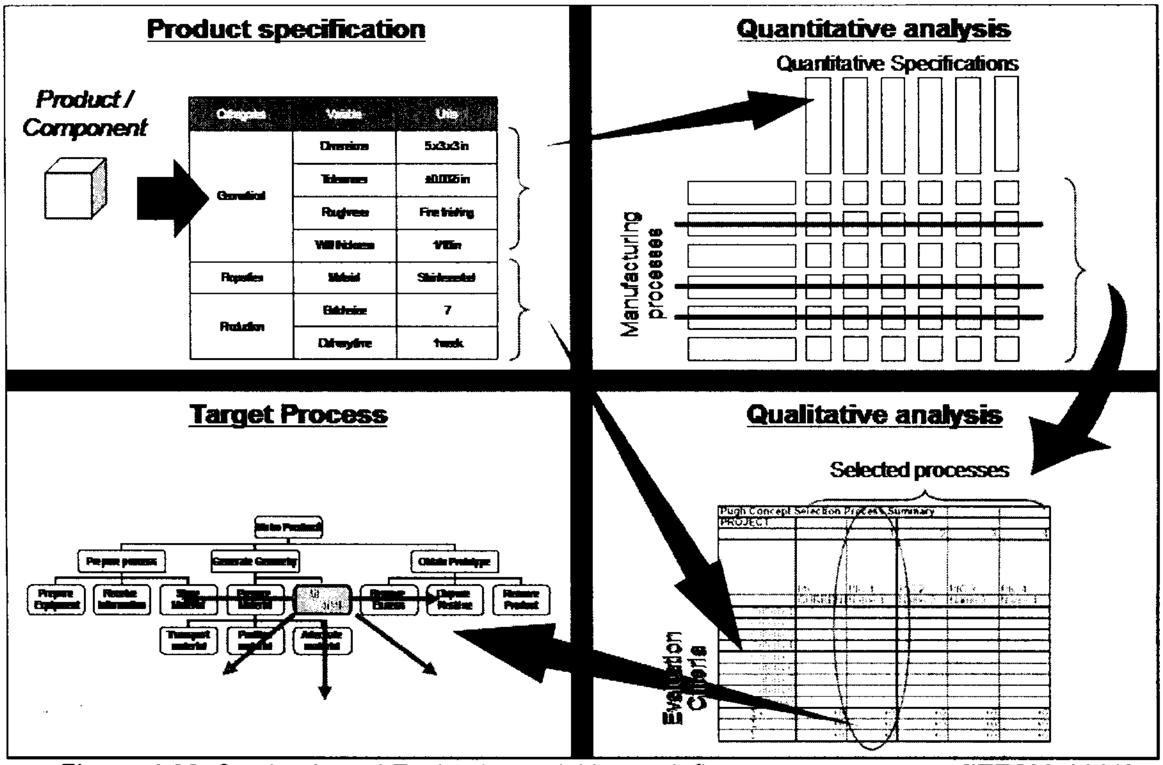


Figure 4.22. Synthesis and Evaluation activities to define prototype process [ITESM, 2003]

The quantitative analysis realized for the process selection is considered as the synthesis activity for this phase. The Qualitative analysis is defined as the evaluation activity for the process. The user has to define the criteria ranks for the three possible values in the evaluation activity (quantitative analysis).

3. Materials-Process Evaluation

Objective: Evaluate the processes analyzed using the criteria:

Geometry
Waste Cost
Tooling Cost
Fixtures Complexity
Set up time
Cycle time production
Batch size production
Products per shoot

Ranks for the criteria should be clearly defined by the design team, this is a very important activity that can make the difference between a successful or wrong selection.

Once the process and materials are decided and evaluated is time to build the prototype.

The Result of this phase is:

- Prototype

Construct the prototype based on the results of the previous activities.

4. Prototype Evaluation

Objective: Evaluate if the product prototype satisfy all the target specification list and experiment to improve the observed, physical behavior.

Many experiments should be developed about product parameters. It is a better way to conduct experiments using the Design of Experiments (DOE) method created by Taguchi.

4.2.4.1 Software Prototype/Product

As was mentioned before, the activities for software products prototyping are different. The next figure present all the activities proposed in the methodology.

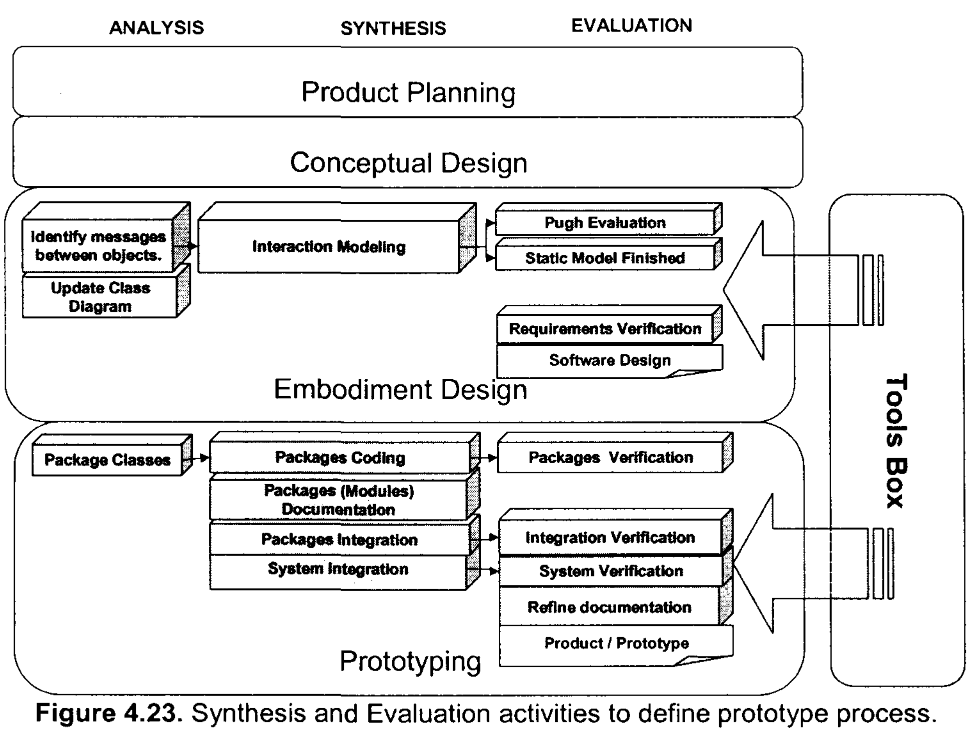


Figure 4.23. Synthesis and Evaluation activities to define prototype process.

The activities defined for this stage are:

1. Package Cases.

Once the class model is finished, packages of classes can be identified. These packages can be distributed between the design people to work simultaneously.

2. Package (Modules) Coding.

The packages are coded in the language best suitable for the application. Transform the system design in to the code.

3. Package Verification.

Software coding is an iterative process that can be checked constantly. Designers write the code and probe the functionality almost immediately. Programming languages are capable to do it.

4. Packages (Modules) Documentation.

It is important to document all the information about the system design because of it save a lot of time when maintenance is needed to the software. Documentation facilitates the understanding of the logical thinking of the programmers. This documentation should contain the entire static and dynamic model.

5. Packages Integration.

This activity refers to the union of the packages. The architecture defined for the product must permit the integration.

6. Integration Verification.

Evaluate the functionality of the product based in the architecture defined for the modules.

7. System integration.

This activity refers to the complete integration of the software product including all supporting and additional activities that may be found in the previous activity.

8. System Verification.

Again, for this activity, the entire product has to be tested in its functionality.

9. Refine and Document the Design.

At this step all the details, and extra comments for further changes in the software have to be documented.

Output for this phase: Product or Prototype.

It is the author recommendation to the reader to review the book of Rosenberg and Scott (Use Case Driven Modeling with UML) for detailed information about the software products.

4.3 Methods-Tools Box

The methodology requires a set of methods or tools that can be selected and applied whenever necessary to improve the results of the activities. Depending in product complexity and special characteristics, these methods can be identified as adequate tools. Detailed information about some of these tools is presented in Appendix D. Table 4.6 contain some example methods that can be used in the methodology.

	Analysis	Synthesis	Evaluation
Product Planning	■ Market Understanding, ■ S-Curves, ■ Competitive Analysis, ■ Customer Interview, ■ Focus Group, ■ Technical questioning, ■ Contextual inquiry, ■ Lead User Analysis, ■ Delphi technique, ■ Contextual Inquiry,	■ Brainstorming, ■ User Profiling, ■ Creativity Sessions,	■ Risk assessment, ■ Pugh Charts,
Conceptual Design	■ Brainstorming, ■ Contextual inquiry, ■ TRIZ, ■ Kano Model, ■ Affinity Diagrams, ■ Creativity Sessions, ■ Functional Decomposition,	■ Osborn's checklist, ■ Whiteboard, ■ Sketching Equipment, ■ QFD, ■ Morphological Charts,	■ Concept Testing (exploratory, assessment, validation, comparison), ■ Weighting and Rating, ■ Idea log, ■ Concept Selection, ■ Controlled Convergence [Pugh Selection],
Embodiment Design	■ Brainstorming, ■ TRIZ, ■ Unit cost Analysis, ■ Tolerance Analysis,	■ Sketches spatial constraints, ■ Morphological matrix, ■ Solid Modeler, ■ Checklist, ■ TRIZ, ■ Modularity, ■ Wire Frame Modeler, ■ DOE, ■ Mathematical Model, ■ UML Language, ■ Pahl and Beitz Design Principles,	■ Checklist, ■ Value Engineering-Analysis, ■ Axiomatic Design, ■ FMEA, ■ DFA, ■ DFM, ■ Mathematical Model, ■ Tolerance Analysis, ■ DFR, DF Cost, ■ Web-based DFX Tools, ■ CAE, ■ Design Efficiency calculation, ■ Design Complexity Scorecard, ■ Model Shop, ■ Analysis Codes,
Prototyping	■ Rapid Prototyping Processes,	■ Conceptual Modelers,	■ Pugh Charts, ■ DOE,

Table 4.6. Methods and Techniques Tool Box.

It could be observed that for the first two phases of design, the majority of methods are categorized like analysis activities, and for the embodiment design phase as evaluation activities.

Chapter 5. CASE STUDY.

5.1 Introduction

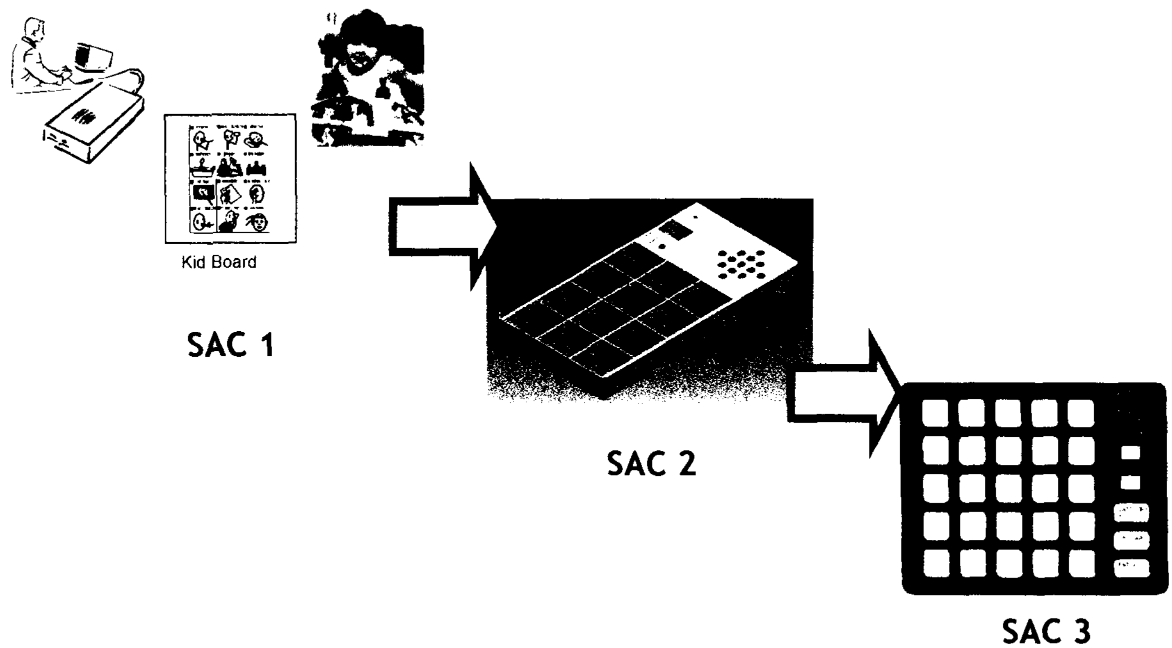
The following chapter describes the implementation of the methodology proposed. The product designed in this research is a mechatronic product. The product SAC (Sistema de Aprendizaje y Comunicación) is designed to people with different capacities, primarily cerebral paralysis. The product is seen as a communication and a didactic instrument.

Two generations of this product exist. The first generation of SAC was a device that has a leds sweep and has to be connected to the computer. It was designed by a mechatronic undergraduate group of students. This project concludes with a useful prototype. The next figure shows the first generation of the SAC.

The second generation of the SAC was a product with the leds sweep with no computer interaction. This project was also developed by undergraduate students of many areas. The functional prototype was not finished.

This case of study will describe the development of the third generation of the SAC. The product has to reproduce sounds (as much as possible) when the person touches a button. The button has a figure that represents something that the person tries to communicate. It has to be reconfigurable, so the teachers or family can record any kind of messages on it.

The next figure shows the three generations of the SAC product development.



This case of study was developed since June 2003 to November 2003 whit a work group at the CSIM laboratory.

5.2 Implementation of the Methodology in a Product Design Process

As was mentioned before, the methodology was applied in a mechatronic product called SAC (Sistema de Aprendizaje y Comunicación).

The methodology is divided in mechanical, electronic and software components of the product. The design team was integrated by graduate students in each area. Many authors have mentioned that the relevant problem in mechatronic design is about the integration of those three areas. This case of study will show us how to face that problem. Even this is a simple product, the methodology can be translated to complex products because the methodology propose a logic sequence of activities that will lead the design team to clear objectives in each activity. The methods or techniques used to get each objective can be selected according to the requirements of the design team, even though there are many indispensable methods already defined in the methodology.

To organize the work, excel tables were develop. These tables contain the most important information about each activity in each phase of design such as the tool, technique, the record and the responsible. Also, this table shows the status of ach activity so any member of the design team can review the progress. This status functions like a traffic light. Color green refers that the activity is completely done, yellow that there is few progress and red refers to no progress. Links to formats and records were created to easy access to the information.

5.2.1 Product Planning Phase.

The product planning phase activities are made once, that is, viewing the product as a whole.

Ideation activities to product planning are activities were developed by two members of the design team and a business leader.

The general objective for this phase is to obtain the *product definition* that is going to be designed, a *schedule* for the project and the *technical requirements* depending on the customers wants.

The excel format defining the activities, tools, techniques and link with formats and records is shown in the next table:

Phase	#	Activity	Format	Tool	Technique	Record	Responsible
Product Planning	1	Ideation	F-BD-001	Internet	Competitive Intelligence	R-BD-001	JA
	2	Product Selection	F-BD-002	Excel	Pugh Charts	R-BD-002	JA
	3	Product Definition	F-BD-003	Word	-	R-BD-003	JA
	4	Project Planning	F-BD-004	Word - MS Project	Gant Diagram	R-BD-004	JA
	5	Competitive Benchmarking	F-BD-005	Internet	Parametric Analysis	R-BD-005	PF
	6	Generating ideas	F-BD-006		Brainstorming	R-BD-006	AP
	7	Patent Analysis	F-BD-007	Internet	-	R-BD-007	AP
	8	Market Requirements	F-BD-008	Word	Interview	R-BD-008	PF
	9	Technical Requirements	F-BD-009	QualiSoft - Word	QFD	R-BD-009	PF
	10	Target Specifications	F-BD-010	Excell	*QFD How's - Interpreted Needs of Interview*	R-BD-010	PF

Table 5.1. Excel Table for the Product Planning Phase

Next, each activity is developed and the objective is stated again. As was mention in Chapter 4, the objective helps the design team to evaluate each activity with the Review Activity Algorithm.

1. Ideation.

Objective: Clearly define the characteristics and capabilities of the project partners (knowledge competences, equipment and software, market technologies) and define the responsible.

Date	July 16th 2003

1. Project partners

Ref.	Partner Name	Responsible
P1	Berkeley Manufacturing Institute (BMI) University of California at Berkeley (UCB)	Prof. Paul Wright
P2	Integrated Manufacturing Systems Research Center (CSIM) Instituto Tecnológico y de Estudios Superiores de Monterrey (ITESM)	Prof. Arturo Molina
P3	Telecommunications an Electronic Center (CET) Instituto Tecnológico y de Estudios Superiores de Monterrey (ITESM)	Prof. Ignacio Celis

2. Knowledge Competences

Ref.	Partner	Knowledge competence
P1	BMI	• Demand Response Energy Tracking • Design of Wireless Sensor Nets • Design process of electrical printed circuit boards and mechanical enclosures • Rapid Prototyping and Mold Making for Consumer Products
P2	CSIM	• Integrated Product Design • Automation and Enterprise integration • Production and Service Engineering • Materials and Process Manufacturing
P3	CET	• Personal communication systems • Telephony and Intelligent Systems • Networks of wide band

3. Technology Capacities

Equipment description

Ref.	Partner	Equipment Description
P1	BMI	• Rapid Prototyping machine - Stratasys FDM 2000 • Rapid Prototyping machine - Z-Corp Color 3-d printing • HAAS CNC milling Machine • Injection molding lab
P2	CSIM	• Surface Mounting Technology Equipment • HURON - High Speed Milling Center • Laboratory of industrial materials

P3	CET	• Microprocessors lab • Telephony lab • Radio Frequency and Personal Communications lab • Digital and analogical electronic lab

Software description

Ref.	Partner	Software Description
P1	BMI	• WebCAD. WebCAD is the newest version of the online CyberCut computer aided design tool • MAS • DUCADE
P2	CSIM	• CAD systems (Pro/Engineer, Unigraphics, Mechanical Desktop) • CAD/CAM systems for machining operations (Pro/Engineer, Avil-5000, DelCAM, WorkNC) • CAE systems (Mold-Flow, C-Mold, ADAMS, Patran/Nastran) • Web-servers and software: Object Oriented Database (ObjectStore) and KBES Environment (AML from Technosoft) and ARIS Tool Set software for process modeling. • SMT Advisor
P3	CET	• PSpice • OrCAD • Protel

4. Market opportunities.

Geographical Location	• USA • Mexico
Sector with higher grow	• Electronic* • Automotive* • Power Industry*
Commercial Agreements	• NAFTA
Potential customer	• Academic Institutes

**Source: SECOFI 1999*

The objective was reviewed by all the team members, and they decided that the information gathered satisfy it and was enough to continue with the next activity.

2. Product Alternatives.

Objective: Define at least three product alternatives that could be develop depending in the characteristics of the project partners defined in the previous activity.

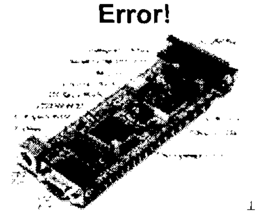
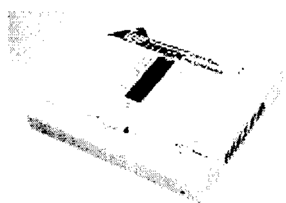
ELECTRONIC SECTOR		
Product Name	**Product Description**	
Prototype board	**Error!** 	This board is especially suited to test digital circuits during the early stages of their development.
Device programmer		It is a software expandable universal device programming workstation that supports a wide variety of programmable devices in addition to the capability of testing digital
Communication Aid		A powerful, portable, easy to use and very durable speech output device. Use it as an introductory communication aid.

Table 5.2. Product Alternatives Activity.

3. Product Selection.

Objective: Evaluate the product alternatives to select the economically and technically viable one. At least five evaluation criteria should be used.

Criteria used to evaluate the product alternatives were: knowledge, Market, Technology, Price and Feasibility.

Tec de Monterrey	**Project Selection**	**R-PD-002**

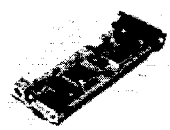
		PRODUCT IDEAS		
CRITERIA	Importance			
Knowledge	8	1	-1	1
Market	10	-1	0	1
Technology	7	0	0	0
Price	5	-1	0	0
Feassibility	8	1	1	1
	Total +	2	1	3
	Total -	-2	-1	0
	Sum	0	0	3
	TOTAL	1	0	26

Table 5.3. Product Selection.

Results in the middle of this phase are:

- Product Definition. After de product selection activity, a more detailed definition of the product is required including the key business goals of the project, the primary and secondary markets, and many assumptions about the product.

General Information about the Product

SAC (Sistema de Aprendizaje y Comunicación)	
Product Description	• A powerful, portable, easy to use and very durable speech output device. Use it as an introductory communication aid.
Key Business Goals	• Prototype presentation: October 2003 • Market introduction: January 2004 • Cost is less than US$ 150.00

Primary Market	• *Nuevo Amanecer* Institute
Secondary Market	• Academic institutes for persons with special needs for communications • Companies oriented to commercialization of products for person wits special needs
Assumptions	• SAC is useful for kids with motorize problems • SAC is easy to operate and requires minimal maintenance • SAC is secure for kids
Stakeholders	• Teachers for persons with special needs
Project Budget	• US $ 500.00

Table 5.4. Product Definition.

- Product Planning. A schedule for the project is defined considering the market necessities and the product competitors.

4. Market Requirements.

Objective: Know and define all the customer information about an analog/new product categorized by:

- Typical uses
- Likes
- Dislikes
- Suggested Improvements

Define the customer statement, the interpreted need and the importance for each one of the last three.

Technique: Customer Interview. Detailed information about the technique is available in Appendix D.

Customer Data: SAC (Sistema de Aprendizaje y Conocimiento)

Customer: Myrna Sánchez García
Adress: Lázaro Garza Ayala No. 1000 Pte
San Pedro Garza García, Nuevo León
Willing to do follow up? Y
Type of user: Teacher

Interviewers: Joaquín Aca, David, Paola FM, Amir P
Date: August 15, 2003
Currently uses: Communication media

Question	**Customer Statement**	**Interpreted Need**	**Importance**
Typical uses	Answer questions Make questions Transmit feelings Inform about needs Call for help		
Likes	Easy to use Small Cheap Not damaged when falling Nontoxic Independent Dual system Manageable Light Easy to clean Reconfigurable Resistant to the liquids Space for user information A lot of information available	Simple Small Cheap Resistant material Non toxic No computer needed batteries-connector With handle With light Flat surface Recordable No holes As much as possible figures	Must Must Must Must Must Must Nice Nice Nice Nice Good Should Should Should Good
Dislikes	Few information available Computer needed Inadequate size of the product Inadequate size of the figures Heavy product	Few figures Computer needed Big products Small figures Heavy product	Must Must Good Good Good
Suggested Improvements	2000 messages and figures available Resistant to: cold, hot, rain,		

Table 5.5. Customer Interview.

5. Competitive Benchmarking.

Objective: Search and present all the information that is possible about analog products. The information refers to parameters or properties about the product. Information must be organized in six steps:

- General function of the Product.
- Most important parameters of the Product (at least five).
- Similar Products or Product competences.

- Matrix analysis.
- Correlations
- References

Technique: Parametric Analysis. Detailed information about the tool is included in Chapter 3. All the information gathered in this activity is shown next.

Date	August 2nd 2003

Describe general function of the Product.

A powerful, portable, easy to use and very durable speech output device. Use it as an introductory communication aid.

Define the most important parameters of the Product (at least five).

Property 1	Price
Property 2	Weight
Property 3	Size
Property 4	Number of Message keys
Property 5	Message keys size
Property 6	Light in keys
Property 7	Recording time
Property 8	Number of Messages
Property 9	Battery
Property 10	Volume control
Property 11	Record function
Property 12	Lock functions
Property 13	Scanning function
Property 14	Speakers
Property 15	Change layers
Property 16	Computer communication
Property 17	Switch option
Property 18	Housing material
Property 19	Expansible

* This list must have the maximum number of properties that the user finds in related products. After Patent Analysis, could be possible that more properties are going to be added.

Name of similar Products or Product competences.

Product 1	Go Talk	
Product 2	Barry Box	
Product 3	Chatbox Deluxe	
Product 4	Easy Talk 8	
Product 5	Mini Message Mate 8/60	
Product 6	VoicePal 8K	
Product 7	TalkTrac range	

Matrix analysis.

	Go Talk	Barry Box	Chatbox Deluxe	Easy Talk 8	Mini Message Mate 8/60	TalkTrac range	VoicePal 8K
Price (US$)	179.00	645.00	645.00	999.00	350.00	115.00	199.00
Weight (gr.)	450	700	700	1000	750	80	300
Size (mm)	230 X 300 X 22	138 X 190 X 45	146 X 190 X 50	300 X 105 X 35	180 X 80 X 35	42 X 74 X 23	145 X 95 X 30
Message keys (touch buttons)	9	48	16	40/20/10/4/2/1*	8	4	8
Message keys size (mm)	50 X 50	15 X 15	25 X 25	20 X 20 (40 locations)	35 X 35	16 X 16	25 X 25
Light in keys	YES	YES	YES	YES	YES	NO	YES
Recording time (s)	216	192	600	480	60	75	90
Messages	36	48	64	160/80/40/16/8/4*	8	4	8
Battery	2 / AA	4 / AA	Rechargeable	Rechargeable	Rechargeable	Rechargeable	4 / AAA
Volume control	YES	YES	YES	YES	YES	NO	NO
Record function	YES	YES	YES	YES	YES	YES	YES
Lock functions	YES	NO	NO	YES	YES	NO	NO
Scanning function	NO	NO	YES	YES	NO	NO	NO
Speakers	YES	YES	YES	YES	YES	YES	YES
Change layers	Layers / 4	NO	Layers / 4	Layers / 8	Layers / 1	YES	NO
Computer communication	NO	NO	NO	NO	NO	NO	NO
Switch option	NO	NO	YES	YES	NO	NO	YES
Housing material	Plastic	Plastic	Plastic	Plastic	Aluminum	Flexible	Plastic
Expansible	NO	NO	NO	YES	NO	NO	NO

* Configurable

Table 5.6. Competitors/Analog Products Matrix.

References.

- http://www.beyondplay.com/ITEMS/C491.HTM
- http://www.greattalkingbox.com/easytalk.htm
- http://www.words-plus.com/website/products/manuals/manual.htm
- http://www.adaptivation.com/voicepal_8k.htm
- http://www.attainmentcompany.com/home.html
- http://www.liberator.co.uk/liberator-pre/docs/main.htm

All the information presented above has to be included in the Competitive Benchmarking.

6. Patent Analysis.

Objective: Find patents about analogous products to avoid law problems and to find new ideas that could be integrated to your product.

Title	Communication aid using multiple membrane switches				
Patent No.	US 5,910,009	**Date of Filed**	August 25, 1997	**Date of Issued**	June 8, 1999
Assignee		**Inventors**	Leff; Ruth B		
Analyzer	Joaquín Aca	**Date of Analysis**	August 4, 2003		

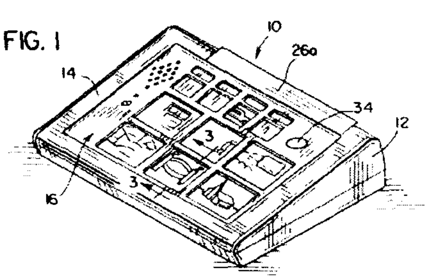
Pages of Interest
Mechanical engineering: 1-6
Electrical engineering: 6-8
information technology: 8-10

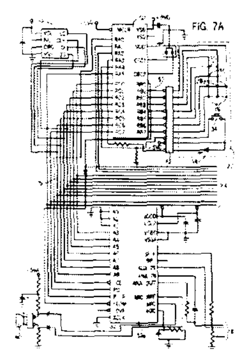
Functions:
Communicate persons with communication problems

Results:
Electronic device that reproduce determined phrases to aid handicapped people

Ways and Important Figures:

FIG. I





A communication aid for helping people with severe communication problems to express their needs or thoughts to others. The communication aid includes a case on which a touch pad contains series of mode selection switches and a plurality of activation switches. An overlay sheet is mounted on the touch pad and includes at least one mode symbol illustrating a general category of need, and a plurality of message symbols, each illustrating a specific need falling within the category. The mode symbols corresponding in location to the mode selection switches and the message symbols corresponding in location to the activation switches. The communication aid also incorporates a memory device for storing a plurality of audio messages, each corresponding to one of the message symbols. When a mode selection switch and on of the activation switches are depressed, a sound message associated with the depressed activation switch is generated.

Claim: 1. A communication aid for a handicapped patient comprising: a case having a flat support surface; a touch pad securely mounted to the case above the support surface, the touch pad having a switch membrane, the switch membrane being divided into a plurality of mode selection switches and a plurality of activation switches; a record button contained on the touch pad, the record button being depressible to record a sound message that corresponds to one of the message symbols; a memory device for storing a plurality of the sound messages, each sound message recorded to correspond to one of the message symbols and having an address defined by a combination of one of the mode selection switches and the activation switch corresponding in location to the message symbol such that a sound message is stored in the memory device for each combination of the mode selection switches and the activation switches; a sound generating device for generating the sound message associated with the combination of one of the mode selection switches and one of the activation switches when the mode symbol and the message symbol on the touch pad are depressed.

Table 5.7. Example of Patent Analysis.

7. Various Technical Requirements and Characteristics.

Objective: List as much as possible characteristics, interpreted needs, and technical requirements from the information gathered in the Customer Interview, Competitive Benchmarking and Patent Analysis.

At this step, lot of information about analogous products is available for the design team. Information that is very useful to define what major characteristics can not be forget in the new design. Also, depending in the information gathered in the competitive benchmarking could be established some technical requirements.

8. QFD.

Objective: Make the match between customer needs and characteristics wanted in the product and the technical requirements. Obtain an importance value for each one of the technical requirements.

Date: August 20, 2003

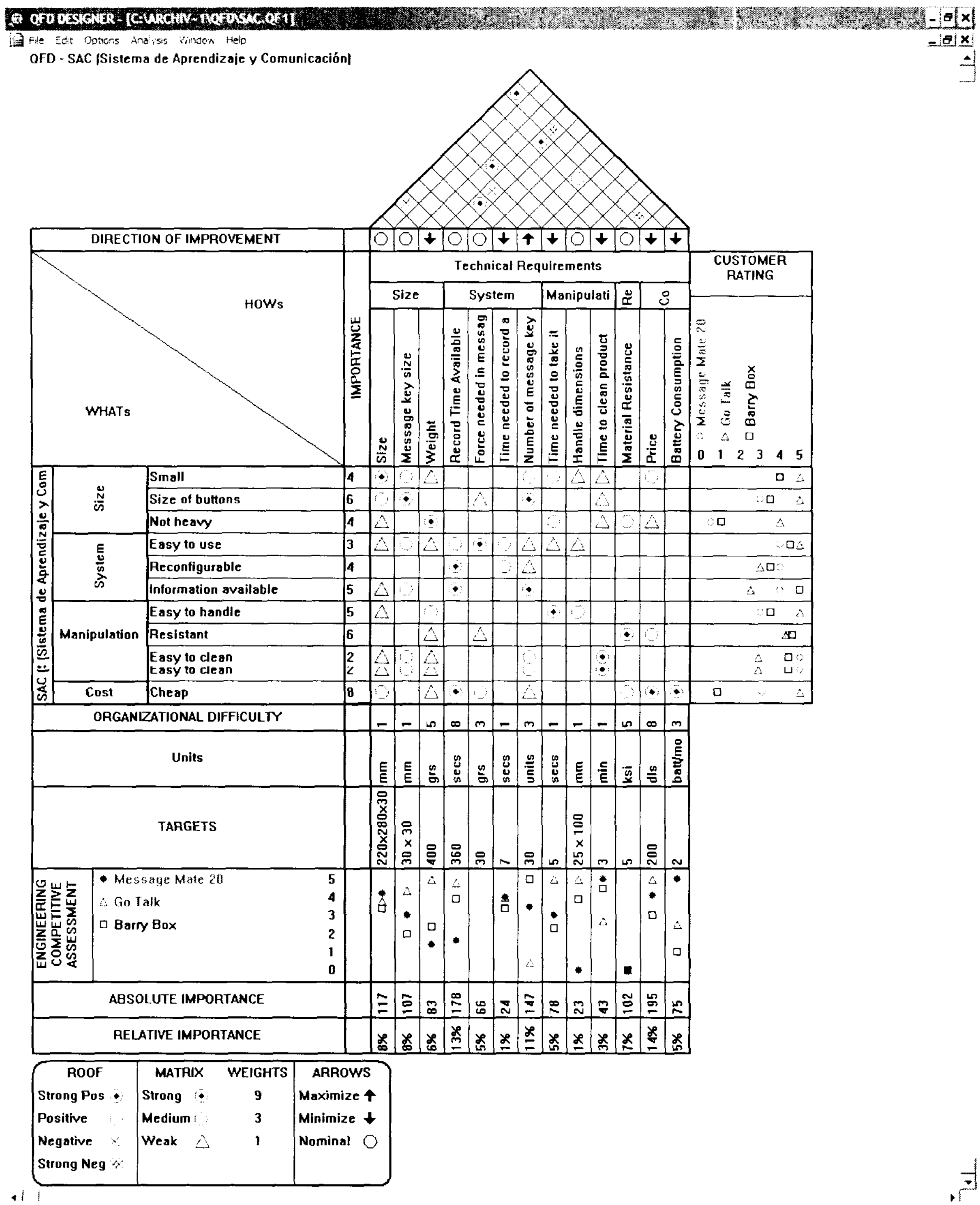


Figure 5.1. QFD technique for SAC.

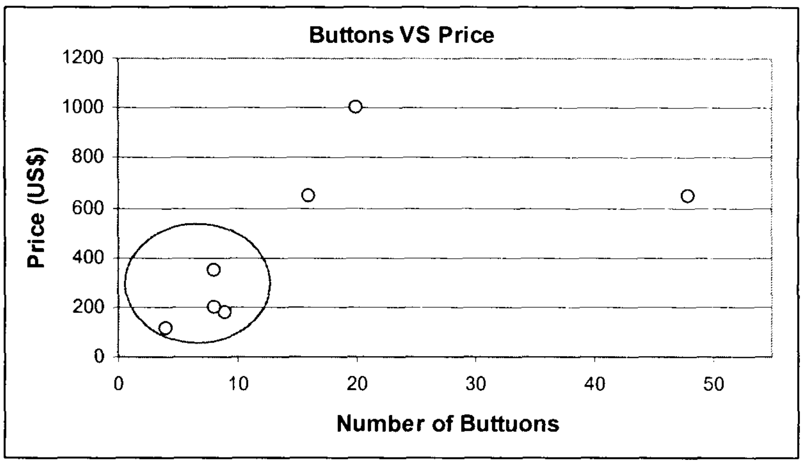
Importance percentages of the QFD shows that the most important parameters are Record Time (13%), Number of message Keys (11%) and Price (14%). Price is going to be the most important parameter because is the major restriction for the product to be competitive. As is going to be shown, designers should accept this restriction and do the best they can. The product is not mentioned in the competitive table because this analysis is going to be made later, in the action called "Competitiveness Analysis", and also this is going to be evaluated in the parametric analysis.

9. Parametric Analysis.

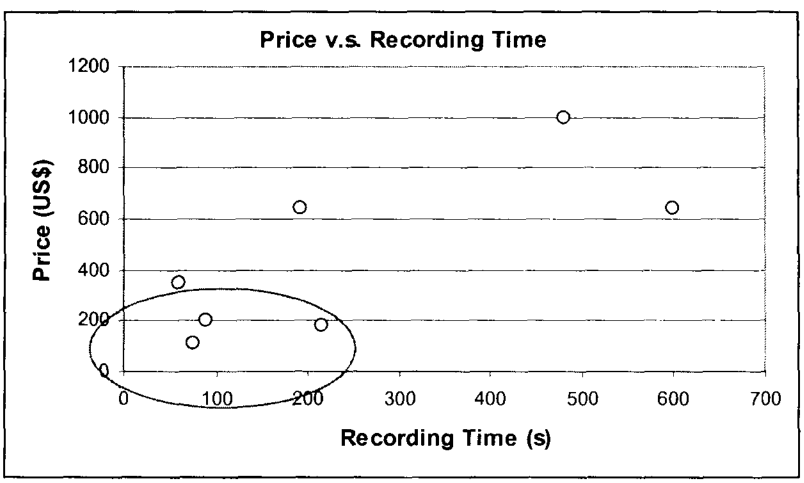
Objective: Identify possible relations between two parameters.

Based in the Matrix Analysis that was presented previously, the parametric analysis was developed by three members of the design team. They discussed about possible relations that could be found between two parameters. This helped the design team to define in which area of the graphic was necessary to place the SAC or which characteristic increase/decrease another.

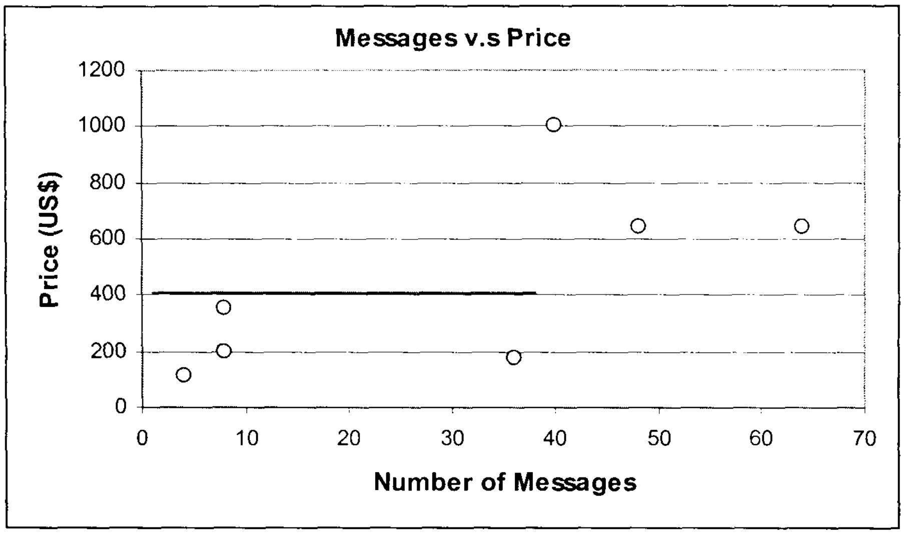
Correlations



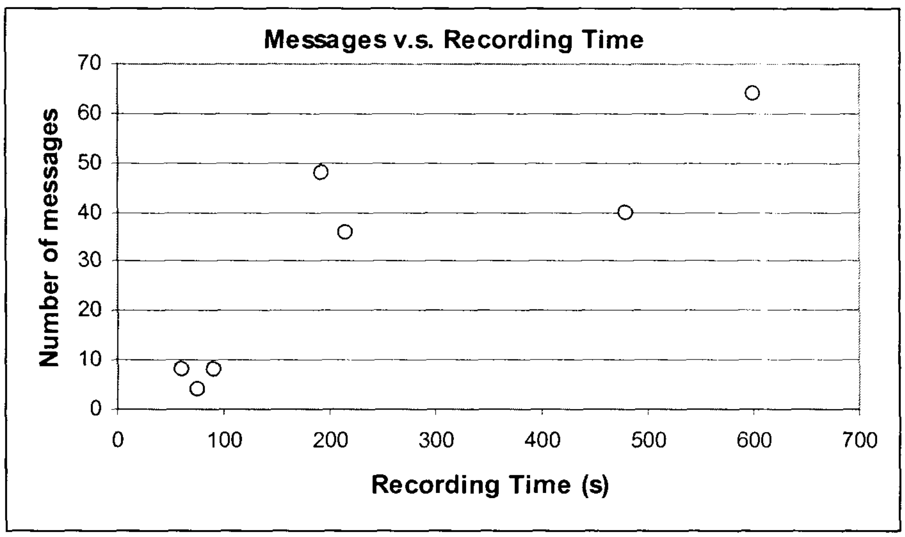
Possible relation between price and number of buttons.



Possible relation between price and record time.



No clear relation.



No clear relation.

Figure 5.2. Parametric Analysis.

Results of this phase are:

- Technical Requirements

After the conversion of customer needs to technical requirements and the evaluation of these, it is necessary to have a document with all that target specifications that will be the basis for the next design activities. This document will help to take decisions in the conceptual and embodiment design phase.

It is important to compare this list with the properties defined in the parametric analysis and complete both.

Date	Aug, 22 2003

1. Target specifications list.

SAC (Sistema de Aprendizaje y Comunicación)		
Metric		
Ref.	**Variables**	**Values**
1	Size	220 x 280 x 30 mm
2	Message Key Size	30 x 30 mm
3	Weight	400 gr
4	Record Time Available	360 sec
5	Force needed in Message Key	30 gr
6	Time needed to record a message	7 sec
7	Number of Message keys	30 units
8	Time needed to take the product	5 sec
9	Handle dimensions	25 x 100 mm
10	Time needed to clean product	3 min
11	Material resistance	5 ksi
12	Price	200 dls
13	Battery consumption	2 AA/month
No Metric		
14	User information space	
15	Light in keys	
16	Batteries and EEE	
17	No computer needed	
18	Switch option	
19	Nontoxic material	
20	Water proof product	

2. Useful ideas for the designer.

Ref	Idea
1	Slowed down activation of the button
2	Buttons below the faying surface
3	Alarm volume change automatically when the button is pushed
4	
5	

Table 5.8. Target Specifications.

10. Review of technical requirements.
Objective: Review that all the customer needs and all the parameters defined in the parametric analysis are reflected in the technical requirements defined in the Target Specification document.

The result for this review show that all the customer wants have a variable defined in the Target Specification List.

11. Product Competitiveness.
Objective: Decide if the product designing is going to be successful with those parameters defined. Compare it in the parametric analysis and make a radar diagram to

Direct competitive analysis

The information from the target specification will be used to compare SAC with all other products. First the categories of the comparison have to be defined. They can be qualitative or quantitative.

SAC will be compared in each category with the best product which is available on the market.

	PRICE	Weight	Message keys	Recording time	Messages
	less	**less**	more	more	more
	179	450	9	216	36
	645	700	48	192	48
	645	700	16	600	64
	999	1000		480	
	350	750	8	60	8
	115	80	4	75	4
	199	300	8	90	8
SAC	200	400	30	360	90
Maximum	999	1000	48	600	90
Division (SAC:MAX)	0.2002002	0.4	0.625	0.6	1
relativ position (1-Division)	**0.7997998**	**0.6**			
relativ position (Division)			0.625	0.6	1

Important notice:

It has to be clear if a bigger or small value of the category will be the constructive for the comparison.

The main result of this activity will be a radar in which the user can see his product compared with the best product in each category which is available on the market.

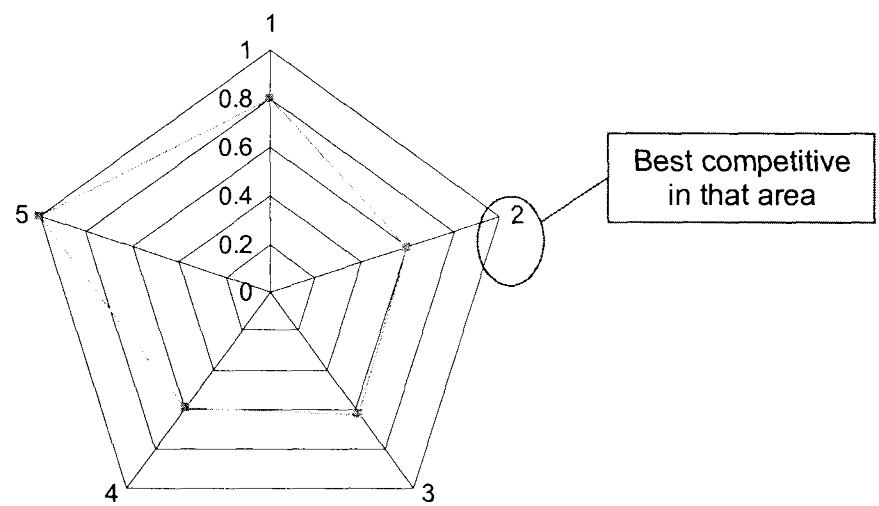


Figure 5.3. Competitive Analysis.

More axes can be added to this sketch in which more qualitative parameters can be considered. E.g. the user can compare the design from the SAC with another product and evaluate SAC manually.

5.2.2 Conceptual Design Phase.

In this phase, all the design team is involved. All express their opinion about the product based in their knowledge and experience. The interaction between mechanical, electronic and software people were in work sessions. Before the session each area worked separately.

The activities developed in the conceptual design phase are described below:

	#	Activity	Format	Tool	Technique	Record	Responsible
Phase	12	Functional Decomposition	F-PD-012	Word - Power Point	Functional Decomposition	R-PD-012	AP
	13	Concept Generation (Sub-functions)	F-BD-013	CREAX	Morphological Matrix (Sub-functions)	R-PD-013	PF
	14	Combine solution principles to fulfill the overall function	F-BD-014	Word	Morphological Matrix	R-BD-014	PF
	15	**Concept Selection (Conceptual design)**	F-BD-015	**Excel**	***Pugh Charts***	**R-BD-015**	PF

Table 5.9. Conceptual Design Activities

1. Product Function

Objective: Make a description that defines the general function of the product and the sub functions that it could realize.

Describe detailed functions of the Product.

A powerful, portable, easy to use and very durable speech output device. Use it as an introductory communication aid. It has to be recordable and easy to carry. With the possibility to change volume level. The product has to be reconfigurable (recordable). Must show the category of messages selected.

2. Functional Decomposition

Objective: Functional model that shows the relations between functional elements.

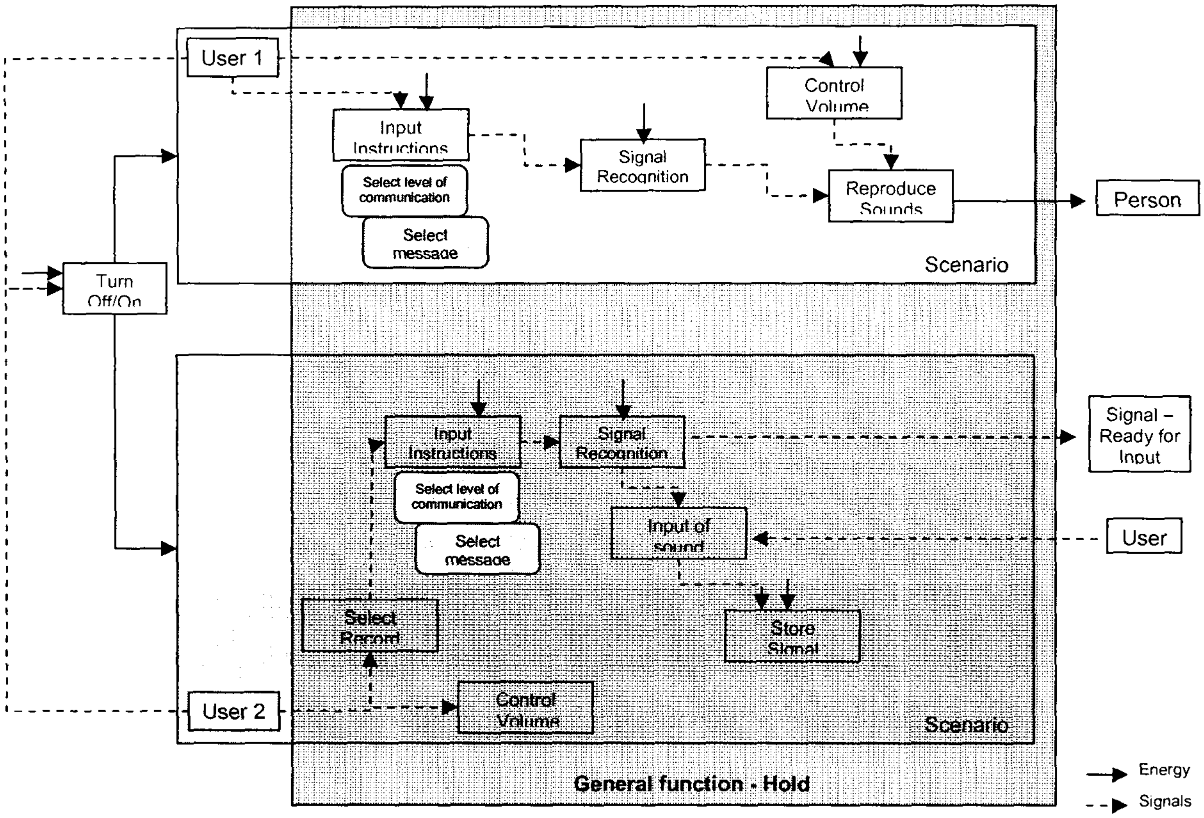


Figure 5.4. Functional Modeling.

After the functional decomposition, the team realizes that other ideas needed to be explored, so the team decided to have another activity called, Ideas Generation Session.

3. Ideas Generation

Objective: Get new ideas for the product concept. At least six new ideas should be obtained from the Creativity Session.

In this activity all the team, was involved. There was needed a moderator. The moderator organizes the session with the "Brainstorming" technique. To do not loose the objective, the requirements from customer and the description of the function of the product was given to each member. Ideas were sketched down and after the brainstorming were discussed in a more detailed way.

Results obtained from the creativity session are shown next:

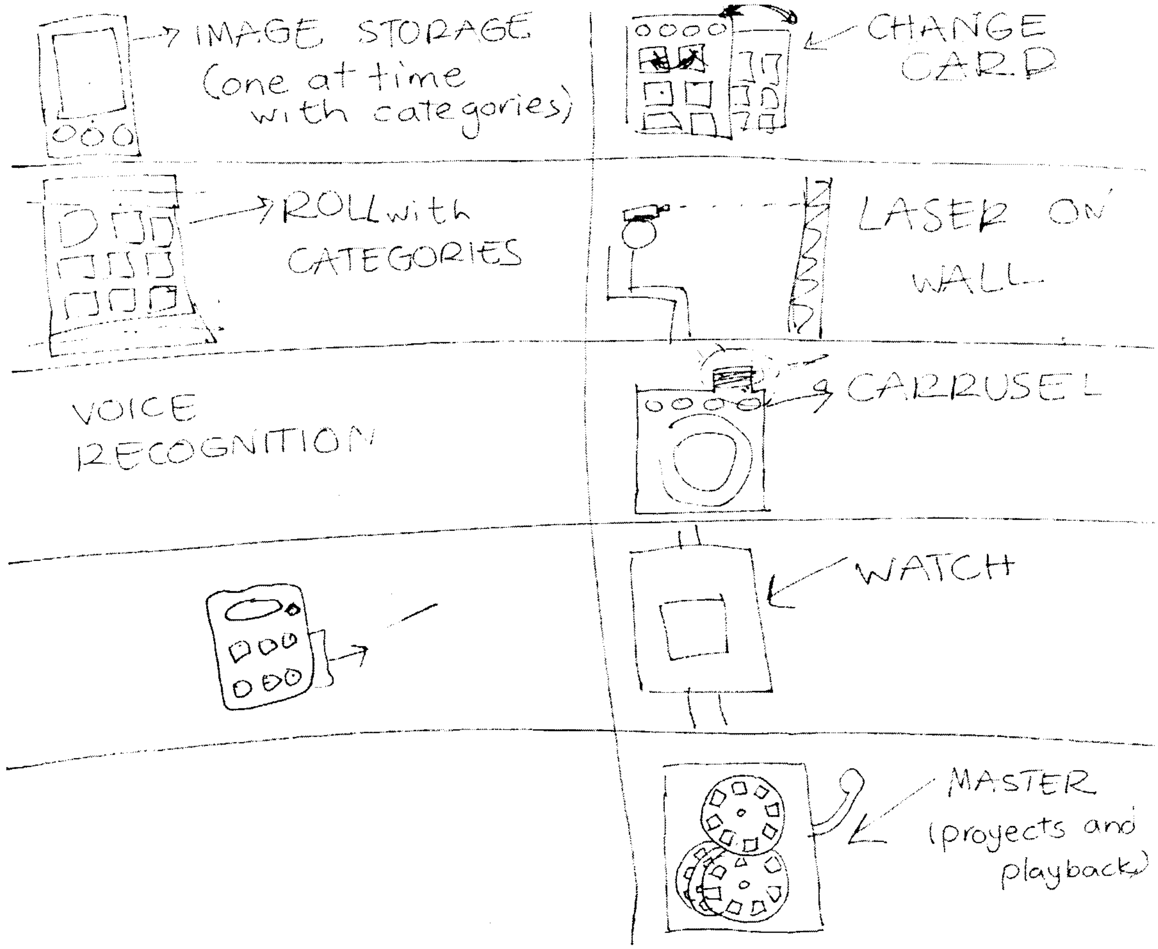


Figure 5.5. Concepts from ideas session.

4. Idea Selection

Objective: Select the one idea from the creativity session.

	Idea Selection	R-BD-012

CRITERIA	Importance	CONCEPTS: Image Storage (PDA principle)	Board with interchangeable cards	Board with roll for all images storage	Head pointer for wall, and wall displayer	Voice Recognition / Traduction	Carrusel (slide projector)	Watch	"Master" (discs for each category)
Knowledge	8	-1	1	1	1	-1	0	0	1
Technology	10	-1	1	1	0	-1	0	-1	1
Price	8	-1	1	0	-1	-1	-1	-1	0
Use Complexity	6	1	1	1	-1	1	0	0	0
Product Size	8	1	1	1	-1	1	0	1	1
	Total +	2	5	4	1	2	0	1	3
	Total -	-3	0	0	-3	-3	-1	-2	0
	Sum	-1	5	4	-2	-1	-1	-1	3
	TOTAL	-12	40	32	-14	-12	-8	-10	26

Table 5.10. Idea selection from creativity session.

The more viable idea was the board with interchangeable cards, the simplest product. The criteria discard the products that require a lot of technology, those that were expensive and others that were voluminous.

5. Solution Principles to Fulfill the Function

Objective: Search and define alternative solution principles (or components) that could realize each function. In the case of software products, define the kind of objects involved to realize each function.

6. Morphological Matrix

Objective: Define one or as much two configurations for the product. Selection of shapes-forms that satisfy the functions (components or structures). Select the shapes or components based in evaluation criteria like price, desirable size, availability, etc

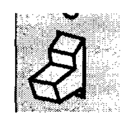
Date	September 01, 2003

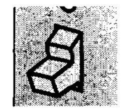
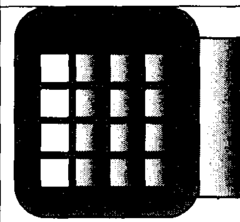
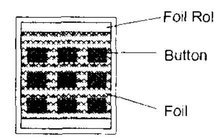
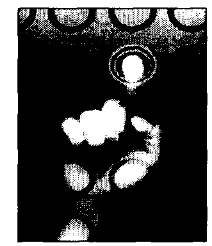
PRODUCT: SAC (Sistema de Aprendizaje y Comunicación)
REFERENCE: SAC Functional Decomposition (R-BD-011)

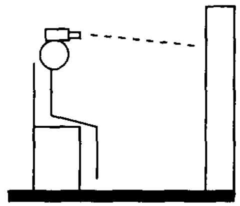
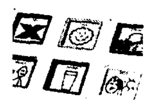
1. Morphologic Matrix

Note.

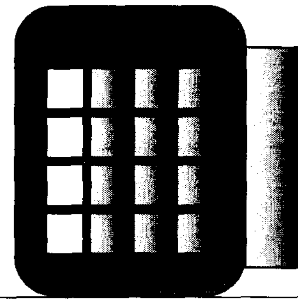
- Use one matrix for each function.
- Give a qualification between 1 and 5 for each part in the two categories: Cost and Ergonomics. (Bigger number refers to less cost and better in human interaction).

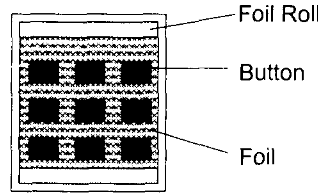
	Possible Solutions				
Function	**1**	**2**	**3**	**4**	**5**
1.0 Turn On/Off	 Big Push button	 Small Push button	 Big Switch	On Off Small Switch	 Top view Lateral view Push button (same level)
Qualification Cost Ergonomics	5 3	5 4	5 5	5 5	4 5

		Possible Solutions				
Function	**Sub functions**	**1**	**2**	**3**	**4**	**5**
2.0 **Input Instructions**	2.1 Select record option	On Off Small Switch	 Top view Lateral view Push button (same level)	 Big Switch		
	Qualification Cost Ergonomics	5 5	4 5	4 5		
	2.2 Select level of communication (it continues in the next row)	Push buttons, display and change cards	 Change cards (automatically recognition)	1 2 3 4 By push button	 Push button by a Roller-Foil	 Touch screen
	Qualification Cost Ergonomics	5 4	3 4	5 5	3 4	

	2.2 Select level of communication	 By laser	Change of carrousel		Voice recognition	
	Qualification Cost Ergonomics	 4 2	 4 1		 3 5	
	2.3 Select message	 Top view Lateral view Push button (same level)	 Push button (inferior level)	Contact activated button	By laser	
	Qualification Cost Ergonomics	 4 5	 5 5	 3 3	 3 4	 1 4

Note.
For reference of Patents writes down the number of patent and annexes first page patent using format MM1
For reference of Products writes down the name product and annexes reference documents using format MM1
For own ideas use the format MM1.

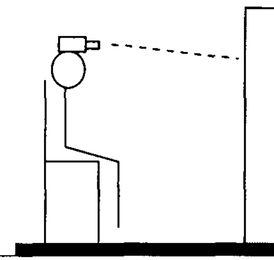
Function or Sub function	2.2 Select level of communication	**Solution Number**	1	**Format MM1**
Source	Creativity session.	**Date**	September 7, 2003	
Description of solution A card for category of words. The product identifies automatically the card that is inside and reproduces the adequate sound.				
Sketch 				

Function or Sub function	2.2 Select level of communication	**Solution Number**	4	**Format MM1**
Source	Creativity session.	**Date**	September 7, 2003	
Description of solution All messages are stored in a roll by categories. By a push button the user change the images. The product identifies automatically in which category is working on.				
Sketch  				

Function or Sub function	2.2 Select level of communication	Solution Number	6	Format MM1
Source	Creativity session.	**Date**	September 7, 2003	

Description of solution
Categories are displayed on the wall, the user selects the category by pointing whit his head one of them in the wall.

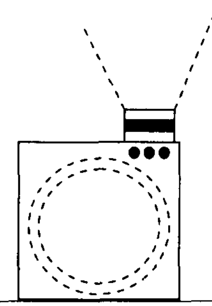
Sketch



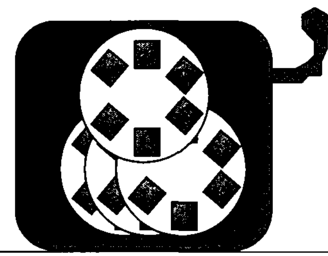
Function or Sub function	2.2 Select level of communication	Solution Number	7	Format MM1
Source	Creativity session.	**Date**	September 7, 2003	

Description of solution
A carrousel stores all the images by category. A button changes between categories. A button changes between images.

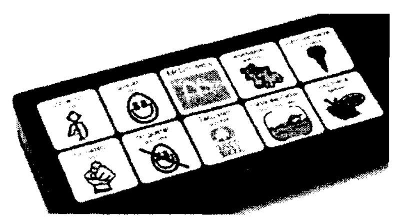
Sketch

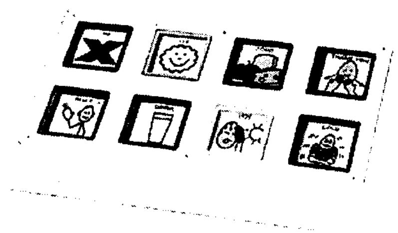


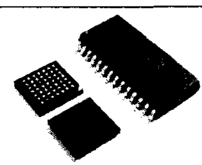
Function or Sub function	2.2 Select level of communication	Solution Number	8	Format MM1
Source	Creativity session.	**Date**	September 7, 2003	
Description of solution Every collection of images (category) is stored in one disc, the product changes between categories by changing the disc in use. The user sees the image by a mirror in to the product.				
Sketch				



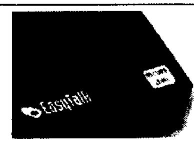
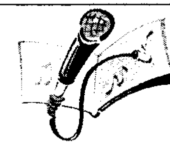
Function or Sub function	2.3 Select Message	Solution Number	1	Format MM1
Source	http://www.greattalkingbox.com/easytalk.htm	**Date**	September 1, 2003	
Description of solution Push button at same level of principal surface of the product.				
Sketch				



Function or Sub function	2.3 Select Message	**Solution Number**	2	**Format MM1**
Source	http://www.beyondplay.com/ITEMS/C491.HTM	**Date**	September 1, 2003	
Description of solution Push button under principal surface of the product.				
Sketch 				

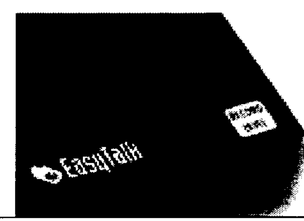
	Possible Solutions				
Function	**1**	**2**	**3**	**4**	**5**
3.0 Signal Recognition	 Microcontroller				
Qualification Cost Ergonomics	 - -				

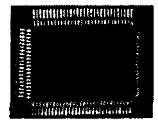
Possible Solutions

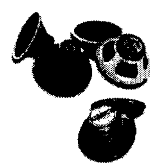
Function	1	2	3	4	5
4.0 Sound Input	 Interior Microphone	 External Device	 Speaker		
Qualification Cost Ergonomics	 4 5	 4 3	 5 5		

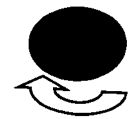
Note.
For reference of Patents writes down the number of patent and annexes first page patent using format MM1
For reference of Products writes down the name product and annexes reference documents using format MM1
For own ideas use the format MM1.

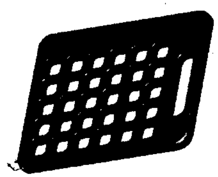
Function or Sub function	4.0 Sound Input	**Solution Number**	1	**Format MM1**
Source	http://www.greattalkingbox.com/easytalk.htm	**Date**	September 1, 2003	
Description of solution Microphone inside the product.				
Sketch				



	Possible Solutions				
Function	**1**	**2**	**3**	**4**	**5**
5.0 Store Signal (Sound)	 Memory	 Sound Chip	 USB - Hard drive		
Qualification Cost Ergonomics	 4 -	 5 -	 3 -		

	Possible Solutions				
Function	**1**	**2**	**3**	**4**	**5**
6.0 Reproduce Sounds	 Internal Speaker	 External Speaker	 External Device (head phones)		
Qualification Cost Ergonomics	 5 5	 5 3	 4 3		

	Possible Solutions				
Function	**1**	**2**	**3**	**4**	**5**
7.0 Volume Control	 + - By push button	Top view Lateral view Push buttons (+, -)	 By drag		
Qualification Cost Ergonomics	5 4	5 5	5 5		

	Possible Solutions				
Function	**1**	**2**	**3**	**4**	**5**
8.0 Hold product	 Plastic Case, 30 buttons	Metallic Case	Plastic Case supported by neck		
Qualification Cost Ergonomics	5 5	3 4	5 5		

Result in the middle of this phase is:
- Concept Alternatives

After the component shapes were selected, the design team defines various configurations for the product. Some examples are shown below. To draw the concepts it was no needed all the team, just one person made them, the design engineer. To make the sketches he took in consideration all the comments of the team.

Tec de Monterrey	Combine Solution Principles to Fulfill the Overall Function	R-BD-014
	Instituto Tecnológico y de Estudios Superiores de Monterrey	

PRODUCT: SAC (Sistema de Aprendizaje y Comunicación)
REFERENCE: SAC Morphological Matrix (R-BD-013)

Objective.

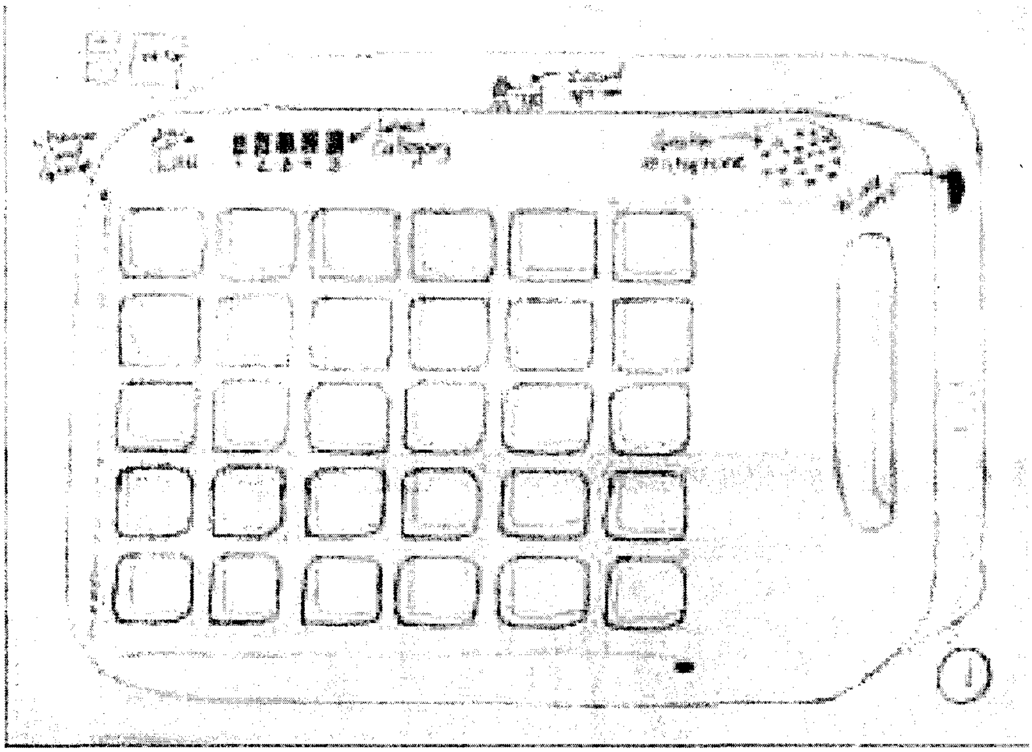
Combine the solution principles selected in the morphological matrix to create many alternatives of the product. Each alternative will be given a qualification in the next activity (Concept Selection by Pugh Charts).

Concepts Selected.

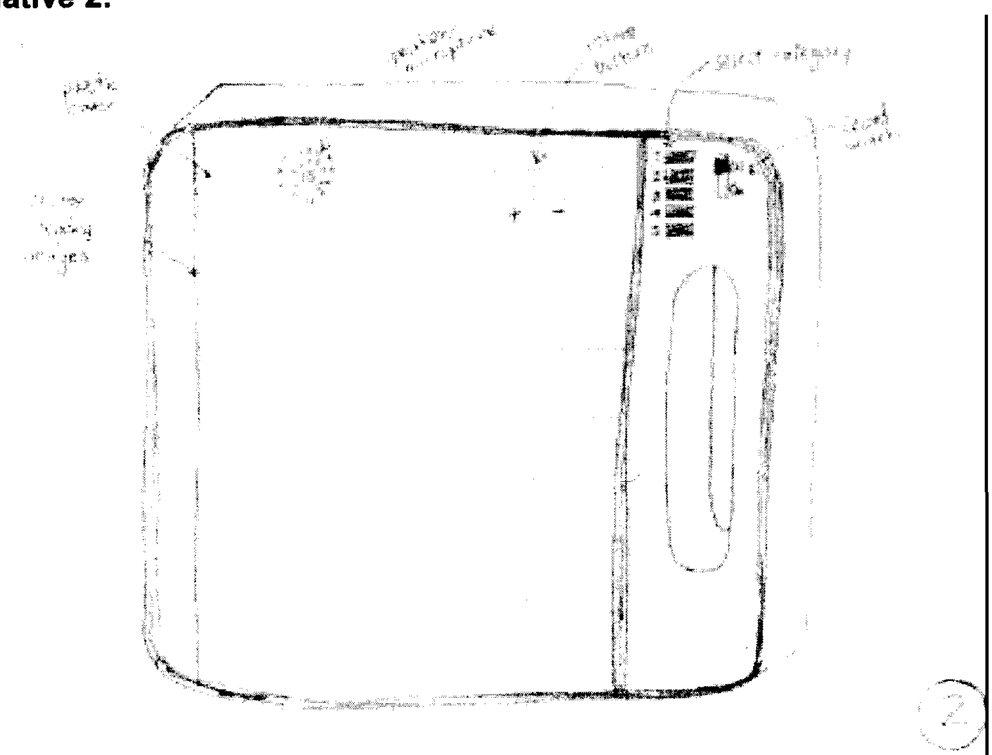
1. Turn On/Off	2. Input Instructions			3. Signal Recognition	4. Sound Input	5. Store Signal (Sound)	6. Reproduce Sounds	7. Volume Control	8. Hold product
	2.1	2.2	2.3						
1.3 **1.4**	**2.1.1**	**2.2.2**	**2.3.1** **2.3.2**	**3.1**	**4.3**	**5.2**	**6.1**	**7.2** **7.3**	**8.1**

Combining these solution principles the proposed alternatives are shown:

Alternative 1.

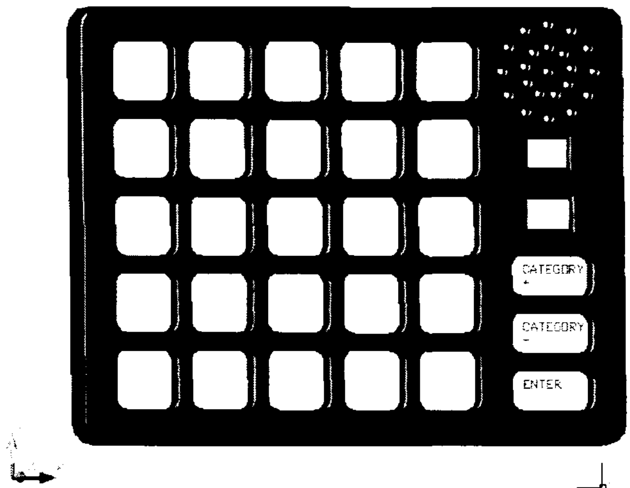


Alternative 2.



Alternative 3.

Use alternative 1 with the display selected in the morphological matrix.



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7. Concept Selection

Objective: Select the best configuration of the product evaluating the options with the appropriate criteria.

After some products alternatives were defined the evaluation of those to alternatives was required. All team members must intervene in this evaluation and discuss many characteristics about the three alternatives.

Tec de Monterrey	Concept Selection		R-BD-015
		CONCEPTS	

CRITERIA	Importance	Alternative 1	Alternative 2	Alternative 3
Case cost	6	1	0	1
Ergonomics	10	1	1	0
Capacity (# figures)	8	-1	-1	1
Easy to use	8	1	1	1
	Total +	3	2	3
	Total -	-1	-1	0
	Sum	2	1	3
	TOTAL	16	10	22

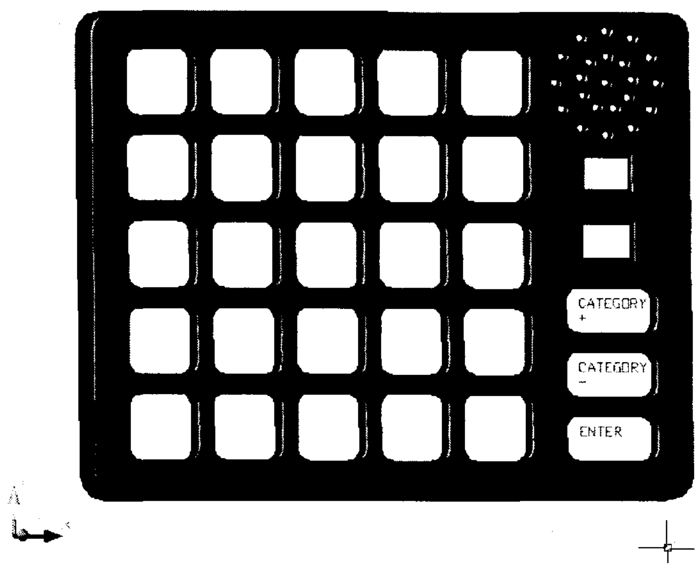
Table 5.11. Concept selection.

The selected concept was the "Alternative 3". This is the concept that includes the display. After the selection was made, the team discusses how to make a more ergonomic product, that was because the qualification in that criteria was 0.

The Result of this phase is:

- Conceptual Design

The conceptual design of the product includes the display. For a better visualization of the product, a CAD drawing was made and is shown in the next figure.



To continue with the next phase, the team made a review of the general objective of the phase and check that the design satisfy al the wants of the customer and the list of technical requirements defined in the below activities.

5.2.3 Embodiment Design Phase.

5.2.3.1 Embodiment Design Phase – Mechanical Design.

The general objective for this phase is to obtain a detailed layout for the product. The next table condenses all the information about the development of this phase.

Phase	#	Activity	Format	Tool	Technique	Record	R
Embodiment Design	16	Identify embodiment-determining requirements	F-ED-016	Word	List – Checklist (Heading 3)	R-ED-016	DV
	17	Scale drawings of spatial constraints.	F-ED-017	Mechanical Desktop, Word	Sketch, Checklist	R-ED-017	PF
	18	Identify embodiment-determining **main function** carriers.	F-ED-018	Word	List	R-ED-018	JA
	19	**Preliminary** layouts for main function carriers	F-ED-019	Mechanical Desktop	Scale Drawing, DFA, DFM, Checklist, CAE	R-ED-019	PF
	20	Select suitable preliminary layouts	F-ED-020	Excel	Checklist, FMEA, VE	R-ED-020	PF
	21	**Preliminary** layouts and form designs for the **remaining main function** carriers.	F-ED-021	Mechanical Desktop	Scale Drawing, DFA, DFM, Checklist	R-ED-021	JA
	22	Search for solutions to auxiliary functions	F-ED-022	Internet	Exploit known solutions	R-ED-022	JA
	23	**Detailed** layouts and form designs for the **main** function carriers.	F-ED-023	Mechanical Desktop	Scale Drawing, Checklist, DFA, DFM, CAE	R-ED-023	PF
	24	**Detailed** layouts and form designs for the **auxiliary** function carriers and complete the overall layouts	F-ED-024	Mechanical Desktop	Scale drawing, Checklist, DFA, DFM, CAE	R-ED-024	JA
	25	Evaluate against technical and economic criteria	F-ED-025	Excel	VE, Pugh Charts, Axiomatic Design	R-ED-025	JA
	26	Preliminary Layout	F-ED-026	Mechanical Desktop	Scale Drawing, DFA, DFM, FMEA, CAE	R-ED-026	PF
	27	Optimize and complete form designs	F-ED-027	Excel, Minitab, Mechanical Desktop	Tolerance Analysis	R-ED-027	JA
	28	Check for errors and disturbing factors	F-ED-028	-	Review	R-ED-028	PF
	30	**Definitive Layout**	**F-ED-029**	**Mechanical Desktop**		**R-ED-029**	PF

Table 5.14. Embodiment Design Activities for SAC.

1. Embodiment requirements.

Tec de Monterrey	**Embodiment Requirements**	**R-ED-016**
	Instituto Tecnológico y de Estudios Superiores de Monterrey	

PRODUCT: SAC (Sistema de Aprendizaje y Comunicación)
REFERENCE: SAC Morphological Matrix (R-BD-013)

Objective.
Here the crucial requirements are identified: size, arrangement, materials.

Function	Component	Characteristics
On/Off	Big Switch Newark InOne Part No.: 23F001 Manufacturer Part No.: 1600-11E	27.4 x 12.34 x 2.99 mm
Select Record Option	Small Switch Newark InOne Part No.: 57F2139 Manufacturer Part No.: MSS-2250G	24 x 6 x 1 mm
Select level of communication	Push buttons Newark InOne Part No.: 03NX2765 Manufacturer Part No.: FC2APSKAC PROG STR KT AC INPUT Display Newark InOne Part No.: 06F5703 Manufacturer Part No.: HDSP-5521	5 x 5 x 5 mm 20 x 12 x 7 mm
Select Message	Push button (inferior level) Newark InOne Part No.: 03NX2765 Manufacturer Part No.: FC2APSKAC PROG STR KT AC INPUT	5 x 5 x 5 mm
Signal Recognition	Microcontroller AT89C51	50 x 18 x 15 mm (memory included)
Sound Input	Speaker	R 56 mm, 15 mm (speaker double function)
Store Signals	Sound Chip	The same with the microcontroller
Reproduce Sounds	Internal Speaker	R 56 mm, 15 mm
Volume control	By drag Newark InOne Part No.: 92N4102 Manufacturer Part No.: MC2001009B	D 0.38" x H 0.6"
Hold Product	Plastic case	To be designed.

Evaluation Method.

Use the Heading number 3 from the checklist to evaluate the selection of the components.

HEADING 3	CHECKLIST
Layout, geometry, and materials	Do the chosen layout, component shapes, materials, and dimensions provide minimal performance variance to noise (robustness), adequate durability (strength), efficient material usage (strength-to –mass ratio), suitable life (fatigue), permissible deformation (stiffness),

	adequate force flows (interfaces and stress concentrations), Adequate stability, Impact resistance, Freedom from resonance, Unimpeded expansion and heat transfer, and Acceptable corrosion and wear with the stipulated service life and loads?

Evaluation:

Component	Performance to variance	Durability (strength)	Suitable life (fatigue)	Permissible deformation (stiffness)	Impact resistance
F001 - Switch	-	100,000 uses	-	Good	Good
F002 - Switch	-	100,000 uses	-	Good	Good
F003 – Buttons	Good	100,000 uses	-	Good	-
F004 - Display	Good	15,000 h	-	-	-
F005 – Microcontroller	Good	100 record	-	-	-
F006 – Speaker	Good	Unlimited	-	-	-
F007 – Drag Switch	-	100,000 uses	-	Good	-
F008 – Case	-	?	?	?	?

Conclusions for the case can not be obtained, a this moment, this will be done after the CAE simulation for estress.

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2. Scale drawings of spatial constraints.

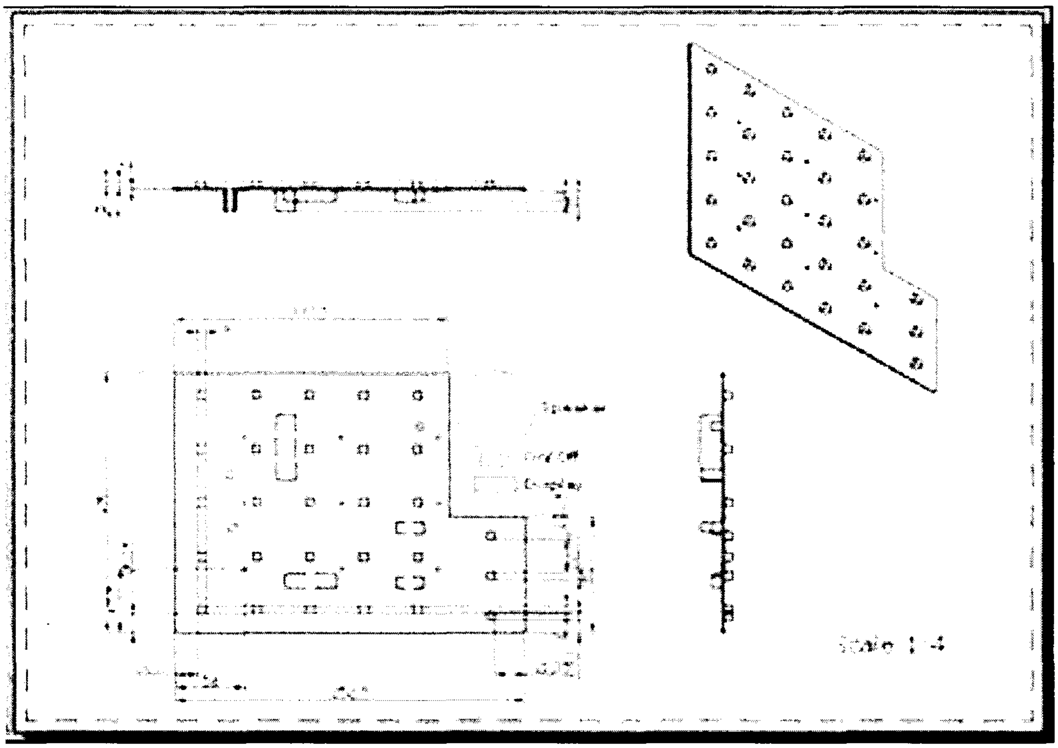
Objective: Define the determining or restricting spatial constraints, like, clearances, axle positions, installation requirements, etc.

Tec de Monterrey	Scale Drawings	R-ED-017
Instituto Tecnológico y de Estudios Superiores de Monterrey		

PRODUCT: SAC (Sistema de Aprendizaje y Comunicación)
REFERENCE: Embodiment Requirements (R-ED-016)

Objective: Obtain a sketch defining the spatial restrictions for the product based on the list defined in the previous activity for the whole product and for the components involved. Evaluate the configuration of the product.

1. Define the determining or restricting spatial constraints, like, clearances, axle positions, installation requirements, etc.



2. Evaluate the spatial restrictions. That implies the distribution of the components in the product.

The team checked the headings that are shown next:

Heading	Check	Check list issue (Partial list)
Function	☑	Are the customer needs satisfied, as measured by the target values? Is the stipulated product architecture and function(s) fulfilled? What auxiliary or supporting functions are needed?
Working principles and form solutions	 ☑ ☑	Do the chosen form solutions (architecture and components per function) produce the desired effects and advantages? What disturbing noise factors may be expected? What byproducts may be expected?
Layout, geometry, and materials	 ☑ ☑ ☑ ☑ ☑ ☑	Do the chosen layout, component shapes, materials, and dimensions provide minimal performance variance to noise (robustness), adequate durability (strength), efficient material usage (strength-to –mass ratio), suitable life (fatigue), permissible deformation (stiffness), adequate force flows (interfaces and stress concentrations),

	☑ ☑ ☑ ☑	Adequate stability, Impact resistance, Freedom from resonance, Unimpeded expansion and heat transfer, and Acceptable corrosion and wear with the stipulated service life and loads?
Energy and kinematics		Do the chosen layout and components provide Efficient transfer of energy (efficiency), Adequate transient and steady state behavior (dynamic and control across energy domains), and Appropriate motion, velocity, and acceleration profiles?
Safety		Have all of the factors affecting the safety of the user; components, functions, operation, and the environment been taken in to account?

3. Identify main function carriers.

Tec de Monterrey	Embodiment Determining Main Function Carriers	R-ED-018

Instituto Tecnológico y de Estudios Superiores de Monterrey

PRODUCT: SAC (Sistema de Aprendizaje y Comunicación)
REFERENCE: Embodiment Requirements (R-ED-016)

Objective: Define the main function carriers answering two questions: 1) Which main function carriers determine the size, arrangement and component shapes of the overall layout. 2) What main functions must be fulfilled by which function carriers jointly or separately?

The carriers that determine the size of the product are:

Component	Reason
CASE	The case define the size of the product because the size and number of the buttons
Electronic Card	The electronic card has to support the buttons. The button holes are distributed in the case face.
Speaker	The speaker is the highest component.

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Remember that some evaluation tools are going to be applied in the next activities to assure product functionality. As was mentioned before, these tools are:

- Checklist
- FMEA
- DFM- DFA
- Value Engineering

4. Preliminary layouts and form designs for main function carriers.

Tec de Monterrey	Preliminary Layouts	R-ED-019
	Instituto Tecnológico y de Estudios Superiores de Monterrey	

PRODUCT: SAC (Sistema de Aprendizaje y Comunicación)

Objective: The general arrangement, component shapes and materials must be determined provisionally. Result must meet the overall spatial constraints and be completed so that all relevant main functions are fulfilled.

Applying DFA.

As working in the design of the SAC, the mechanical and electronic experts followed the guidelines mentioned in the Appendix D.

Design guidelines used were:

- Modularize multiple parts into single subassemblies (Crow 1988): the buttons were included on the electronic card to avoid another extra part.
- Assemble in open space, not in confined spaces. Never bury important components (Tipping 1965): the SAC is divided in two parts to permit the easy assembly of the electronic components.
- Standardize to reduce part variety (Tipping 1965): all the buttons were design to use the same component.
- Design the mating features for easy insertion. (Iredale 1964, Tipping 1965, Baldwin 1966): The electronic card will be assemble by easy insertion in the back part of the product.
- Provide alignment features. (Baldwin 1966): Screws have a channel to provide alignment and easy insertion.

The next table shows the results for the Design for Assembly analysis made to the product. Components were reduced from 17 to 14. Designers realized that they did not need an extra buttons support and screws for the record button.

DFA - SAC

Hour Cost = $ 15 15

Component	No	Cant.	COD1	T1	COD2	T2	Min	T T	$
Case Down	1	1	30	2	00	1.5	1	3.5	0.015
Case Up	2	1	30	2	03	5.2	1	7.2	0.030
Screws	3	4	16	2.6	06	3.6	4	24.8	0.103
Speaker	4	1	12	2.3	02	2.6	1	4.9	0.020
Display	5	1	12	2.3	00	1.5	1	3.8	0.016
Plastic Layer	6	1	04	2.2	00	1.5	1	3.7	0.015
Category Card	7	1	14	2.6	01	3	1	5.6	0.023
On/Off button	8	1	30	2	04	1.8	1	3.8	0.016
Control volume	9	1	21	2.1	02	2.6	1	4.7	0.020
Record option button	10	1	30	2	04	1.8	1	3.8	0.016
Batteries cover	11	1	20	2	00	1.5	1	3.5	0.015
Buttons support	12	1	30	2	01	3	0	5	0.021
Screws for record button	13	2	3.2	2.7	07	5.3	0	16	0.067
TOTAL		**17**					**14**	**90.3**	**0.376**

Design Efficiency = $\frac{3 * \# \text{ min parts}}{\text{Total Time}} = \frac{42}{90.3} =$ **47%**

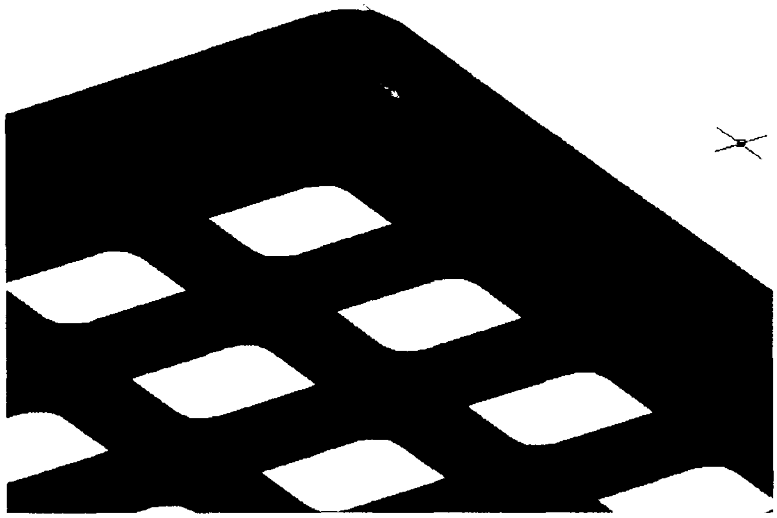
Applying DFM.

Guidelines used in Design for Manufacturing were:

- Minimization of section thickness, 3mm to have the proportional cooling time.
- A draft angle of 2° for easy mold removal.
- Cleared corners.
- Symmetry

When applying the DFM guidelines and rules, three designs were discarded because they were no manufactureable or were costly. Also many details were added to the design. Fillets were rounded, in order to easily retire the product of the mold, an angle was defined in the walls. Columns distribution also had to be symmetrical.

One example about the preliminary design before applying DFM is shown next.



Checklist.

In this step, a lot of work was required to check some headings of the checklist.

Heading	Check	Check list issue (Partial list)
Function	☑	Are the customer needs satisfied, as measured by the target values?
	☑	Is the stipulated product architecture and function(s) fulfilled?
	☑	What auxiliary or supporting functions are needed?
Working principles and form solutions	☑	Do the chosen form solutions (architecture and components per function) produce the desired effects and advantages?
	☑	What disturbing noise factors may be expected?
	☑	What byproducts may be expected?
Layout, geometry, and materials		Do the chosen layout, component shapes, materials, and dimensions provide
	☑	minimal performance variance to noise (robustness),
	☑	adequate durability (strength),
	☑	efficient material usage (strength-to –mass ratio),
	☑	suitable life (fatigue),
	☑	permissible deformation (stiffness),
	☑	adequate force flows (interfaces and stress concentrations),
	☑	Adequate stability,
		Impact resistance,
	☑	Freedom from resonance,
	☑	Unimpeded expansion and heat transfer, and
	☑	Acceptable corrosion and wear with the stipulated service life and loads?
Energy and kinematics		Do the chosen layout and components provide
	☑	Efficient transfer of energy (efficiency),
	☑	Adequate transient and steady state behavior (dynamic and control across energy domains), and
	☑	Appropriate motion, velocity, and acceleration profiles?
Safety	☑	Have all of the factors affecting the safety of the user; components, functions, operation, and the environment been taken in to account?
Ergonomics	☑	Have the human-machine relationships been fully considered?
	☑	Have unnecessary human stress or injurious factor been predicted and avoided?
	☑	Has attention been paid to aesthetics and the intrinsic "feel" of the product?
Production		Has there been a technological and economical analysis of the production processes, capability, and suppliers?
Quality control		Have standard product tolerances been chosen (not to tight)?

		Have the necessary quality checks been chosen (type, measurements, and time)?
Assembly	☑ ☑	Can all internal and external assembly operations be performed simply, repeatedly, and in the correct order (without ambiguity)? Can components be combined (minimize part count) without affecting modular architectures and functional independence of the product?
Transport		Have the internal and external transport conditions and risks been identified and solved? Have the required packaging and dunnage been designed?
Operation	☑	Have all the factors influencing the product's operation, such as noise, vibration, and handling been considered?
Life Cycle	 ☑ ☑	Can the product, its components, its packaging be reused or recycled? Have the materials been chosen and clumped to aid recycling? Is the product easily disassembled?
Maintenance	☑ ☑	Can maintenance, inspection, repair and overhaul be easily performed and checked? What features have been added to the product to aid in maintenance?
Costs	☑	Have the stipulated cost limits been observed? Will additional operational or subsidiary costs arise?
Schedules		Can the delivery dates be met, including tooling? What design modifications might reduce cycle time and improve delivery?

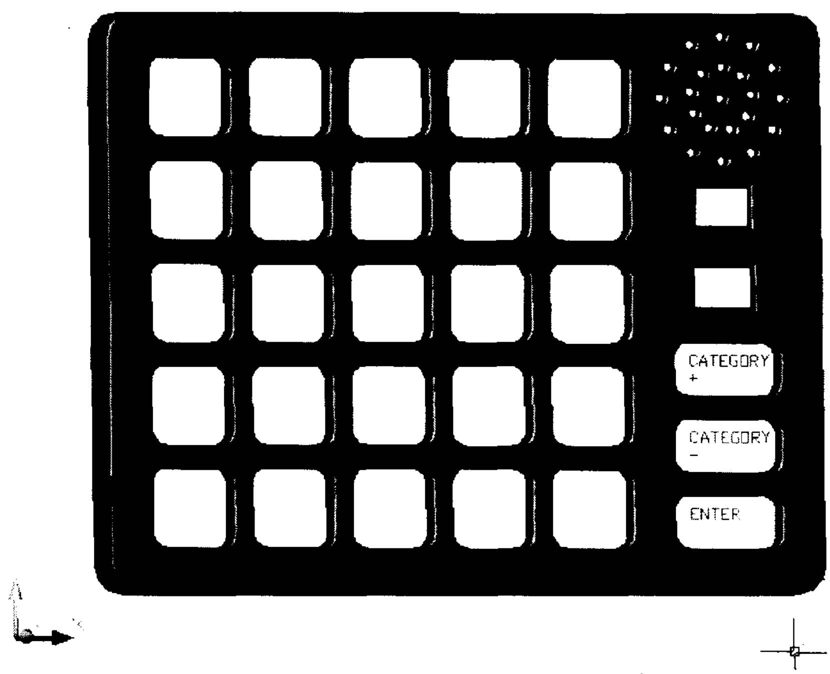


Figure 5.8 Front part preliminary layout for SAC.

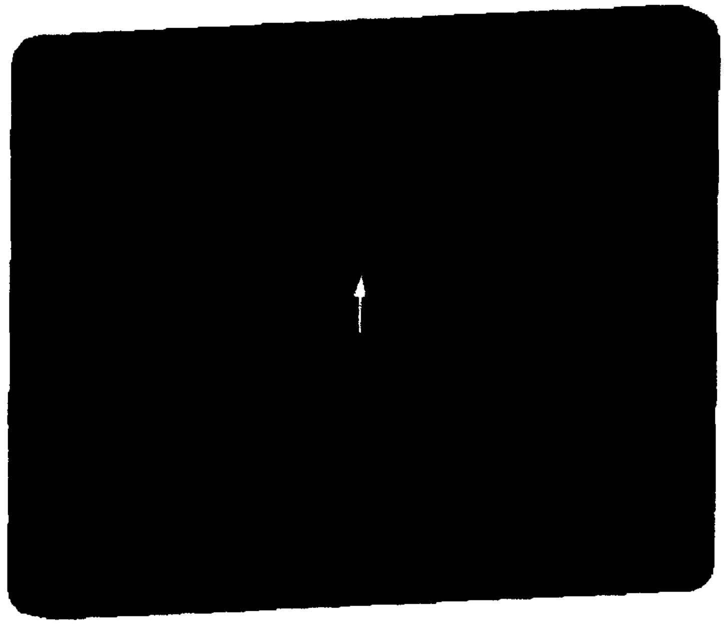


Figure 5.9 Back part preliminary layout for SAC.

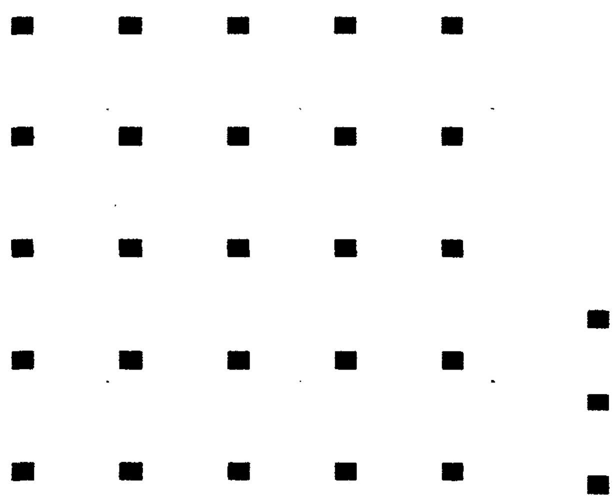


Figure 5.10 Concept for electronic Card to define geometry.

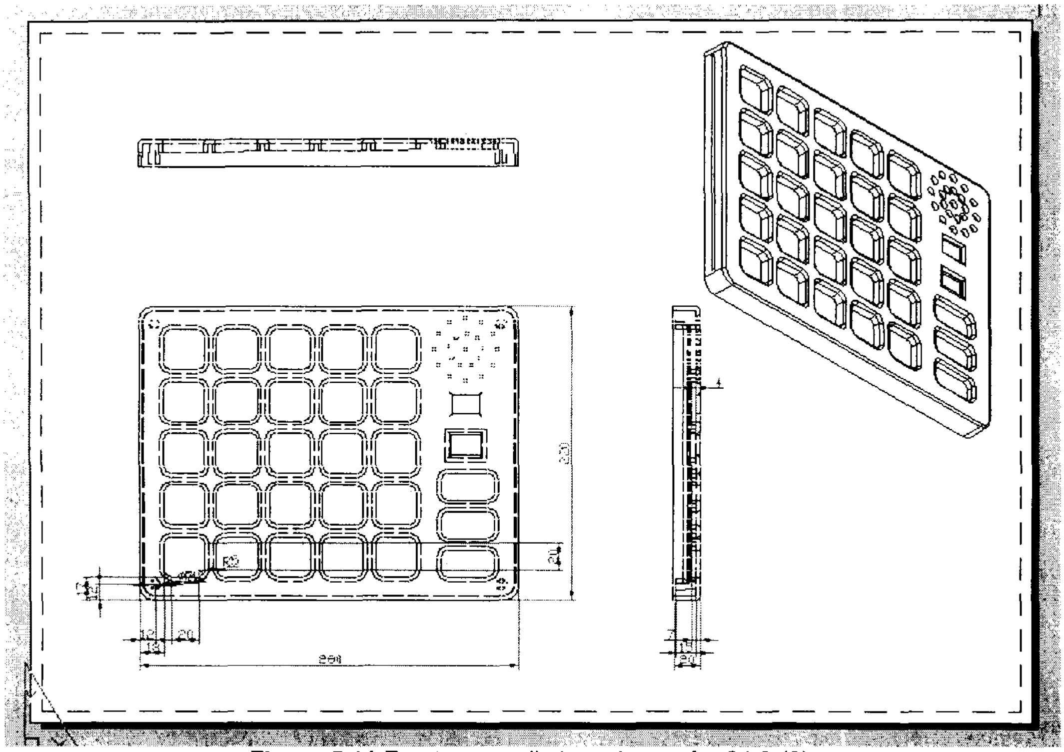


Figure 5.11 Front part preliminary layout for SAC (2).

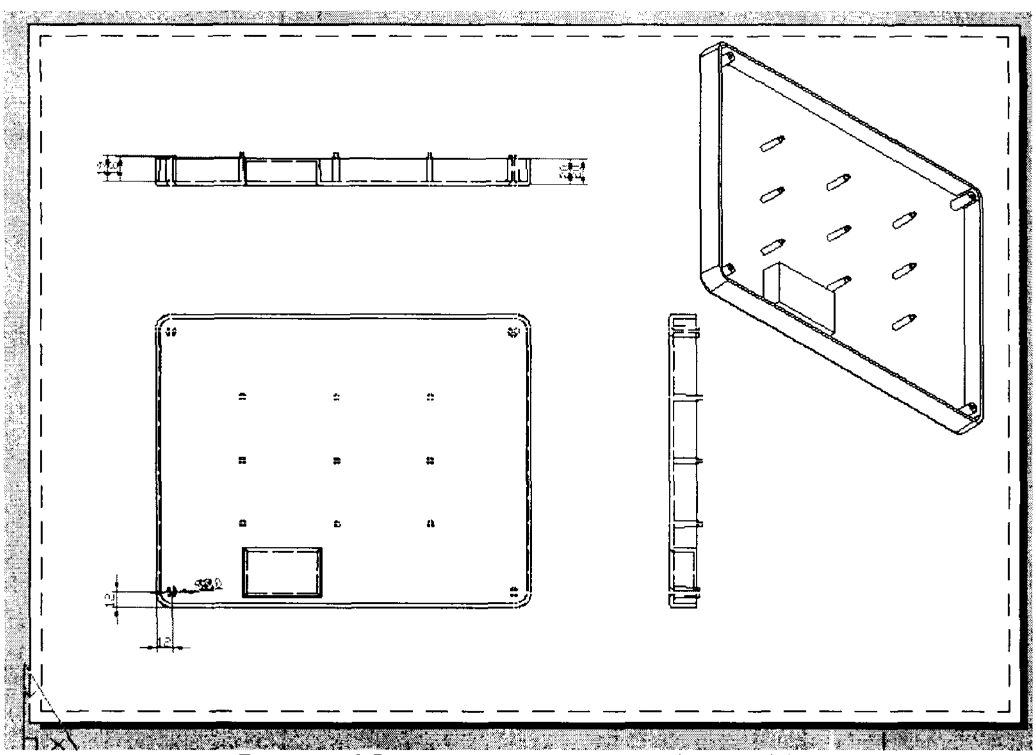


Figure 5.12 Back part preliminary layout for SAC (2).

5. Select suitable preliminary layouts.

To select the suitable preliminary layouts the method used was the AMEF. This technique is useful to evaluate the entire design of the product. The resultant AMEF is shown next.

	Select Suitable Preliminary Layouts	R-ED-020
Tec de Monterrey	Instituto Tecnológico y de Estudios Superiores de Monterrey	

PRODUCT: SAC (Sistema de Aprendizaje y Comunicación)
Objective: Evaluate preliminary layouts (if many) or evaluate the preliminary layout making a FMEA.

FMEA

Potential Failure Mode and Effects Analysis
(Design FMEA)

System	SAC (Sistema de Aprendizaje y Comunicación)	FMEA Number	ED-001
Subsystem	-	Prepared by	PF
Component	-	FMEA Date	07-Oct-03
Design Lead	Paola Farías Moreno	Revision date	12-Oct-03
Core Team	JA, DV, CM, PF, AP	Page 1 of	1

Item/Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	SEV	Potental Causes / Mechanism (s) of Failure	PROB	Current Design Controls	DET	RPN	Recomended Action(s)	Responsibility & Target Completion Date	Actions Taken
Switch Turn On/Off	Clog, Fail in weld	Can not turn On/Off the product	8	Large tolerances in switch design, Few welding material	3	Switch inspection, Welding inspection	6	144	Develop a inspection procedure of components and welding process	DV / Ene 04	-
Button/Select level of communication	Clog, Insufficient load, Fail in weld	Do not reproduce the correct sound	6	Hard buttons, few welding material	2	Buttons inspection	3	36	Inspection procedure for buttons	DV / Ene 04	-
Button/Select Message	Clog, Insufficient load, Fail in weld	Do not reproduce sound	8	Failure in welding	2	Welding Inspection	6	96	Inspection procedure for welding	DV / Ene 04	-

Microcontroller / Signal Recognition	Misunderstood signal	Reproduce another sound	6	Bad programming	3	Simulation of program	3	54	Review and simulation of program	DV / Ene 04	-
	Fail in weld	Do not reproduce sound	8	Failure in welding	2	Welding Inspection	6	96	Inspection procedure for welding	DV / Ene 04	-
	Insufficient memory	Less messages available	4	Incorrect capacity selection	2	Capacity evaluation	3	24	Procedure to review technical characteristics of components	DV / Ene 04	-
	No signal recognition	Do not reproduce sound	8	No power supply	3	Circuit inspection	6	144	Inspection procedure for circuit connections	DV / Ene 04	-
Hold product	Break	Do not reproduce sound	8	Incorrect material, Incorrect wall thickness	3	Prototype, CAE simulation	3	72	Design Procedure to check deformation, impact resistance, etc.	JA / Feb 04	-

Table 5.13. FMEA SAC.

6. Detailed layout and form designs.

To this activity DFA and DFM guidelines are reviewed again. Information gathered in the FMEA technique is used to improve the design if possible.

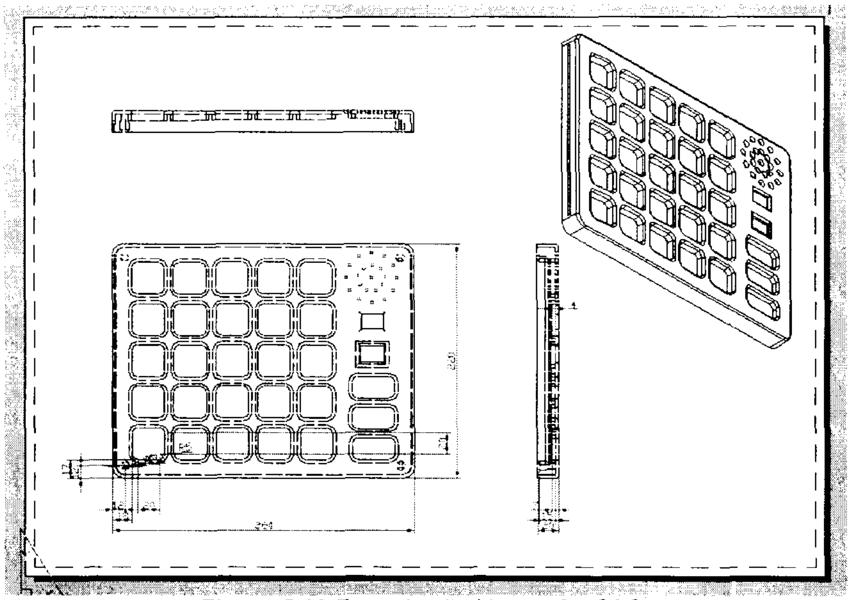


Figure 5.13 Front detailed layout for SAC.

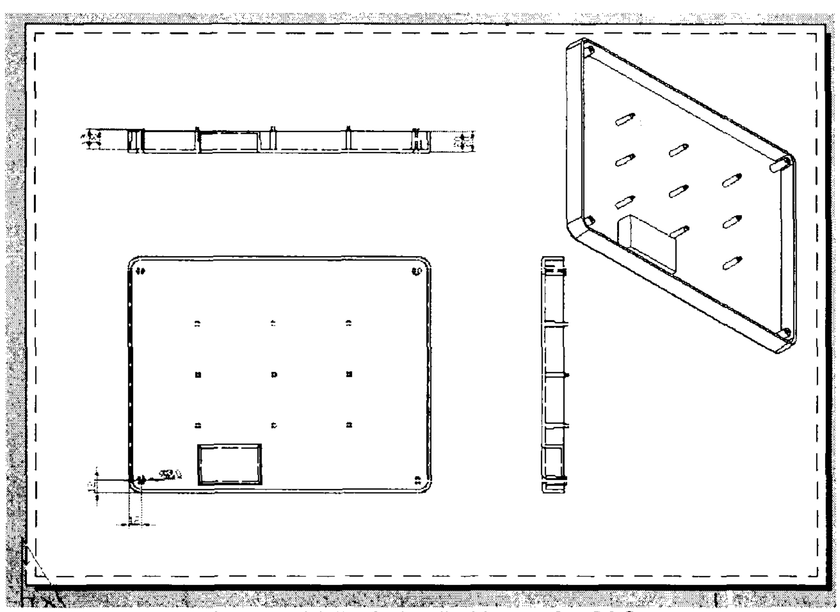


Figure 5.14 Back detailed layout for SAC.

Once the detailed layout is completed, we can continue with the next “evaluation methods”.

- CAE/CAM
- Tolerance Analysis

CAE/CAM analyses realized to the SAC case were stress analysis and plastic injection.

Manufacturing Modeling.
To evaluate the manufacturability of the product, some analyses were performed using the software CadMould. Because the case is a plastic injected part, some problems can occur. Some results about the temperature and the pressure in the mould were analyzed. At the end of the simulation we observed that there were no problems with the geometry defined for the product to be injected.

As was mentioned before, two parts define the geometry of the product, the upper part and the back part of the case.

In Cad Mould there is a probe to identify problems in the filling activity. The figure 5.15 shows the results for the upper part of the case.

Other parameters as pressure, temperature and time to pass the flow front could be observed.

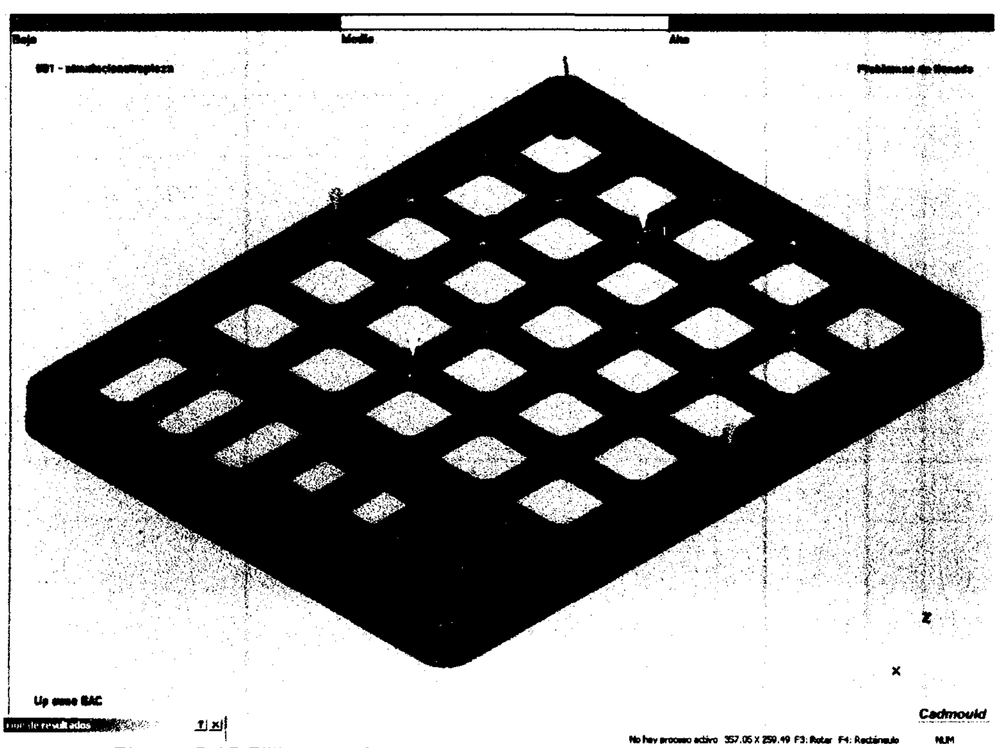


Figure 5.15 Filling test for plastic injection of the upper case of the SAC.

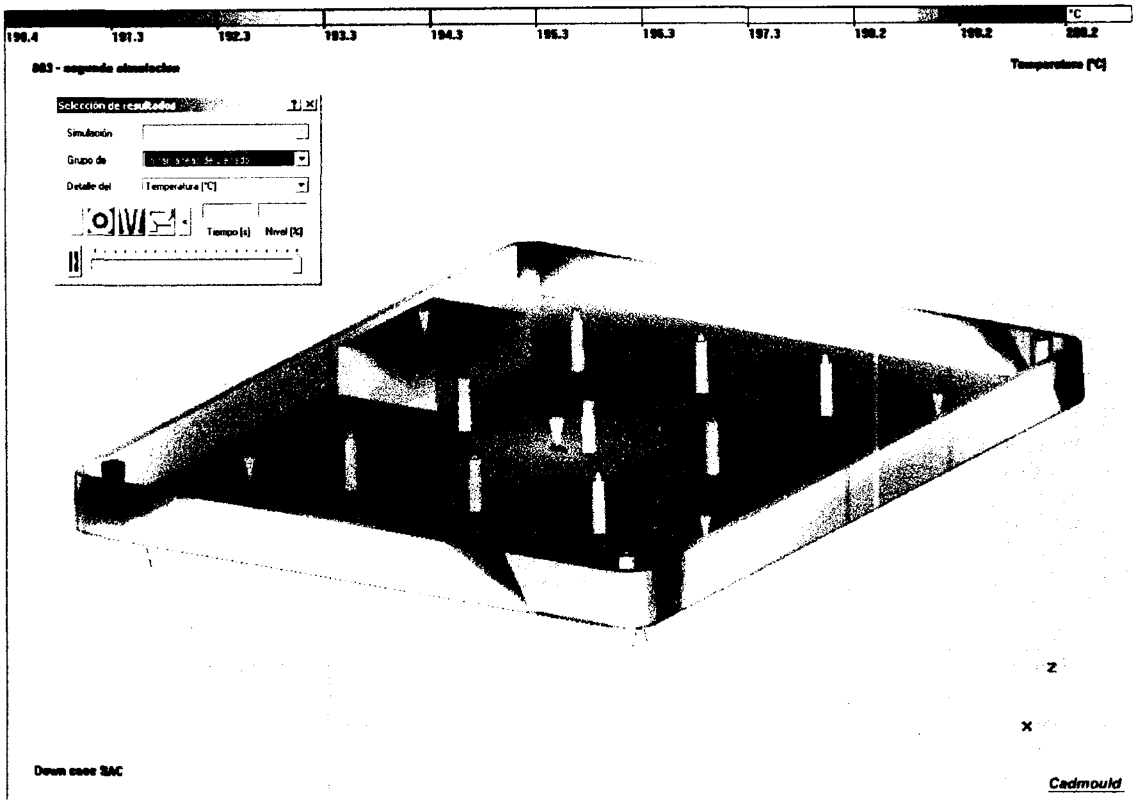


Figure 5.16 Temperature in the filling simulation for the down case of the SAC.

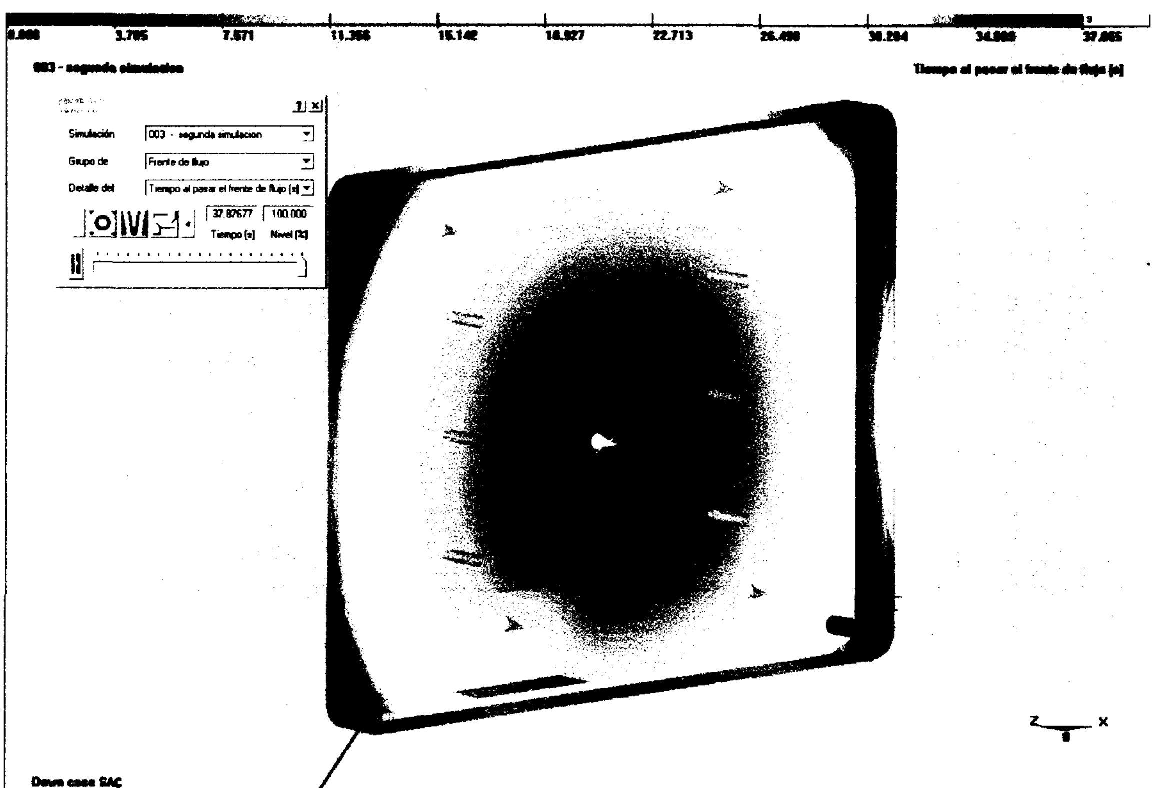


Figure 5.17 Time to pass the front flow for the down case of the SAC.

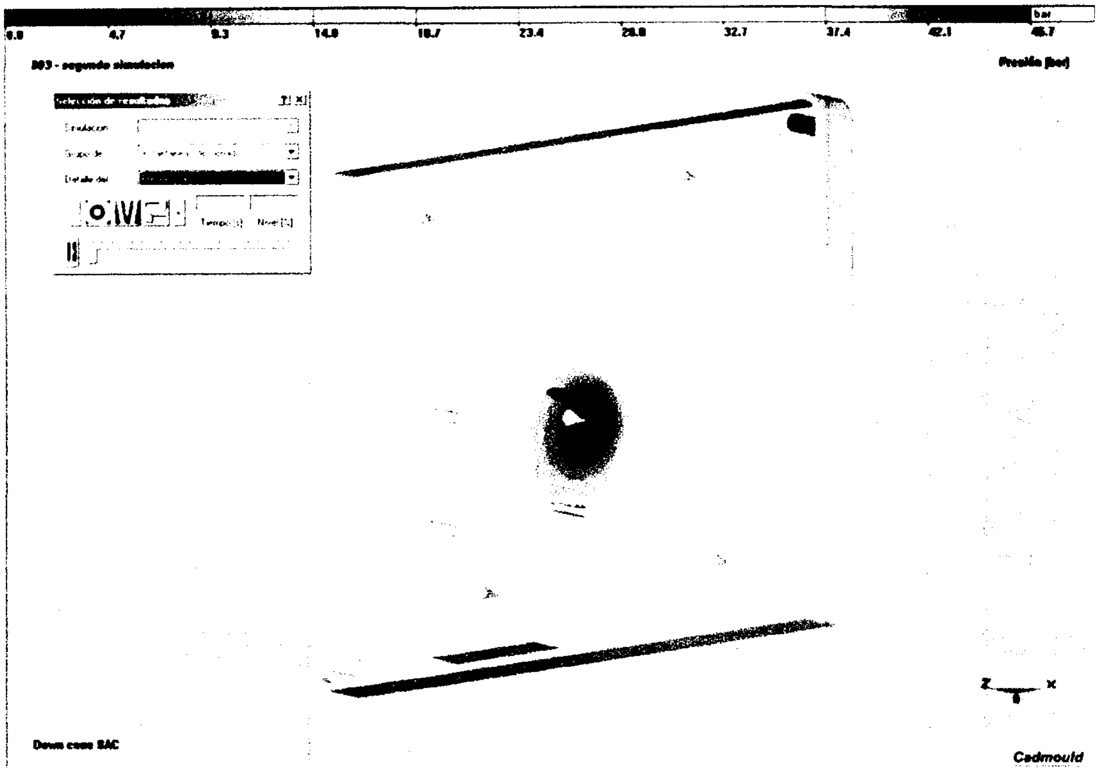


Figure 5.18 Simulation of pressure for the down case of the SAC.

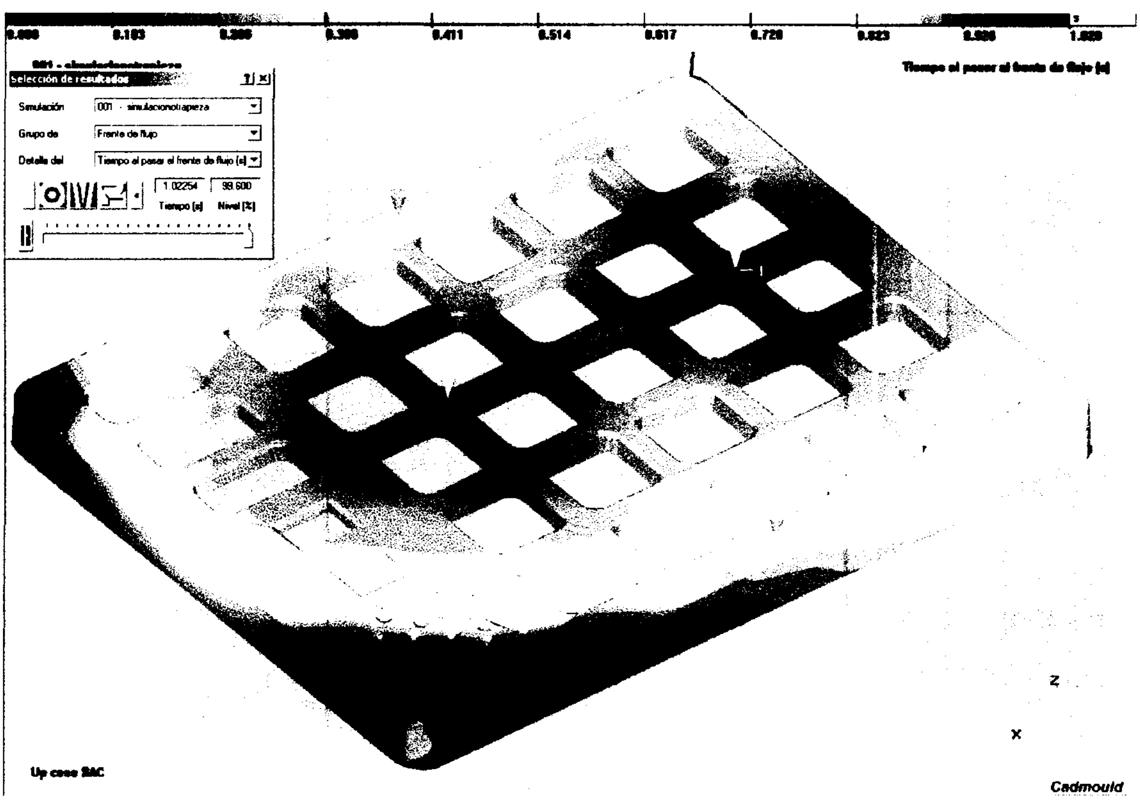


Figure 5.19 Time to pass the front flow for the upper case of the SAC.

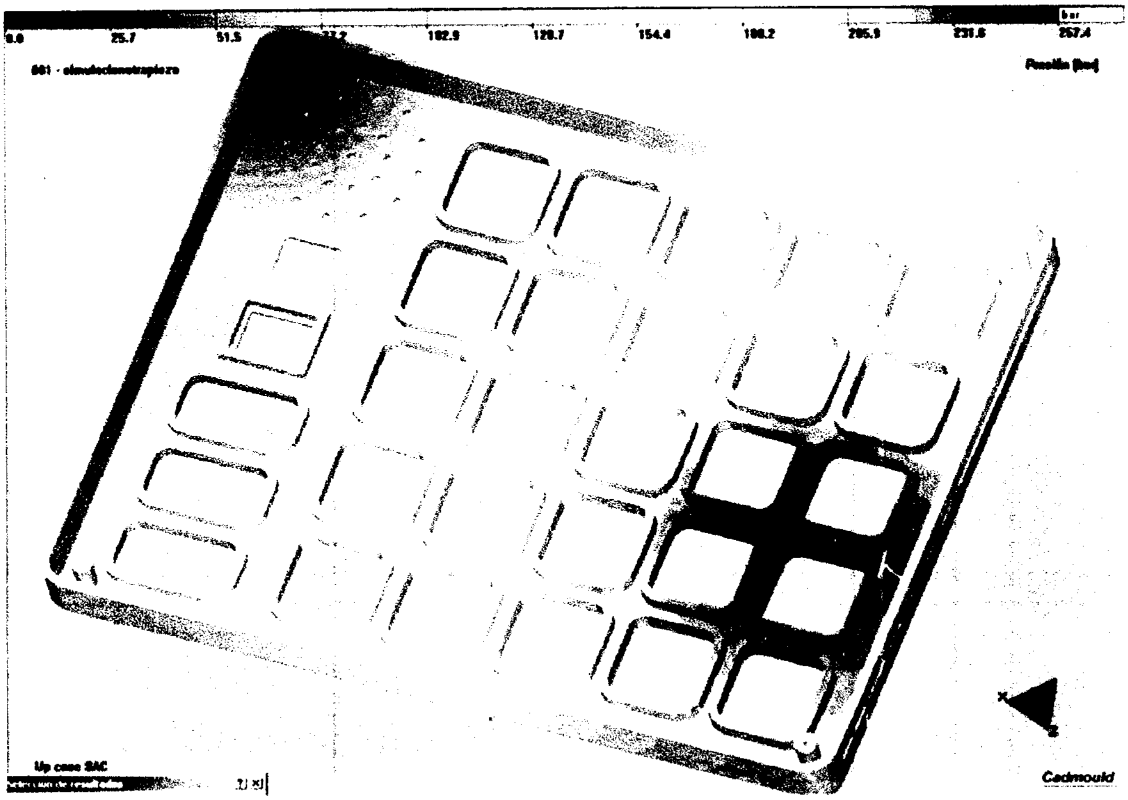


Figure 5.20 Simulation of pressure for the upper case of the SAC.

Stress Analysis.

When the designers had the experience interacting with the kids that are going to use the product they notice that some times the product was going to be enough resistant to support heavy loads. Cerebral paralysis kids can not control their movements and the force applied from their hands.

The stress analyses help us to identify if the material selected and the wall thickness parameter were selected correctly in the product to be resistant to heavy loads.

The software used to simulate the down part of the case was Patran/Nastran. Results presented are Von Misses stresses and deformation. The product proves to be functional with a 500N load. Material selected for fabrication was polyestyrene (termoplastic). Input parameters for material were: Yield Strength = 0.33 Young Modulus = 3GN/m^2. The material selected was poliestirene.

Some results for the down part of the SAC are showed below.

The boundary conditions were created in the four screw holes as shown in Figure 5.21 and 5.22.

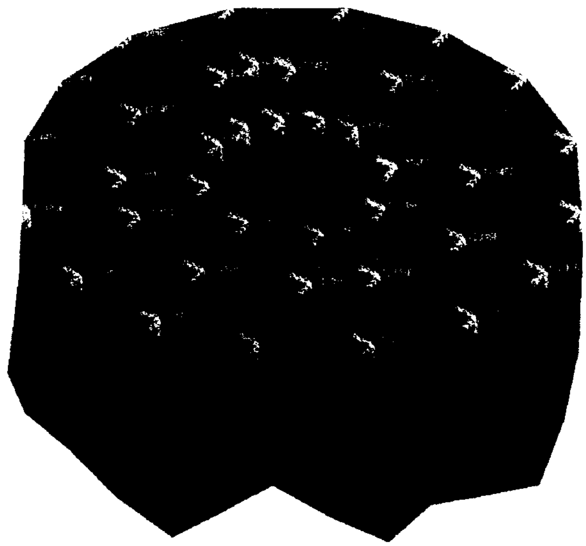


Figure 5.21 Detail of boundary conditions for the down case of the SAC.

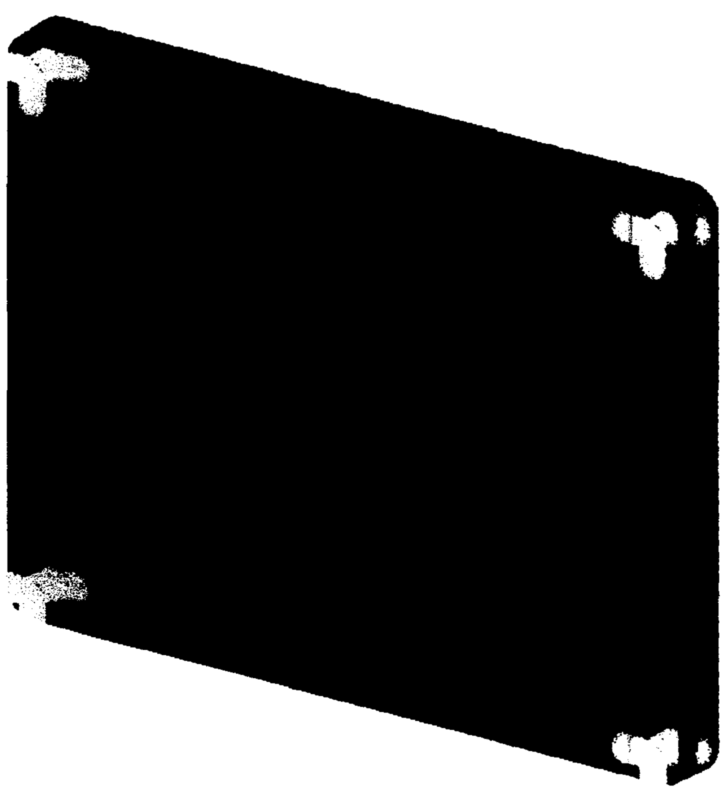


Figure 5.22 Location of Boundary conditions for the down case of the SAC.

One force was simulated to evaluate product deformation. Figure 5.23 shows the location of the force applied. For the first simulation the force was defined as 196 N, for a second simulation it changes to 500N. The product parameters probe to be successful to those conditions.

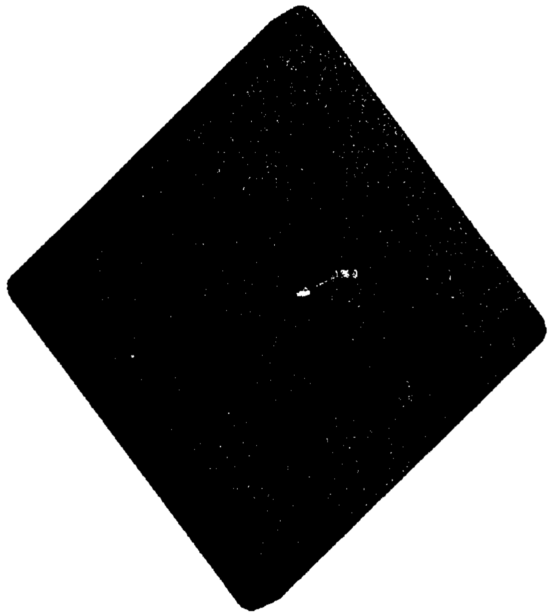


Figure 5.23 Force applied for the down case of the SAC.

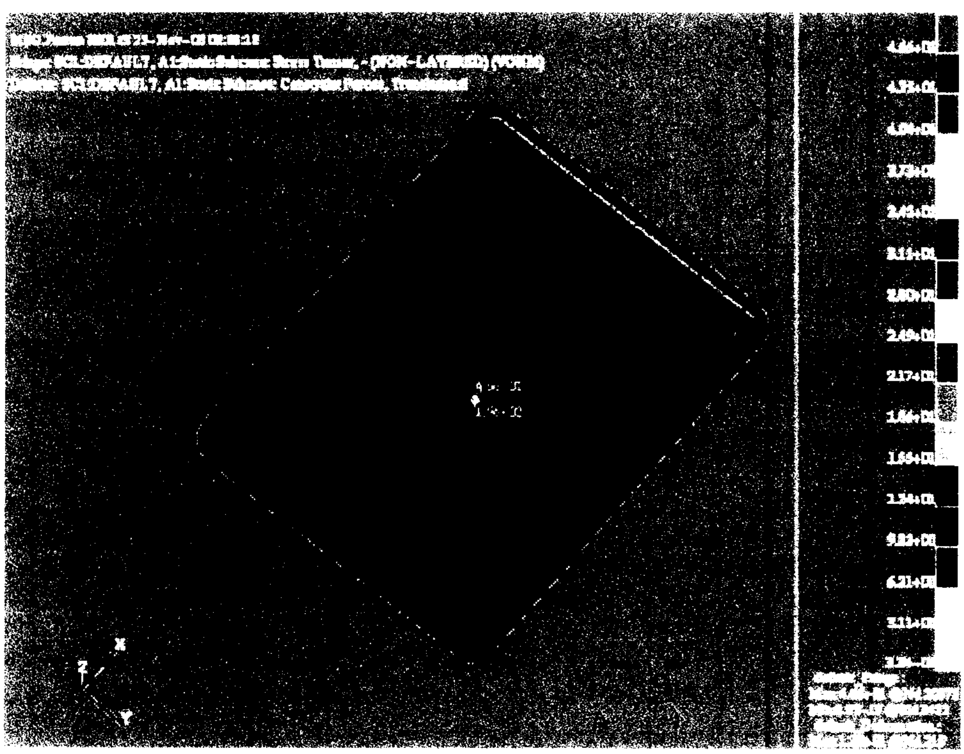


Figure 5.24 Von Mises stress (196 N) for the down case of the SAC.

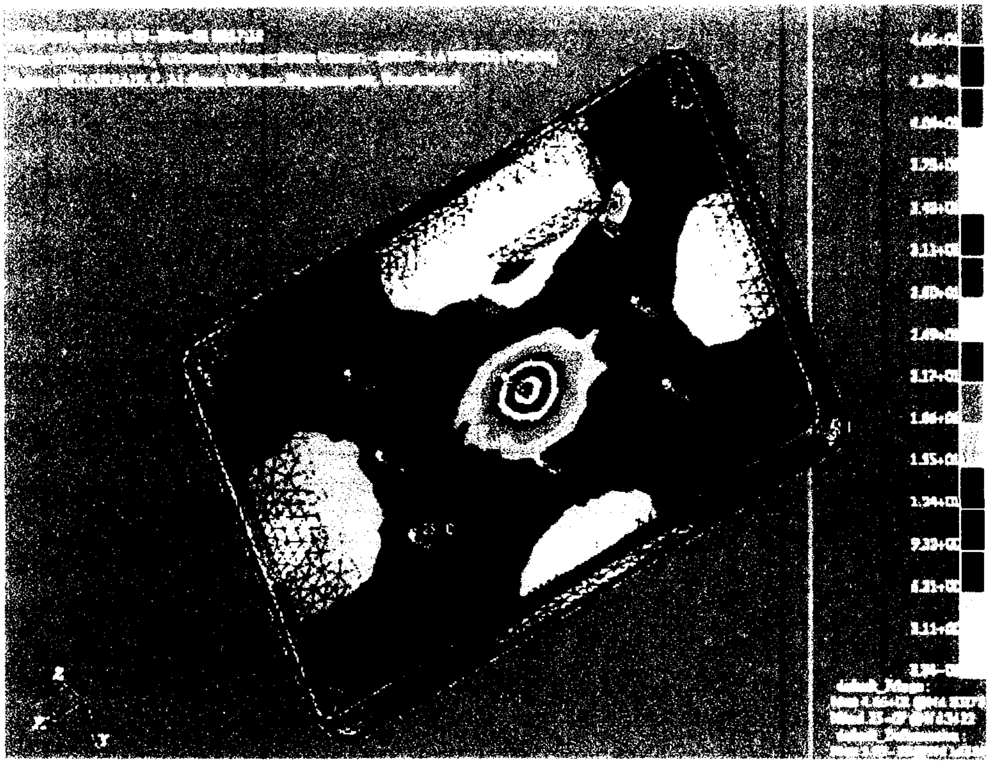


Figure 5.25 Von Mises stress (500 N) for the down case of the SAC.

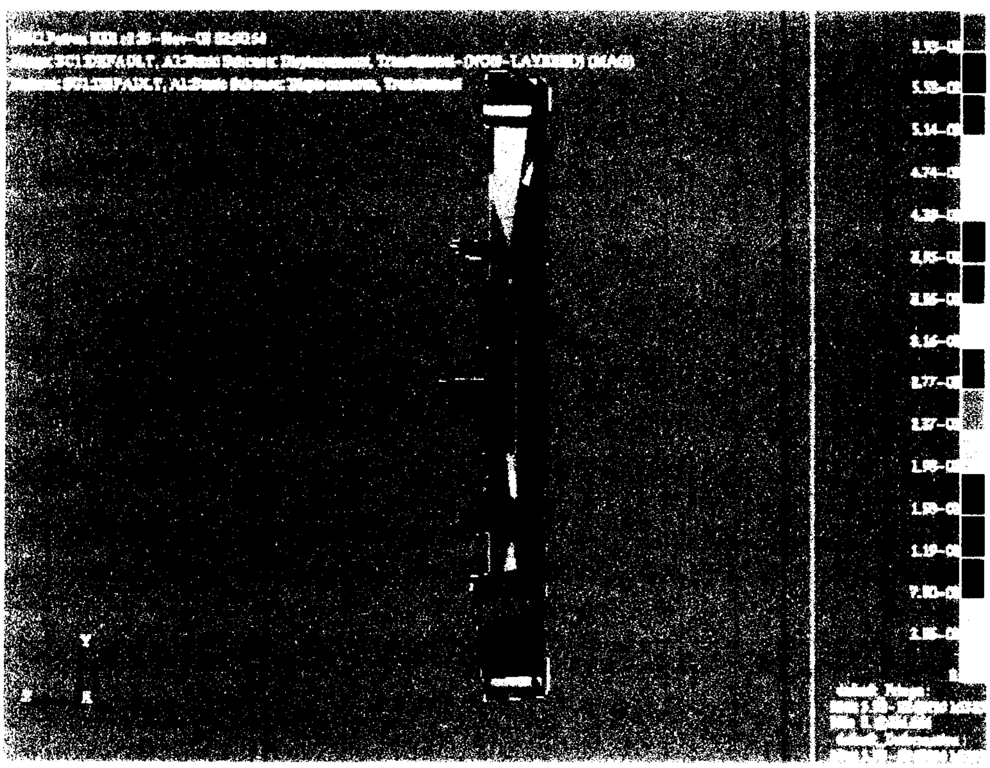


Figure 5.26 Lateral view of deformation for the down case of the SAC (500N) amplified.

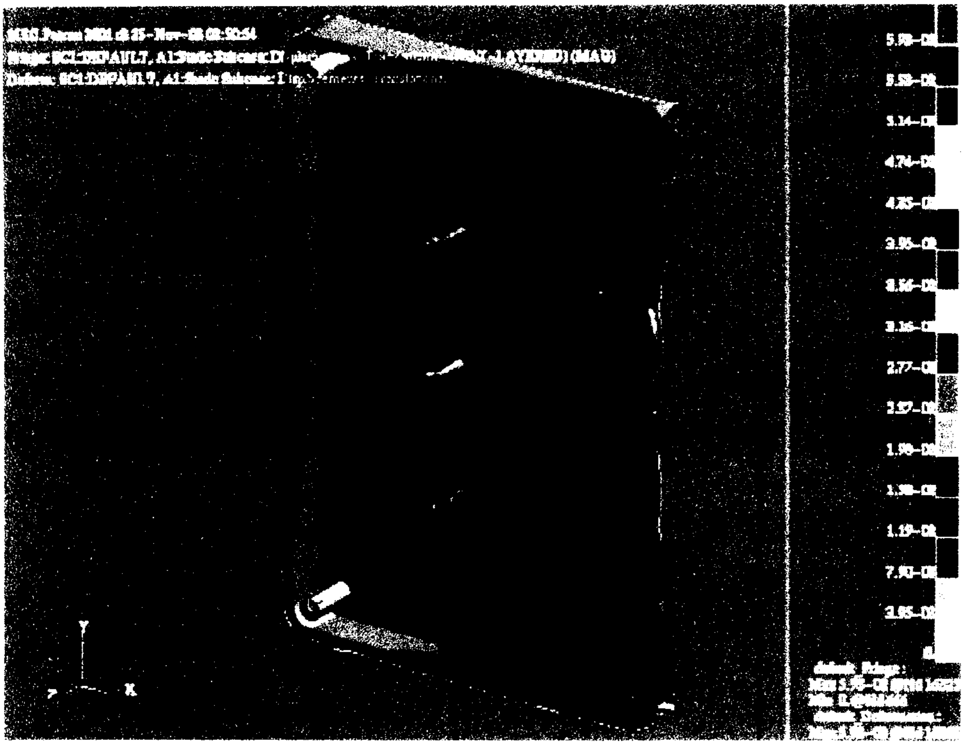


Figure 5.27 Deformation for the down case of the SAC (500N).

To simulate the upper part of the case the software utilized was ANSYS because in patran was not possible to made the mesh. The results are shown below. The restrictions and input parameters were the same.

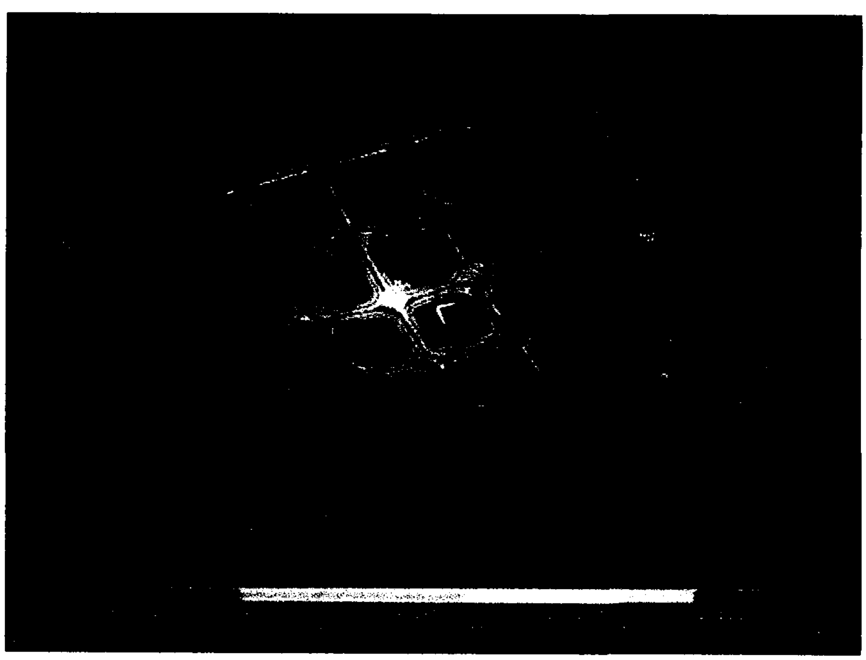


Figure 5.28 Von Mises stress (500 N) for the down case of the SAC.

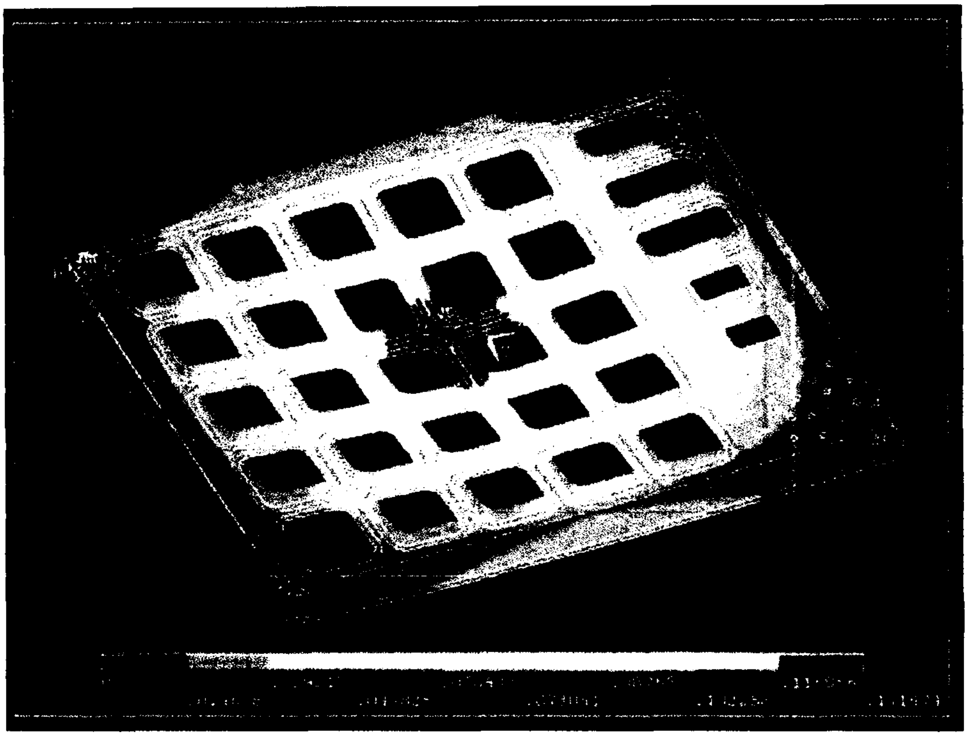


Figure 5.29 Deformation for the upper case of the SAC (500N).

CAD-CAM are relevant tools to evaluate product parameters and to optimize the design. Designers save a lot of time proving new ideas with computer simulations. The evaluations realized to the product probe that there are no manufacturing problems with the layout design, and it is enough resistant with the material selected.

While the embodiment design phase for the electronic product, some activities about the electronic design were made concurrently. The next section will describe in detail the embodiment design for electronic products.

5.2.3.2 Embodiment Design Phase – Electronic Design.

The activities realized for the electronic embodiment design are summarized in the next table.

Phase	#	Activity	Format	Tool	Technique	Record	R
Embodiment Design	16	Subsystems Involved	F-ED1-016		Functional Modeling	R-ED1-016	DV
	17	Subsystems virtual construction	F-ED1-017	E Workbench – P Spice	-	R-ED1-017	DV
	18	Simulation	F-ED1-018	E Workbench – P Spice	-	R-ED1-018	DV

PRODUCT: SAC (Sistema de Aprendizaje y Comunicación)
REFERENCE: SAC Functional Modeling (R-BD-012)

Objective.
Identify all the possible electronic subsystems involved to accomplish the product function described by the functional modeling.

Function	Subsystem
Select Level of Communication	Display with category selection
	Board for Category Selection.
Reproduce Sounds	Reproduction of sound

2. Subsystems Virtual Construction

After the subsystems identification, they have to be constructed to make a functionality evaluation. The tool used for this activity was eWorkbench software.

Tec de Monterrey	Subsystems Virtual Construction	R-ED1-017
	Instituto Tecnológico y de Estudios Superiores de Monterrey	

Objective.
Virtual construction of all the subsystems involved in the functions defined for the product.

The subsystems defined are:

1. **Display with category selection**

Function of the subsystem.

This subsystem will be useful for the user so that it will inform to him into the selection of filmina that has done. The selection of category will allow the device to know what category or that figures are placed in the board so that the microcontroller of automatic way reproduces the sounds that correspond to the figures that the user is seeing. The unfolding of two numbers from the one to the fifteen will give notification to the user of the number of the category that is being chosen. Display used for this intention is the Dac-05, which is display dual of seven segments that are controlled by a decoder BCD to 7-segments, the model of this coder is the 74LS47. The data to codify are originating of the microcontroller through port 0. The connection diagram is next.

Virtual Construction.

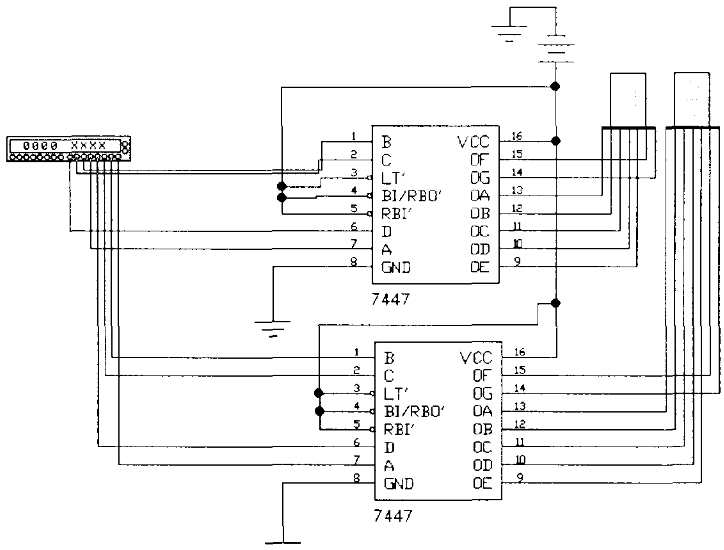


Figure 5.30. Virtual construction of display subsystem with eWorkbench.

In the left part of the simulation, a generator of words was placed that in this case makes the function of the microcontroller. This offer in binary from the 0 to the 15, whereas both 74LS47 are in charge to decode that binary number in and igniting the LEDs corresponding. The table of values is next.

Byte	Segments state														Number showed in display
	Display 1							Display 2							
	a	b	c	d	e	f	g	a	b	c	d	e	f	g	
0000 0000	0	0	0	0	0	0	1	0	0	0	0	0	0	1	00
0000 0001	0	0	0	0	0	0	1	1	0	0	1	1	1	1	01
0000 0010	0	0	0	0	0	0	1	0	0	1	0	0	1	0	02
0000 0011	0	0	0	0	0	0	1	0	0	0	0	1	1	0	03
0000 0100	0	0	0	0	0	0	1	1	0	0	1	1	0	0	04
0000 0101	0	0	0	0	0	0	1	0	1	0	0	1	0	0	05
0000 0110	0	0	0	0	0	0	1	1	1	0	0	0	0	0	06
0000 0111	0	0	0	0	0	0	1	0	0	0	1	1	1	1	07
0000 1000	0	0	0	0	0	0	1	0	0	0	0	0	0	0	08
0000 1001	0	0	0	0	0	0	1	0	0	0	1	1	0	0	09
0000 1010	1	0	0	1	1	1	1	0	0	0	0	0	0	1	10
0001 0001	1	0	0	1	1	1	1	1	0	0	1	1	1	1	11
0001 0010	1	0	0	1	1	1	1	0	0	1	0	0	1	0	12
0001 0011	1	0	0	1	1	1	1	0	0	0	0	1	1	0	13
0001 0100	1	0	0	1	1	1	1	1	0	0	1	1	0	0	14
0001 0101	1	0	0	1	1	1	1	0	1	0	0	1	0	0	15

Table 5.16. Codes for display component.

2. Keyboard for Category Selection

The keyboard for categoryselection consists of three basic buttons: up, down and enter. These buttons have the main function to make the selection correct of the number of filmina with which he is desired to work. When igniting the SAC, always is in the selection 00, which is shown in displays, nevertheless this category physically does not exist, reason why to initiate the sweeping or the selection by button of a figure, is necessary to raise or to lower to the number of category, which will not happen of 15, which it is the maximum number of categories with which it will be possible to be worked.

These buttons are connected to switches miniature, who simultaneously are connected to 5 V on the one hand, whereas by the other they are connected the microcontroller. Therefore when pressing them, V in the pin of the microcontroller puts 5 which does that that sends to the signals corresponding to the BCD to 7 segments that later unfold the number of displays.

3. Reproduction of sound

The voice chip is one of the most important elements of the system. The due precaution in the selection was taken from this chip, was taken into account the time, the cost and the facility of programming. As far as the time the possible one was necessary greater, since it was wanted to make a product that had much more capacity of storage, more capacity of categories, therefore storage capacity was required of a chip with the Maxima. Finally the ISD4004 was selected. With a price of $15 USD and one capacity of storage of 16 minutes, this chip is able to be handled by a microcontroller. Unfortunately, between greater time of duration, greater difficulty has the programming of the same one, by such reason it has taken us more from the time available to program it and to put it to work.

Anatomy.

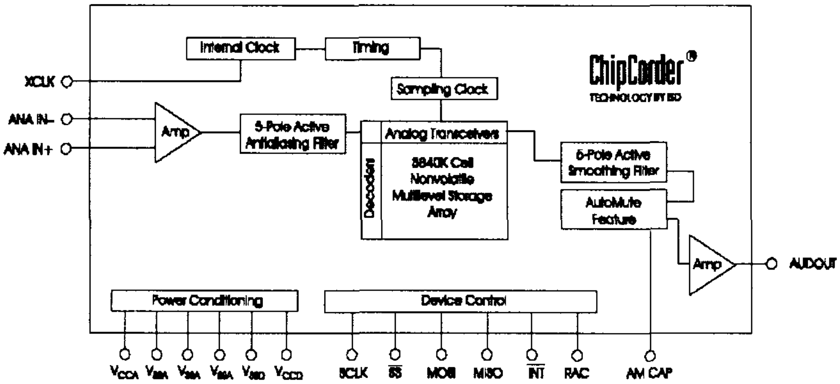


Figure 5.31. Anatomy of sound chip.

Virtual construction.

Figure 11: Application Example Using SPI Port on Microcontroller(1)

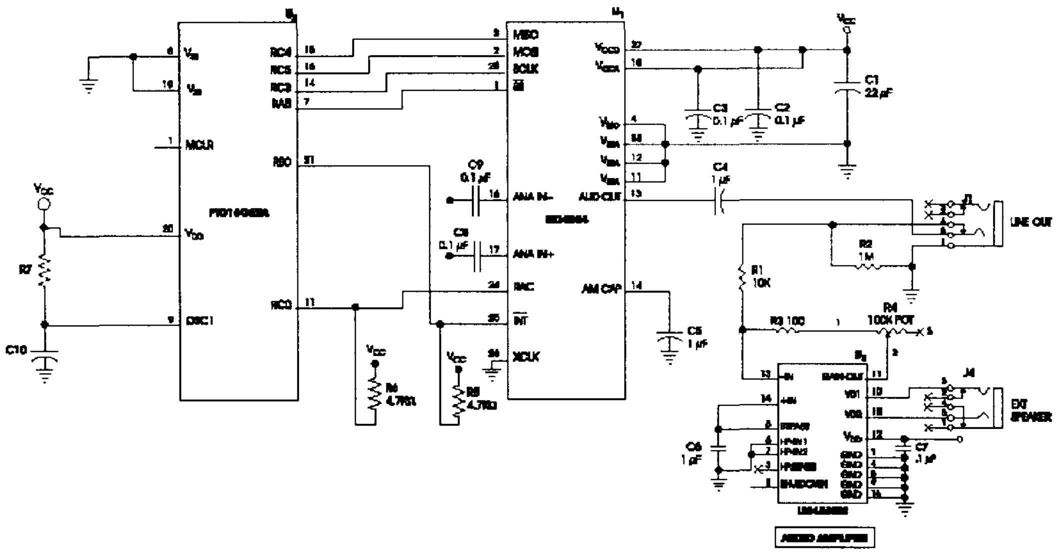


Figure 5.32. Virtual construction of sound chip.

As we can see, they are 4 basic lines that they interconnect to the ISD4004 with the microcontroller, which are: MISO, MOSI, SCLK and SS.

MISO: Masters In Slave Out, is the serial exit of the ISD4004, in this case is going to serve to us to determine in that direction is pointing the device, so that we run the correct sound.
MOSI: Masters Out Slave In, is the serial entrance of the ISD4004, this is going to us to be very useful since it is the basic line of communications with the microcontroller, since this last one is going to him to determine in that direction is the sound that is desired to reproduce.
SCLK: It is a clock signal that enters the originating ISD4004 of the microcontroller. This signal of clock will serve to synchronize all the data transfers of the MISO and the MOSI.
SS: Slave Select, this is a selector of the ISD4004, when this it is in low, the voice chip is selected.

3. Simulation.

After the subsystem is built it is easy to run a simulation for the product. The same tool (eWorkbench) used in the construction was used to run a simulation and demonstrate the functionality of the subsystems.

4. Identify Programmable Components

In this case of study we have only one programmable component, the microcontroller. This is an AT89C51 microcontroller. A lot of information for electronic products is available in internet to define the component characteristics.

5. Programming

To develop the program that is required by the microcontroller we will use the Embodiment Design Phase for Software Design that is explained in the next section. An Object Oriented approach was used and also the simulation is going to be developed in that section.

6. Simulation

Simulation of the program includes the codification that is prototype/product construction. As was mentioned before, for this activity we will apply the Embodiment Design Phase for Software Design described in the next section.

7. Embodiment Requirements

The concurrency of activities is shown in this step. Electronic engineers have to have the detailed information about the space defined for the electronic components, so a adequate assembly/integration of the product can be made. The embodiment space restriction for the product was defined previously, when all the team decide how to configure the product. The information about the electronic card embodiment is shown next. This embodiment is going to be basic layout for the electronic system layout design.

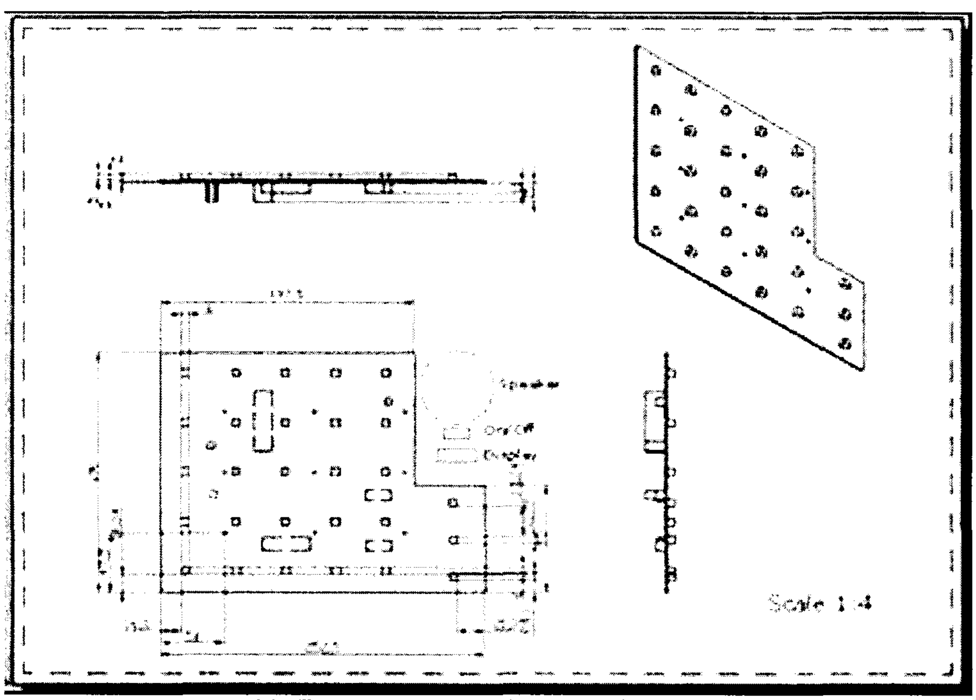


Figure 5.33. Embodiment requirements for electronic card.

8. System Design

Here, the tool used was Protel software program. This program help the designer construct the layout for the electronic card.

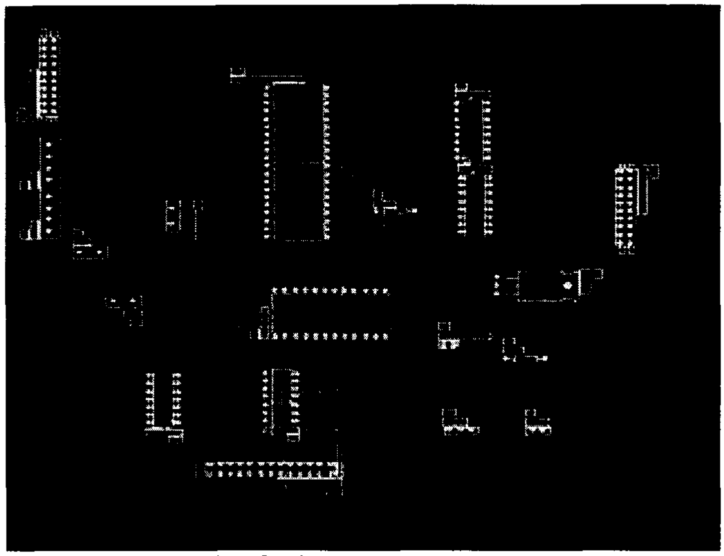


Figure 5.34. SAC system design with Protel.

9. Simulation

Protel software is also designed to run a simulation about the functionality of the layout of the electronic components.

Output for this phase are:

- Components Characteristics
- Layout

For component characteristics we have the bill of components and the characteristics of each one. The final layout is that one that success in the simulation of the system design.

5.2.3.3 Embodiment Design Phase – Software Design.

The general objective for this phase is obtain a detailed Sequence Diagram, also refine and complete the Domain Model and the Class Diagram that will serve as a base for the coding activity.

Phase	#	Activity	Format	Tool	Technique	Record	R
Embodiment Design	16	Identify messages between objects	F-ED2-016	-	-	R-ED2-016	LC
	17	Interaction Modeling	F-ED2-017	Visual UML / Racional Rose	Sequence Diagram / Collaboration Diagram	R-ED2-017	LC
	18	Evaluation	F-ED2-018	Visual UML / Racional Rose	Pugh Charts	R-ED2-018	LC
	19	Finish Static Model	F-ED2-019			R-ED2-019	LC

	20	Requirements Verification	F-ED2-020	Visual UML / Racional Rose	Static Model	R-ED2-020	LC
	21	**Software Design**	**F-ED2-021**			**R-ED2-021**	**LC**

Table 5.17. Software Design Methodology Model.

For this case of study, the methodology had to be reconfigured because of the simplicity of the programming. Many activities were not realized, but it is important for the methodology to be as general and complete as possible.

Output information from conceptual design is referent to Uses Cases diagrams and Robustness Diagrams because the simplicity of the product. This information serve as a basis for the embodiment design phase and because of that is going to be presented.

Use Cases Diagrams.

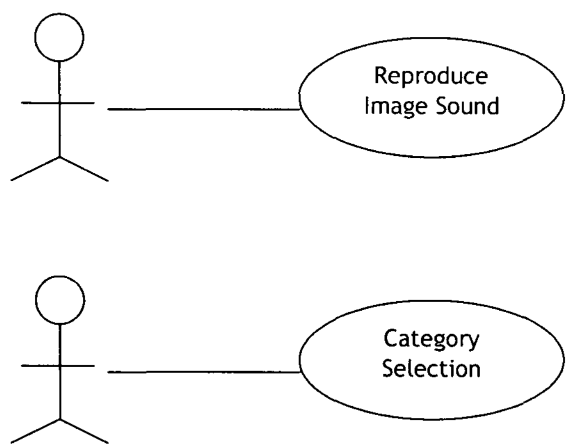


Figure 5.33. Use Cases for the SAC.

Robustness Diagrams.

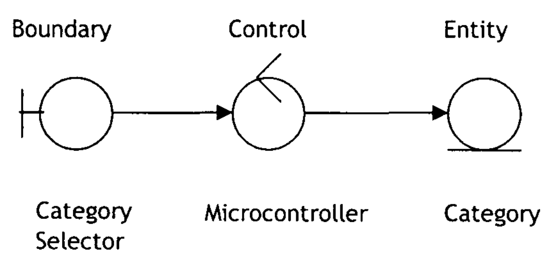


Figure 5.34. Robustness Diagram for Category Selection Use Case.

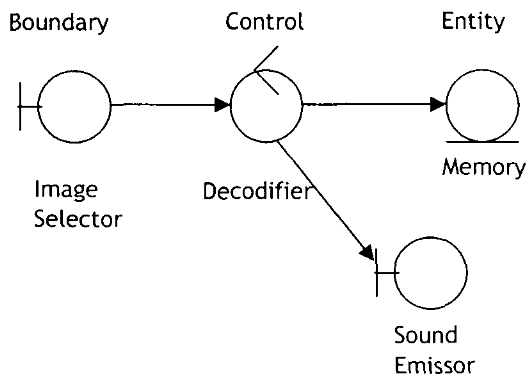


Figure 5.35. Robustness Diagram for Reproduce Image Sound Use Case.

The activities defined for this phase are:

1. Identify messages between objects.

Objective: Define which objects are responsible for which bits of behavior.

Messages identified from the Robustness Diagram were:

- Increase category
- Select category
- Enter Category
- Define Category
- Diminish Category

- Image Selection
- Sound Selection
- Sound Emission

2. Sequence Diagram.

Objectives:

- Validate and Flesh out the logic of a usage scenario.
- Provide a way to visually step through invocation of the operations defined by the classes.
- Detect bottlenecks within an object-oriented design.
- Give you a feel for which classes in your application are going to be complex.

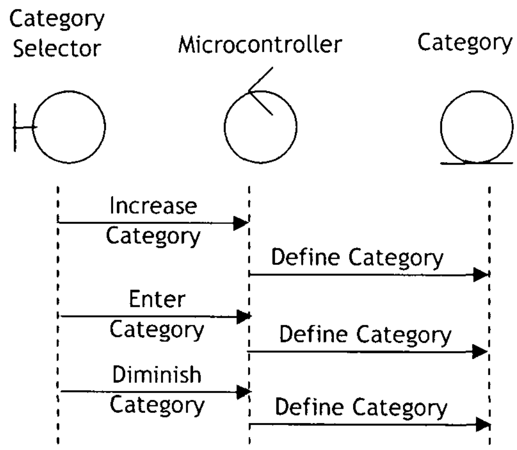


Figure 5.36. Sequence Diagram for Select Category Use Case.

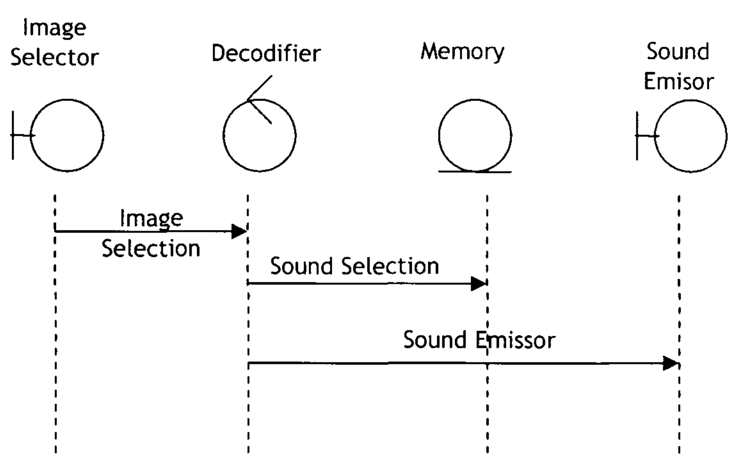


Figure 5.37. Sequence Diagram for Reproduce Image Sound Use Case.

3. Update Class Diagram.

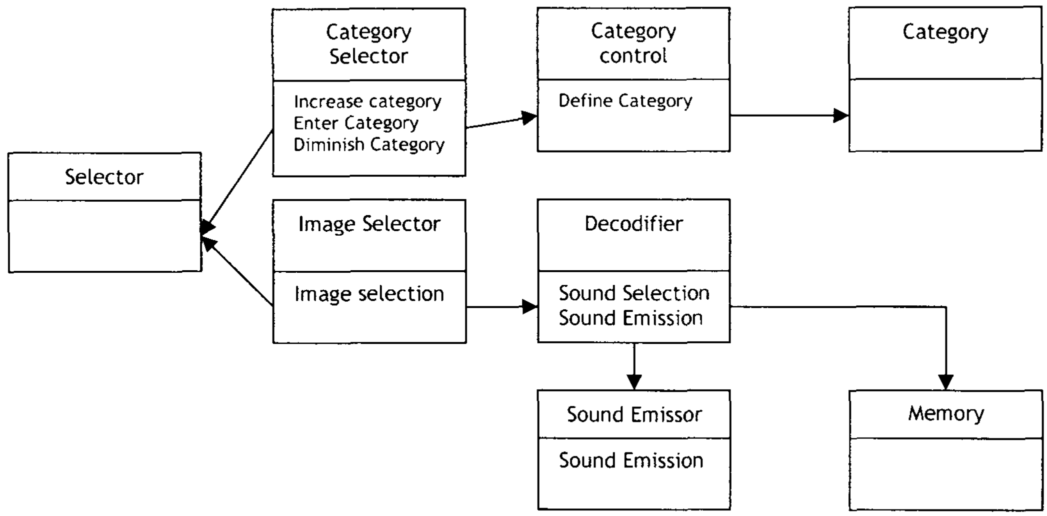


Figure 5.38. Class Diagram.

4. Requirements Verification.

For this activity a match between the user requirements and the classes defined in the class diagram was made.

5. Software Design

For this activity, the packages were identified.

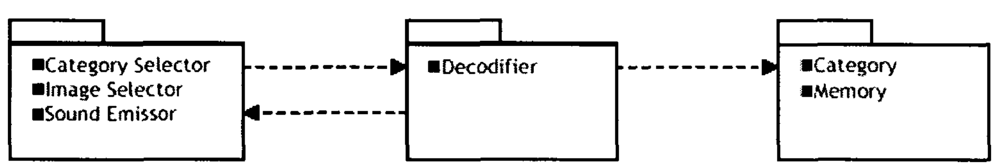


Figure 5.39. Software Design.

5.2.4 Prototyping

The general objective for this phase is to evaluate the functionality of the product through the elaboration of a prototype.

Prototyping phase for mechanical or electronic products is different to software products. In software, while the designer is coding, is also building the prototype. If the product is just one there is no prototype, the prototype converts into the final product.

The activities defined to the prototyping phase for the SAC are described below.

1. Type of Prototype.

Objective: Define the type of prototype that is going to be built.

Two types of prototypes were constructed for the SAC, a physical and a virtual prototype. The virtual prototype was used in the embodiment design phase to evaluate the design with CAE and CAM for the case.

2. Materials-Process Definition

Objective: Define the materials and building process for the prototype.

The material selected for the final product case of the SAC was polystyrene like Pro-fax, Tenite or Moplen. Because the nature of the product, the processes selected for the prototype were those related to plastic materials, some other characteristics were taking in count like manufacturability, dimensions, roughness, tolerance and wall thickness. All those selection parameters are quantitative parameters, after this selection is necessary to evaluate a qualitative analysis and then the final evaluation.

The table presented below was obtained from a excel database with filters for all the processes defined by the research chair of mechatronics.

PROCESS	PROCESS CLASSES	MATERIAL	MANUF	HEIGHT (IN)	WIDTH (IN)	LENGTH (IN)	ROUGHNESS (Min)		TOL (+- in)	WALL THICKNESS (IN)	
Thermo jet Printer	Prototype	Plastics	5	7.5	8	10		Very fine finish	0.0016	N.I	N.I
Reaction Injection Moulding	Prototype	Plastics	5	20	20	52		Superfine finish	0.008	0.12	0.4
Rapid Parts	Prototype	Plastics	5	11	15	15		Superfine finish	0.008	2	20
Fused Deposition Modeling	Prototype	Plastics	5	20	24	24	300	500	0.005	0.01	5
Three Dimensional Plotting	Prototype	Plastics	5	6	8.5	12	32	63	0.001	N.I	N.I
Stereolithography	Prototype	Plastics	5	23.6	25.2	83			0.004	N.I	N.I
Selective Laser Sintering	Prototype	Plastics	5	11.9	11.9	23.6			0.008	0.04	N.I
Laminated Object Manufacturing	Prototype	Plastics	5	10	14	150				N.I	N.I

Table 5.18. Process Selection for Prototype.

3. Materials-Process Evaluation

Objective: Review the materials and process defined in the previous activity.

For this activity the tool used was also the Pugh Charts.

		PROCESSES						
	Importance	Reaction Injection Moulding	Rapad Parts	Laminated Object Modeling	Stereolithogr aphy	Three Dimensional Plotting	Fused Deposition Modeling	Selective Laser Sintering
Geometry	10	-1	-1	1	1	1	1	1
Waste Cost	5	-1	1	1	1	1	1	1
Tooling Cost	4	-1	1	-1	0	1	1	1
Fixtures Complexity	4	0	1	1	1	1	1	1
Set up time	6	1	0	-1	0	-1	1	1
Cycle time production	5	1	1	1	0	0	-1	-1
Batch size production	6	0	0	-1	1	1	1	1
Products per shoot	2	0	0	0	0	0	0	0
Total +		**2**	**3**	**4**	**4**	**5**	**6**	**6**
Total -		**3**	**1**	**3**	**0**	**1**	**1**	**1**
Sum		**-1**	**2**	**1**	**4**	**4**	**5**	**5**
Weighed Total		**-8**	**8**	**8**	**25**	**23**	**30**	**30**

Table 5.19. Evaluation of Processes for Prototype.

The process defined for the prototype construction was FDM because the facilities for it construction. The project partners have the technology and a better price than making it with stereolithography.

The Result of this phase is:

- Prototype

Although the embodiment design phase for the product was completed satisfactory, and some activities of the prototyping phase were made, the physical prototype was not finished for various reasons. The major obstacle was the price of the case and the electronic card.

Chapter 6. Results and Conclusions.

6.1 Results.

i. A Methodology for Rapid Mechatronic product Development and Manufacturing was developed and proved with a case of study.
ii. A classification of many applicable design methods and techniques by design phase and type of activity: analysis, synthesis and evaluation.
iii. A case of study that proves the utility of the methodology with a mechatronic product.
iv. A reconfigurable methodology depending on the special characteristics of the product to be developed.
v. An evaluation of design methodologies.
vi. An information organization chart of the product development process for the three disciplines.

6.2 Conclusions.

The methodology proves to be useful and a good guide to designers in order to develop mechatronic products.

The conclusions on this thesis are:

- The methodology developed in this work allows non-expert people to design and integrate a new methodology with useful methods depending in the product that is going to be developed.
- Evaluation activities include groups of techniques-tools of generic application, and also give the designer the freedom to choose specific tools depending in the kind of product that is being developed.
- Pugh charts (concept selection tool) were proved to be an effective method that facilitates the designer to make decisions.

- One of the key aspects of the development process is direct observation to customer-product interaction. This is a key issue that must be realized ever.
- The tool box activities are guides to designers in order to be able to select the method that better satisfy the requirements.
- As mechatronics is a new discipline, the maturity of mechatronic product development methodologies or processes is not enough. Therefore, this thesis is a contribution to fulfill the existing gaps in mechatronics.
- The methodology organizes all the activities, the flow of product information, methods that can be applied in each phase, and some other organizational issues as documentation.
- The proposed methodology is applicable to mechatronic products, and it is also possible to apply it to mechanical, electronic or software products separately.
- The proposed methodology tends to be useful to define organizational issues in the product development processes.
- The methodology includes the phases of the product development process and the engineering activities, so permit a clear logical thinking in the designer by identifying the analysis, synthesis and evaluation activities. All the phases must have at least one engineering activity.

6.3 Further Research.

Because the time limits, several opportunities for further exploration are defined and presented in this section.

Some other methods can be applied in the methodology to prove their usefulness. Especially axiomatic design can be included in the evaluation activities to select the layout design that best satisfy the axioms. Suh theory it is intended to design more functional products.

In designing electronic products, methods like Design for Assembly can be applied and proved to electronic cards layout design, comparisons between the methods applied to different products can be done. New methods can be develop and proved.

Mathematical modeling is another area to do research in. Complex systems like magnetic actuators and specialized sensors need to be modeled to evaluate their performance.

In the development process of mechatronic products like cars or airplanes, will be helpful to obtain the detailed set of activities and design teams interactions (the whole process applied today) to identify the existing gaps and the potential failures to develop a methodology that support design teams avoiding complex mechatronic product development mistakes.

Product division (subsystems) in mechatronic products is a common activity because product complexity. Interactions between subsystems in complex mechatronic products can also be studied to define detailed methodologies.

Mechatronic product development is an extensive and relative new area where research and knowledge is not enough yet.

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Appendix A. Design Methodologies Comparison.

OTTO AND WOOD **(Generic Design Process)**	ULLMAN **(Mechanical Design)**	PAHL AND BEITZ **(Engineering Design)**	PRIEST **(Engineering Design)**	ALVAREZ CSIM ITESM **(Product Design)**	XEROX **(Mechanical-Electronic Design)**	EDGE, TX P. D. FIRM **(Electronic Design)**	MICROSOFT **(Software Design)**	FORD * **(Engineering Design)**	RAYTHEON CO **(High Tech Products)**
Reverse Engineering. (Investigation, Prediction & Hypothesis)	Specification Development / Planning Phase	Clarification of the task.	Requirements Definition.	Specifications Determination.	Define Market Attack Plan & Technology.	Understand Product Task.	Specification (Idea, Players, Planning)	Start: Define Product and Process	Understand Requirements
Modeling and Analysis. (D. Models, D. Analysis)	Conceptual Design Phase	Conceptual Design.	Conceptual Design Phase.	Conceptual Design.	Define Product and Deliver Technology.	Preliminary Conceptual Design.	Coding (Development)	Approval	Understand Functions
Redesign. (Parametric, Adaptive and Original)	Product Design Phase	Embodiment Design.	Detailed Design.	Detailed Design.	Design Product. (Uses methods discussed by Otto and Wood)	Layout Design.	Stabilization (Testing)	Appearance: - Vehicle - Systems - Subsystems - Components	ID Alternatives & Allocate Requirements
		Detail Design.	Test and Evaluation.		Demonstrate Product.	Final Layout Design.	Manufacturing, Sales, Support	Readiness: Verify/Build/ Produce Product and Process	Create Designs and Assess defects, cost, performance, etc.
			Production and Sustaining Engineering.		Deliver Product.	Design/Tooling Design.		Launch: Manage Program	Aggregate: Rollup Assessments
					Delight Customers.				Evaluate: Meets Requirements?
									Analysis and Trade Studies

* See below: DFSS Algorithm, Kusiak Engineering Design,

OTTO AND WOOD **(Generic Design Process)**
Reverse Engineering: - Select a product - Develop a vision - Customer Needs Analysis - Market opportunity analysis
Develop a redesign: - Functional Modeling - Competitive Analysis - Product Architecture Development - Concept Engineering
Implement a Redesign: - Embodiment Engineering - Physical and Analytical Modeling - Design for X - Robust Design

ULLMAN **(Mechanical Design)**

Specification Development / Planning Phase:
- Understanding the design problem
  - Developing customer requirements
  - Assessing the competition
  - Generating engineer requirements
- Establishing engineering targets

Conceptual Design Phase:
- Generating concepts
  - Functional Decomposition
  - Generating concepts from functions
- Evaluating Concepts
  - Judging Feasibility
  - Assessing Technology Readiness
  - Go/no-go screening
  - Using the decision Matrix

Product Design Phase:
- Generating the product
  - Transforming existing products
  - Embodying the functions
  - Designing product and production concurrently
  - Patching and refining the product
- Evaluating the product
  - Monitoring functional changes
  - Evaluating performance
    - Using experimental models
    - Using analytical models
    - Optimizing design
    - Using robust design
  - Evaluating cost
  - DFA
  - Designing for the other "ilities"
- Finalizing the product

PAHL AND BEITZ **(Engineering Design)**
Clarification of the task: TASK - Clarify the task - Elaborate the specification SPECIFICATION
Conceptual Design: SPECIFICATION - Abstract to identify the essential problems - Establish function structures - Overall function - sub-function - Search for solution principles to fulfill the sub-functions - Combine solution principles to fulfill the overall function - Select suitable combinations - Firm up into concept variants - Evaluate concept variants against technical and economic criteria CONCEPT

Embodiment Design: CONCEPT - Identify embodiment-determining requirements - Produce scale drawings of spatial constraints - Identify embodiment-determining main function carriers - Develop preliminary layouts and form designs for the embodiment-determining main function carriers - Select suitable preliminary layouts - Develop preliminary layouts and form designs for the remaining main function carriers - Search for solutions to auxiliary functions - Develop detailed layouts and form designs for the main function carriers ensuring compatibility with the auxiliary function carriers - Develop detailed layouts and form designs for the auxiliary function carriers and complete the overall layouts - Check and refine the overall layouts - Evaluate against technical and economical criteria PRELIMINARY LAYOUT - Optimize and complete form designs - Check for errors and disturbing factors - Prepare preliminary parts list and production documents DEFINITIVE LAYOUT
Detail Design: DEFINITIVE LAYOUT - Finalize details - Complete detail drawings and production documents - Check all documents DOCUMENTATION SOLUTION

PRIEST **(Engineering Design)**
Requirements Definition. - Market research and analysis - Customer requirements and needs - System requirements, including producibility and reliability
Conceptual Design Phase. - Trade studies - Simulation and modeling - Functional allocations - System specifications - Design requirements - Design guidelines - Design to cost - Program plans
Detailed Design. - Analysis, modeling simulation, and prototypes - Detailed design specifications - Circuit Design - Parts selection - Component design - Part qualification - Mechanical design - Thermal design - Logistic engineering - Human engineering - Safety engineering - Packaging design - Software design - Production engineering - Quality engineering - Design to cost - Testability - Documentation - Make or buy analysis - Test planning - Producibility - Quality specifications - Manufacturing planning - Environmental testing - Off-line maturing of new technologies
Test and Evaluation. - Developmental testing - Test, analyze and fix - Process engineering - Test software Development - Failure Analysis - Design to cost - Producibility - Manufacturing prototypes - Environmental stress screening - Configuration management

- Customer test
Production and Sustaining Engineering: - Production readiness - Specification verification - Drawing release - Documentation - Manufacturing procedures - Tooling design and Release - Quality control - Configuration management - Quality assurance - Spares provisioning - Environmental stress screening - Sustaining engineering

EDGE, TX P. D. FIRM **(Electronic Design)**
Understand Product Task: -Market domain Study
Preliminary Conceptual Design: -Brainstorm concepts -Sketch and Record -Compile Design -Repeat daily/Weekly -Client Evaluation of Concepts
Layout Design: - Identify Components - Gather components - Specify Locations - Spatial Layouts - Construct Component Database - Initiate Concept Refinement - Draw and Fabricate Foamcore Models - Create Wire Frame Models - Fabricate Blue and With Foam Models - Check spatial Feasibility
Final Layout Design: - Build Component Database with final specs - Integrate ID Geometry - Embody mechanism - Embody Plastic Parts

Design/Tooling Design: - Refine Components - Design Tooling - Prototype Pre-Production Version

MICROSOFT **(Software Design)**
Specification: - Development - Vision Statement - User Profile - Delivery Date Target - Core Product Activity
Coding (Development): -Product Features: · Stand-alone modules · Prototyped · Product Architecture · Layers · Interacting modules -Delivery Dates
Stabilization (Testing): -Test and Debug

ALVAREZ, CSIM, ITESM **(Product Design)**
DETERMINACIÓN DE ESPECIFICACIONES: Conversión de los requerimientos del mercado (cliente) en especificaciones de ingeniería para comenzar el diseño del producto. Representar la voz del cliente y el problema de diseño debe ser completamente entendido. a) Cuestionario de situación innovativa, b) QFD
DISEÑO CONCEPTUAL: Propuesta de diversos conceptos de solución. Se establece además, de forma aproximada, el diseño de dichas soluciones.

DISEÑO DETALLADO: El producto obtiene su forma definitiva, se realizan estudios detallados de sus características críticas, se fijan las especificaciones, tolerancias y métodos de manufactura.

Yang. El-Haik **(Product Development)**
Phase 1: Identify requirements. (I) 1. Draft Project Charter. 2. Identify business requirements
Phase 2: Characterize Design. (C) 1. Translate customer requirements 2. Generate Design Alternatives 3. Evaluate Design Alternatives
Phase 3. Optimize the design. (O) Tools used: Design/simulation tools, DOE, Taguchi method, Parameter design, Tolerance design, Reliability-based design, Robustness assessment.
Phase 4. Validate the design. 1. Pilot test and refining 2. Validation and process control. 3. Full commercial rollout and hardcover to new process owner.

Yang. El-Haik **(DFSS Project Algorithm)**
Identify Phase. Step 1: Form Team Step 2: (QFD Phase I and II) Determine customer expectations 2.1 Research customer activities 2.2 Define the pursued (intended) ideal design from customer data 2.3 Understanding the voice of the customer (Klein Model) 2.4 Categorize customer attributes into classes of wants, needs, and delights and map into critical-to-satisfaction (CTS) requirements. (QFD1) 2.5 Refine and prioritize customer wants, needs, and delights 2.6 Translating CTSs to functional requirements (FRs) 2.7 Map CTSs into functional requirements (FRs) 2.8 Define FR specification target values and allowable variations. 2.9 Exiting step 2
Characterize Phase. Step 3: (TRIZ) Understand FRs Evolution. Step 4: (TRIZ, Pugh) Generate concepts. Step 4.1: Analyze and Derive Concepts Step 5: (Pugh Selection) Select the Best Concept Step 6: (Axiomatic Design) Finalize the Functional Structure of Selected Concept Step 6.1: (Axiomatic Design) Perform Mappings
Optimize Phase. Step 6.2: (Axiomatic Design) Uncouple or Decouple Selected Concept Step 6.3: Simplify Design Using Axiom 2 Step 7: Initiate Design Scorecards and Transfer Function Development Step 8: (FMEA/PFMEA) Assess Risk Step 9: (DOE, Analytical) Transfer Function Organization 9.1 Finalize the physical structure 9.2 Use the transfer function to identify design parameters for optimization 9.3 Identify noise factors 9.4 Plan the optimization experiments 9.5 Collect data and analyze results Step 10: Design for X Step 11: (Tolerance Design) Finalize Tolerance Settings
Validate Phase. Step 12: Pilot/Prototype Design Step 13: Validate Design (Product/Service and Process) Step 14: Launch Mass Production Step 15: Celebrate Successful Completion.

Kusiak Andrew (1999) **Engineering Design**
Identify Customer Requirements

Preliminary Design
System Design
Detail Design
Testing and Evaluation

Appendix B.

DESIGN THEORY DEVELOPMENTS 1950-2003 (Farías, 2003)

(Adapted from: Otto and Wood, 2001)

Author	Publication Title	Theory or Development	Origin	Year
Altshuller	Theory of Inventive Problem Solving	First systematic tool to explore past inventions	Russia	1956
Osborne, Alexander	Applied Imagination	Brainstorming	USA	1963
Simon, Herbert	The sciences of the Artificial	Design is a study of nonphysical artificial phenomena	USA	1969
	ASME Design Automation Conference	First ASME conference on design automation	USA	1974
Stiny, George	Pictorial and Formal Aspects of Shape and Shape Grammars	Design can be represented as a formal geometric rules	USA	1975
Pahl & Beitz	Engineering Design: A systematic Approach	Systematic design as a complete process	Germany	1977
Taguchi, Genichi	Jikken Keikakuho (System of Experimental Design)	Robust Design	Japan	1977
Nam Suh	Axiomatic Design	Axiomatic design and design information content	USA	1978
Mead, Carver, & Conway, Lynn	Introduction to VLSI System	Compiler theory of design synthesis, VLSI design	USA	1979
Ross, Douglas		Structured Analysis and Design Technique (later called IDEF by the U.S. Department of Defense)	USA	1970
Boothroyd and Dewhurst	Design for Assembly	Rules for easy assembly reduced to design principles	USA	1983
Brown, D. & Chandrasekaran, B.	An approach to expert systems for Mechanical Design	First expert system to do mechanical design	USA	1983
Ullman, David	Proceedings, Design Theory and Methodology Conference	First ASME conference on design theory and methodology	USA	1989
Stuart Pugh	Total design : integrated methods for successful product engineering.	Matrix evaluation technique that that subjectively weighs each concept against the important technical criteria and customer concerns from a total perspective. Systematic design and concept selection.	USA	1991
Wang et al	DAER (design-analysis-evaluation-redesign)	Model for conceptual design combining numerical calculations with symbolic reasoning.	Canada	1994
Alvarez, CSIM, ITESM	QTC Methodology	Product Design Methodology	México	1998

Kaufman Consulting Group	Integrated Product Development (The Real History)	Fundamentals of IPD and an implementation approach.	USA	1999
Campbell, Cagan, Kotovsky	A-Design: and agent-based approach to conceptual design in a dynamic environment	New design generation methodology, which combines aspects of multi-objective optimization, multi-agent systems, and automated design synthesis.		1999
Toye, Cutkosky, Leifer, Tenenbaum, Glicksman	SHARE: A Methodology and Environment for Collaborative Product Development.	Seeks to apply information technologies in helping design teams gather, organize, re-access, and communicate informal and formal design information.	USA	2000
Wang, Shen, Xie	Collaborative Conceptual Design	Clarify the current conceptual design practice, classify the available technologies, study the future trends.	Canada	2001
Yang, El-Haik	Design for Six Sigma: A Roadmap for Product Development	DFSS project algorithm.	USA	2003

Appendix C

Tools Description

User / customer interviews

Support in-depth understanding of user requirements, following a pre-determined structure. A structured interview enables the researcher to focus on issues of particular relevance to the proposed product. Tried and tested.

Description

Interviewing remains one of the most popular ways of gaining user insights. With appropriate preparation, interviews are relatively simple to conduct, provide insight into customer needs relatively quickly with comparatively low levels of expertise. Interviewing can be used to establish responses to current products elicit requirements for future products and understand preferences for competitive offerings. Customer interviews are generally conducted one-on-one, with a single customer and a small number of representatives of the design team. Where possible, the tasks of interviewing and recording the data should be separated. If acceptable, it is useful to record or video interviews for later analysis with a larger team.

General approach

Typically, a user interview should last no more than 2 hours, preferably less than 1 hour. The customer or user is often giving up valuable time, so detailed preparation is required to make the most of the opportunity. Due to the complex nature of many distribution chains, customer visits are often attended by local sales representatives. Care should be taken to ensure that the sales force and the customer do not view the visit as a sales call, but as an opportunity to listen to the customers needs. Care also needs to be taken to be objective and not introduce interviewer bias.

Experience has demonstrated that 90-95% of 'needs' can be revealed from 20-30 interviews - the time to stop is when no new needs are being found. Some general rules for questions: ask open questions, avoid closed questions, avoid leading questions, avoid biased questions, don't combine questions, avoid price questions, avoid 'feature checking'. Although a guide is essential, it should not constrain interesting avenues of discussion. Some themes worth considering are:

- Images which come to mind about the product: How do you feel, how do you see yourself, describe the product, how and when do you use it, product comparisons (what type of car, fruit, shop, person etc)
- Complaints, problems and weaknesses: Does it live up to expectations, is it good value for money, has it ever failed or broken, what problems have you experienced, have you had any complaints, what annoys you about it
- What features are important: which do you use, which don't you use, which aspects influenced your buying decision, where did you buy it, what requirements are not met, what do you like best
- What new features: If you were to buy again what would you look for, how could it be improved, what would product x of the future look like, what else could you use instead
- Competition: what made you buy it, which did you consider and why, how did you find out about them

Notes

- Can encounter difficult interviewees and good interviewing requires some skill and practice
- Good listening skills are important, along with judgment to know when to let the discussion run

- Preparation is essential
- Avoid bias and where possible involve a number of perspectives from the design team
- Always involve the full design team whenever possible

Brainstorming

Extremely popular approach to idea generation, but often not done as effectively as it could be. A basic tool that all design teams should be able to apply well.

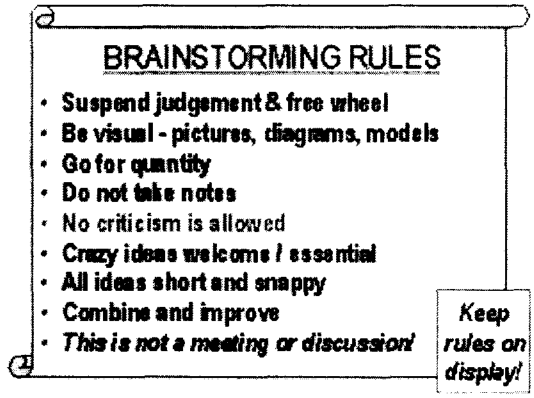
Description
Originally developed by Alex Osborn in the 1930s as a tool so support fact, idea and solution finding, based on two principles:

- Deferred judgment - in a typical meeting, we both ideate and evaluate simultaneously and are trained to be dominant at judgment. It is essential in a brainstorm to be able to suspend judgment and focus on the ideation.
- Quantity breeds quality - taking the view that the best way to find a good idea is to have lots of ideas, which can be combined, built on and developed.

Method

1. **Warm up and prepare**
No physical exercise should be taken without first warming up and this is also true for mental exercise. Treat brainstorming as mental exercise and begin with some warm up exercises, such as word games. In addition, it really helps to start a session having first prepared. If the brainstorm is about kettles, then go to a shop and look at some kettles. Show and tell thing that you like and dislike and why. Look for elegant solutions from other areas.
2. **Establish and agree playful rules**
The rules are not there to constrain but to ensure that the brainstorm is effective (see illustration). Put the rules up on the wall so everyone can clearly see them. Nominate a chairperson to ensure that the rules are adhered to. Maybe have a buzzer to press when too much discussion starts, or perhaps a 'yellow card' to raise when the rules are broken.
3. **State and discuss the problem - have a sharp focus**
Always begin with a clear problem statement. Avoid being too narrow (e.g. 'spill proof coffee cup lids') and avoid suggesting a solution. Don't be too product focused (e.g. 'bicycle cup holders') or too inward looking (e.g. 'how can we gain market share, or increase sales of product X'). Focus on both the problem and the customer's needs (e.g. 'how can we help cyclists to drink hot drinks without spilling it or burning their mouths?').
4. **Brainstorm**
Try to build and combine different ideas - build on an ideas strengths and develop any interesting aspects. Combine elements of different ideas. If a good idea is proposed, look for other ways of achieving the same result. When ideas dry up, try a new approach or re-pose the problem in a different way.
5. **Capture and display - be visual**
Ensure that all ideas are captured and displayed, either in written or graphical form. Encourage sketching (however poor) rather than writing at all times. Use the wall space as a way of recording and keeping track of the flow and development of ideas. It can sometimes be useful to map the relationships between different ideas. To support this stage, it can be useful to cover the walls with paper before starting.
Any visual approaches should be encouraged, from sketching to diagrams, mind maps, stick figures or even simple models. Have the necessary materials to hand, including tape, card, foam, blocks and modeling clay.
6. **Evaluate**
Only once the session has dried up, should the team begin to evaluate the different ideas.

Firstly, sort the ideas into categories, based on some elements of similarity. Second, evaluate the ideas against some general criteria for success.



Notes

- **Do's and don'ts**
  Below is a summary of some brainstorm do's and don'ts, along with a summary of the key items which are needed and the role of the brainstorm leader.
- **Drawbacks of brainstorming**
  It is possible for a brainstorm to be dominated by one or two individuals, of for the facilitator to be over zealous. This can result in an atmosphere which inhibits participation by some members. In addition, unless the team is good at expressing ideas visually, it is normally orally and verbally driven.

DO	DON'T	NEED	LEADER
• Encourage noise	• Tape record	• Min 4 people	• Member of group
• Allow wild & crazy ideas	• Allow observers	• Optimum 8 people	• Contributes ideas
• Enforce suspended judgement	• Accept interruptions	• Mixed group (in & outsiders)	• Manages session
• Allow variety of ideas	• Drag out a dried up session	• Low barriers	• Leads into new areas
• Enforce rules		• No hierarchy	• Writes down ideas
		• Large sheets of paper	• Enthusiastic
		• Pens	• Enforces rules
		• Walls	
		• 45 minutes max	

Quality function deployment - QFD

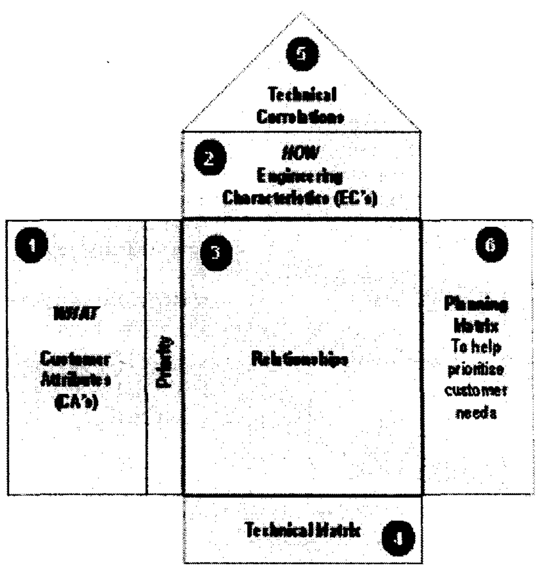
QFD is a powerful tool to support product definition and aims to link customer requirements to technical or engineering characteristics. The tool provides a conceptual map for communication across functions and provides a focus for design priorities. QFD promotes cross functional teamwork and negotiation and focuses the mind on 'what you don't know'.

Description
QFD originated in Japan in the late 1960's and is used extensively in the far east to support product development in a range of industries including automotive, consumer electronics, clothing, construction and shipbuilding. Since the 1970's, it has become increasingly adopted in the west and has been credited with supporting the revival of the US automotive industry.

QFD is a tool to help structure product planning and design and aims to ensure that customer needs are focused on throughout a project from concept design through to manufacture. At the heart of QFD is the House of Quality which links predetermined customer attributes to specific technical characteristics.

The House of Quality is built up from 6 interrelated matrices:

1. **The customer attributes**
   Describing what the product must do, a structured list of needs and wants, determined by market research. Represents the Voice of the Customer
2. **The engineering characteristics**
   Describing how the product may achieve its required performance in general terms which are not solution specific. Represents the Voice of the Designer.
3. **Relationships**
   Between the customer attributes and the engineering characteristics, indicating where there are strong, moderate or weak relationships.
4. **Technical matrix**
   Indicating the technical priorities based on the relationships between customer requirements and engineering characteristics. Also providing quantitative design targets for each of the engineering characteristics, based on the technical priorities and competitive benchmarking.
5. **Technical Correlations**
   Recording how the engineering characteristics may be wither mutually supporting or contradictory
6. **Planning Matrix**
   Providing quantitative market data for each of the customer attributes. Values can be based on user research, competitive analysis or team assessment



THE HOUSE OF QUALITY

Notes

- Demands a cross functional team, including market, technical and production representation
- Can be exceedingly complex and time consuming, sometimes tedious
- Can be too analytical - a numerical answer can be treated as a 'right' answer
- Requires some training and strong facilitation initially

Comments to QFD Method

Quality Function Deployment (QFD) is an adaption of some of the TQM tools. In Japan, in the last sixties, QFD was invented to support the product design process (for designing large ships, in fact). As QFD itself evolved, it became clear to QFD practicioners that it could be used to support service development as well.

Today its application goes considerably beyond product and service design, although those activities are quite commonly supported by QFD. QFD has been extended to apply to any planning process where a team has decided systematically to prioritize their possible responses to a given sot of objectives. The objectives are called the "Whats", and the responses are called the "Hows". QFD provide a method for evaluating "How" a team should best accomplish the "Whats".

The basic problems of product design are universal: customers have needs that relate to using products; these needs must be addressed by designers who have to make hundreds or thousands of technical decisions; and there are never enough people, time, and dollars to put everything that could be imagined into a product service.
These problems confront the developers of automobiles, cameras, hot-line service centers, school curricula, and even software. QFD can be used to help development teams decide how best to meet customer needs with available resources, regardless of the technology underlying the product or service.

Customers have their own language for expressing their needs. Each development team has its own language for expressing its technology and its decisions. The development team must make a translation between the customer's language and their technical language. QFD is a tool that helps teams systematically map out the relationships between the two languages.

Software engineers are fortunate in that several languages are available to them for expressing their top-level design: the disciplines of object-oriented design, structured design, and structured analysis provide excellent methods for expressing the technical aspects of a software system. These languages can and have been used in software QFDs. Other technical language elements that software engineers have used in QFD are performance measures, subsystem modules, and brief descriptions of product functions. What works best in QFD is the technical language that the development team is most comfortable with.

Selection Process – Pugh Charts.

This process applies thoughts from Pugh (1990), Ulrich and Eppinger (1995), Ullman (1995), and Otto (1995). Another description for this method is found in this appendix called Controlled Convergence.

Description
Is a team-based decision-making effort. The process is focused on clearly articulating differences in understanding among team members, forming common definitions, and expanding the options considered that are due to these differences in understanding.

The concept selection process should be completed in a room with at least three walls that can be written on, paper attached to, or overhead projectors shown on. One wall will have definitions of criteria and alternatives displayed, another wall will be a working wall with the evaluation interaction, and a final wall will be used to keep notes and rejected information.

Method

The selection process is a five-step process plus iterations:

1. Forming consensus on the criteria
2. Forming consensus on the alternatives
3. Ranking the alternatives
4. Evaluating the alternatives
5. Attacking the negatives

Forming Consensus on the Criteria.

Establish evaluation criteria on which the concept selection decision will be based. Generally, most concept selection decision are based on three evaluation criteria of (1) cost; then (2) development risk, technical difficulty, or ability to meet schedule delivery; and finally (3) performance or customer satisfaction. These three general criteria are expressed in a variety of case-specific ways for any specific selection process. The problem is that once the criteria are stated, every design team member will have different perceptions of what these statements mean. An initial task is to resolve these differences into definitions that are common to the team.

To establish criteria definitions, a design team should start with one member articulating a proposed list of evaluation criteria. The list should be developed from the customer needs and engineering specifications of the product (QFD, Parametric Analysis).

As this list is formed, other team members should chime in with more criteria, until a set of criteria is on the board that every one agrees could be legitimate criteria.

Once this process is complete, each criterion is refined into a common definition. Whoever suggested the criterion provides a definition, and the everyone argues (debates) over its scope. The definitions should be consistent with previous metrics chosen for the criteria (QFD).

Once complete, the criteria and their definitions (along with measurable scales) should be posted in large, easily readable characters on a side wall during the decision-making process, thereby permitting quickly visual reference by any team member.

Forming Consensus on the Alternatives.

Once the evaluation criteria are initially established, different alternatives need to be understood on a common basis.

1. Voice alternatives from concept generation.
2. Refine alternatives (all members may understand them without ambiguity).
3. Each alternative is given a commonly understood definition and articulation of what will be needed to engineer the concept into a final product.
4. In new alternatives appear, they should be labeled

Is good to have each alternative drawn in isometrics views so it can be visualized from anywhere in the room. Further, the definition should be written out under the drawing in large, easily read characters.

Ranking.

The next step is to rank each clearly defined alternative on each clearly defined criterion.

1. Use a decision matrix chart on the main wall.
2. A team should consider each criterion once at a time and rank all the different alternatives on each criterion.
3. Rank the alternatives with a scale such as (-,s,+)

Assessment.

1. The evaluations should be collected into overall summary rankings on each alternative.
2. Compare the ranks.
3. Order the alternatives from overall worst to overall best.

Attacking the negatives.

1. Take off of the cart those alternatives that rate poorly.
2. Examine closely the alternatives that rate favorably. The alternatives that rate high overall but have a few low scores should be closely scrutinized.
3. For the alternatives with such negative-ranked criteria. A design team should clearly state what is causing the negative rankings. Then each of these effects should be interrogated by the team to understand how each engineer might apply his or her discipline to eliminate the negative.

TRIZ can be used, keep in mind that attacking the negatives is not a trade-off exercise.

FAST Method

Hierarchical approach for modeling the function of a product or system.

Description
Fast (VAI, 1993) is used to define, analyze, and understand product functions, how the functions relate to another, and wich functions require attention to increase the product value. It is used to display functions in a logical sequence, prioritize them, and test their dependency.

Method

1. **Limits**
   Construct two vertical lines, one to the extreme left and one to the right. These lines define the scope of the product development objective.
2. **Basic functions**
   Place the basic functions to the right of the left-hand scope line. Pose the question "Why is the basic function being performed?" A higher order function will answer this question. Place this function to the left of the basic function and connect with a line, beginning the critical path.
3. **Generate Functions**
   Generate functions to the right of the basic function. These functions should always follow a how and why answering scheme and represent the secondary functions. Connect these functions with lines to define the further of the critical path.
4. **Assumed functions**
   The critical path will end with an "assumed function", outside the right scope line. This function is external to the product, such as "supply electricity".
5. **State the objective**
   State the objective of the development effort above the basic function. In addition, add one-time or all-time functions to the top of the diagram.

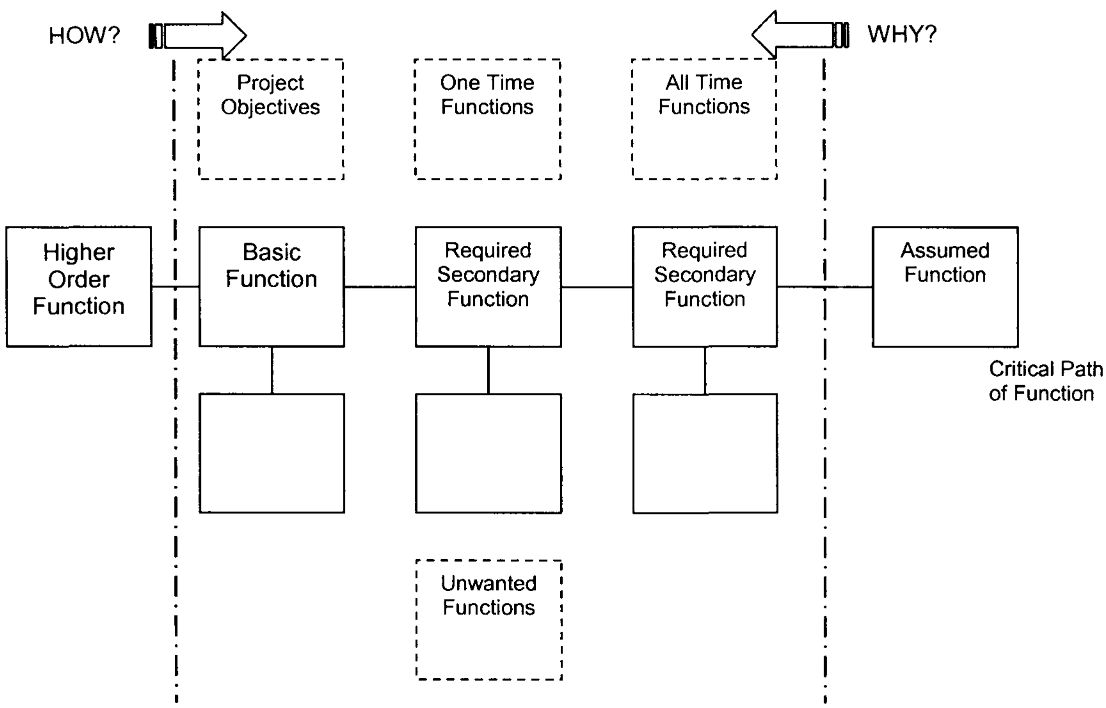


Figure D1. FAST Method

Subtract and Operate Procedure

It is a very logical process, based on common sense. What better way of figuring out the function of a component than removing it and operating the system without it, or, alternatively, conceptually removing components from a concept to understand their effects.

Description
Is one bottom-up approach to develop a functional tree. The underlying assumption to use this method is that either a form concept or actual product exists. This product or concept will then be reverse engineered using the Subtract and Operate procedure.

Method

1. **Step 1. Disassemble (subtract) one component of the assembly.**
   Removal of components may occur in any order. However, it may be necessary to remove one or several components in order to remove the desired component. These prerequisite components should be reassembled if possible. If they cannot be reassembled, measures should be used to replicate the function(s) of the missing component(s).
2. **Step 2. Operate the system through its full range.**
   This step should test the product through the range of customer requirements. After removing a component, the product should be thoroughly tested. For each customer requirement (structural, ergonomic, kinematic, etc.), the product must be tested to verify the effects of removal of the component.
3. **Step 3. Analyze the effect.**
   This step is most commonly completed through a visual analysis. However, it may be necessary to use a testing device if the effect of removal is not obvious.

4. **Step 4. Deduce the sub function of the missing component.**
From step 3, the sub function of the missing component may be deduced. A change in any degree of freedom (DOF) during operation should be a major focus. This change is a critical issue in determining component functionality.
5. **Step 5. Replace the component and repeat the procedure**
Replace the component and repeat the procedure n times, where n is the number of components in the assembly. Document the results in an effects table. Step 5 is the reassembly of the removed component. Repeating the process n times allows for the analysis of each component in the assembly. In certain cases, it may be necessary to analyze a product according to sub assemblies and components.
6. **Step 6. Translate the collection of sub functions into a function tree.**
One does this by grouping the sub functions of Step 5 into common groups. Each group becomes a higher level functional description node. This process is repeated until the higher level functions collapse into the overall product function as a single node at the root of the tree.

Morphological charts

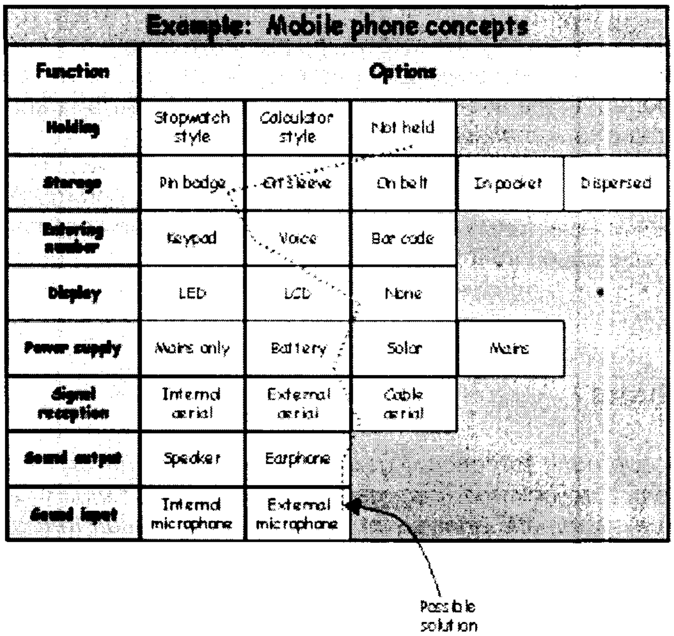
Provide a structured approach to concept generation to widen the area of search for solutions to a defined design problem. Can help the team generate a complete range of alternative design solutions for a product through a systematic analysis of the form/configuration that a product or machine might take.

Description
A morphological chart is a visual way to capture the necessary product functionality and explore alternative means and combinations of achieving that functionality. For each element of product function, there may be a number of possible solutions. The chart enables these solutions to be expressed and provides a structure for considering alternative combinations. This can enable the early consideration of the product 'architecture' through the generation and consideration of different combinations of 'sub-solutions' that have not previously been identified. Used appropriately, it can help to encourage a user driven approach to the generation of potential solution.

Method

1. **List product functions**
List the features (or functions) that are essential to the product. The list should not be too long, but should encompass the major product functions, at a appropriate level of generalization. Ideally, there should be no more than 10. It can be useful to list functions according to a predetermined order - most important, position in structure, energy flow, information flow. Care should be taken to list functions and not components - e.g. 'warning indicator' rather than 'bell'. Always ask 'what function is this component fulfilling?' Each function should be mutually exclusive. Possible functions for a mobile phone could include: holding, storage, dialing, display, power supply, signal reception, signal processing, sound output, sound input etc.
2. **List the possible 'means' for each function**
For each function, list the 'means' or possible solutions by which it might be achieved. Think about new ideas, as well as known solutions or components and where possible ideas should be expressed visually as well as in words. Any important characteristics of the solutions should be recorded. Try to maintain the same level of generality for each possible solution - for example, it may be beneficial to consider different power sources or perhaps it may be more relevant to just investigate different battery options. Possible means of achieving 'holding' for a mobile phone could be a stopwatch-type grip, attached to clothing, watch style, gun grip etc.
3. **Chart functions and means & explore combinations**
Draw up a chart containing all possible sub-solutions. This is the 'morphological chart' which should represent the total 'solution space' for the product - made up of combinations of sub-

solutions. Try wherever possible to express all options visually. It is now possible to identify feasible combinations of sub-solutions. The total number of combinations may be very large, so they may need to be limited to the most feasible or attractive options. Name each viable combination as a potential solution for further evaluation later. An example is shown below.



Example: Mobile phone concepts					
Function	Options				
Holding	Stopwatch style	Calculator style	Not held		
Storage	Pin badge	On sleeve	On belt	In pocket	Dispersed
Entering number	Keypad	Voice	Bar code		
Display	LED	LCD	None		
Power supply	Mains only	Battery	Solar	Mains	
Signal reception	Internal aerial	External aerial	Cable aerial		
Sound output	Speaker	Earphone			
Sound input	Internal microphone	External microphone			

Notes

Generating a morphological chart can be tedious and may result in a lot of solutions which may not be relevant or practical. Attention should be paid to both the soft and hard aspects of the design mix, but it can be difficult to include 'stylistic' options.

Check List. (Pahl-Beitz, 1988; Otto y Wood, 2001)

Embodiment design is characterized by repeated deliberation and verification. Every embodiment design is an attempt to fulfill a given function with appropriate layout, component shapes and materials. The process starts with preliminary scale layout drawings based on spatial requirements and rough analysis, and proceeds to consider safety, ergonomics, production, assembly, operation, maintenance and costs.

In dealing with these factors, the designer will discover a large number of interrelationships, so that his approach must be progressive as well as reiterative (verification and correction). His approach must always be such as to allow the speedy identification of those problems that must be solved first.
The designer can derive important checklist headings form the general objectives or constraints. The checklist ensures that nothing essential is forgotten in the embodiment phase.
Reference to the headings will help designer to develop and test his progress in a systematic and time-saving way. Each heading should be examined in turn, regardless of its interrelationship with the rest.
The actual sequence is no indication of the relative importance of the various headings, but ensures a systematic approach. For instance, it would be futile to deal with assembly problems before ascertaining if the requires performance or minimum durability is ensured. The checklist thus provides a consistent scrutiny of embodiment design and one that is easily memorized.

Heading	Check list issue (Partial list)
Function	Are the customer needs satisfied, as measured by the target values? Is the stipulated product architecture and function(s) fulfilled? What auxiliary or supporting functions are needed?
Working principles and form solutions	Do the chosen form solutions (architecture and components per function) produce the desired effects and advantages? What disturbing noise factors may be expected? What byproducts may be expected?
Layout, geometry, and materials	Do the chosen layout, component shapes, materials, and dimensions provide minimal performance variance to noise (robustness), adequate durability (strength), efficient material usage (strength-to –mass ratio), suitable life (fatigue), permissible deformation (stiffness), adequate force flows (interfaces and stress concentrations), Adequate stability, Impact resistance, Freedom from resonance, Unimpeded expansion and heat transfer, and Acceptable corrosion and wear with the stipulated service life and loads?
Energy and kinematics	Do the chosen layout and components provide Efficient transfer of energy (efficiency), Adequate transient and steady state behavior (dynamic and control across energy domains), and Appropriate motion, velocity, and acceleration profiles?
Safety	Have all of the factors affecting the safety of the user; components, functions, operation, and the environment been taken in to account?
Ergonomics	Have the human-machine relationships been fully considered? Have unnecessary human stress or injurious factor been predicted and avoided? Has attention been paid to aesthetics and the intrinsic "feel" of the product?
Production	Has there been a technological and economical analysis of the production processes, capability, and suppliers?
Quality control	Have standard product tolerances been chosen (not to tight)? Have the necessary quality checks been chosen (type, measurements, and time)?
Assembly	Can all internal and external assembly operations be performed simply, repeatedly, and in the correct order (without ambiguity)? Can components be combined (minimize part count) without affecting modular architectures and functional independence of the product?
Transport	Have the internal and external transport conditions and risks been identified and solved? Have the required packaging and dunnage been designed?
Operation	Have all the factors influencing the product's operation, such as noise, vibration, and handling been considered?
Life Cycle	Can the product, its components, its packaging be reused or recycled? Have the materials been chosen and clumped to aid recycling? Is the product easily disassembled?
Maintenance	Can maintenance, inspection, repair and overhaul be easily performed and checked? What features have been added to the product to aid in maintenance?
Costs	Have the stipulated cost limits been observed? Will additional operational or subsidiary costs arise?
Schedules	Can the delivery dates be met, including tooling? What design modifications might reduce cycle time and improve delivery?

Table D1. Checklist for embodying a product concept (after Pahl and Beitz, 1996).

This checklist is created from generic (and historically proven) design principles of ensuring robustness, clarity, simplicity, and safety in a product.

Robustness is the design principle that seeks to minimize the variability in performance of a product under all expected environmental and user conditions. This principle provides a basis for understanding the impact of noise on a product's performance.

Clarity is the basic principle that all functions should be unambiguously specified, in form, parameters, manufacturing, and assembly. Unintended functions should not be present in a product. It also assumes that product functions (or function chains) will be implemented as independent as possible. In doing so, the performance of each product function (or function chains) can be controlled and modified without deteriorating or compromising the performance of other product functions.

The design principle of simplicity, on the other hand, is the minimization of information content within a product design. For this principle, component shapes are simplified to aid in production ease and cycle time. The number of components is also reduced to simplify ease of assembly and increase the reliability of a product. Component actions and motions are also reduced to increase reliability.

Safety its purpose is to minimize the risk created by the use of a product. As such, this principle seeks to ensure that a product has the desired strength, reliability, environmental impact, ergonomics, and accident prevention measures.

FMEA (Failure Modes and Effects Analysis)

A tool to enable potential errors or faults to be predicted during the early design stages.

Description
Many companies use FMEA as a central pillar of their design process. FMEA provides a structured approach to the analysis of route causes (of failure), the estimation of severity or impact, and the effectiveness of strategies for prevention. The ultimate output is the generation of action plans to prevent, detect or reduce the impact of potential modes of failure. In a nutshell, it encourages the design team to consider:

- What could wrong
- How badly it might go wrong
- What needs to be done to prevent or mitigate the problem

FMEA emerged from the US Military in the late 1940s as a tool to improve the evaluation of reliability of equipment. Its benefits quickly became apparent and it was adopted by aerospace industries and NASA during the Apollo program in the 1960s. It was later taken up by many of the larger automotive companies, including Ford in the 1970s. It has since become a core tool in product development in many organizations and is recommended as a part of an organization's quality management system.

The basic logic can be applied at a number of levels, including organizational issues, strategy issues, product design issues, production processes and individual components. Typically, it is used to analyze either a product design or production process:

Product or Design FMEA

What could go wrong with a product while in service as a result of a ***weakness in design***?

- Carried out during the early stages of a design project
- Tends to assume that the product will be produced to the required design specifications
- Aims to reduce reliance on process controls and inspection to overcome limitations in the basic design and thus, need to consider the technical and physical limitations of the manufacturing and assembly processes

Process FMEA

What could go wrong with a product during manufacture or while in service as a result of ***non-compliance*** to specification or design?

Typically, the information is collated and presented in a tabular format, as shown below:

FMEA worksheet

Project Product ① System					Date Prepared by ②					FMEA Number Reference documents ③	
System / Component / Function	*Potential failure mode*	*Potential effect(s) of failure*	*Severity*	*Criticality*	*Potential cause(s) of failure*	*Occurrence*	*Current design controls*	*Detection*	*Risk Priority Number*	*Recommended action(s)*	*Responsibility & completion date*
④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮

Method

1. **Level of analysis**
   The analysis can be carried out at a project, product, system, subsystem or component level. It is important to be clear about the level at which the current analysis is taking place. A hierarchical organisation of analysis enables the design team to drill down to detail where appropriate.
2. **Date & prepared by**
   To record who was involved and when the analysis took place.
3. **FMEA number & reference information**
   Clear numbering is important, to enable the team to trace an analysis from system to component level. It may also be important to reference any important test results, documents or drawings here.
4. **System / component / function**
   The specific name / number of the element or issues under study.
5. **Potential Failure Modes**
   The manner in which a component, subsystem or system could possibly fail while being used. Here the design team must be creative in seeking ideas for all potential modes of failure. Ask open and general questions: How can it fail? Under what conditions? What types of use? etc.
6. **Potential Effects of Failure**
   For each mode of failure, what will the likely effect be? How would the failure affect different stakeholders? What will be the likely outcomes if the system or component fails? Provide as detailed description as is necessary of the potential impact of failure. An individual failure mode may have many possible effects.
7. **Severity rating**
   Each failure effect can be judged for it's potential seriousness. Typically, this is done by scoring the effect on a 1 to 5 (or 10) scale. This value should be discussed and negotiated by

all members of the team. A team may wish to define for itself the severity to go with each score, below is a suggested scheme:
Rating Criteria
5 (9-10) With potential safety risk or legal problems - potential loss of life or major dissatisfaction
4 (7-8) High potential customer dissatisfaction - serious injury or significant mission disruption
3 (5-6) Medium potential customer dissatisfaction - potential small injury, mission inconvenience / delay
2 (3-4) The customer may notice the potential failure and may be a little dissatisfied - annoyance
1 (1-2) The customer will probably not detect the failure - undetectable

8. **Critical?**
A column is provided to enable the rapid identification of potentially critical failures which must be addressed (e.g. safety issues, sales issues etc.)
9. **Potential Cause / Mechanisms of Failure**
Each failure mode will have an underlying root cause. Thus, it is important to spend time to establish the potential root causes or mechanisms of failure, by asking '***what is the likely cause of the failure mode?***' Possible causes could include: Wrong tolerances, poor alignment, operator error, component missing, fatigue, defective components, maintenance required, environment ... etc.
10. **Occurrence Ranking**
It is also necessary to consider the likelihood of the potential failure occurring. Here, a 'probability' assessment is made by the team and scored on a 1 to 5 (or 10) scale. Possible occurrence ratings (you can define them in other ways) are shown below:
Rating Criteria
5 (9-10) Very high probability of occurrence
4 (7-8) High probability of occurrence
3 (5-6) Moderate probability of occurrence
2 (3-4) Low probability of occurrence
1 (1-2) Remote probability of occurrence
This section is critical in the FMEA procedure and each of the responses categorized as very high or high should be considered and addressed.
11. **Current design controls**
Are there any design controls which aim to reduce or eliminate the potential failure? These could include labels, barriers, instructions or total redesigns. Other controls could include prototyping, evaluation or possibly market surveys.
12. **Detection rating**
The final rating aims to establish how 'detectable' the potential fault will be. Will it be instantly noticeable or will it not be apparent. In addition, how likely is it that the controls listed will enable the detection of the potential failure? Suggested ratings on a scale of 1 to 5 (or 10):
Rating Criteria
5 (9 or 10) Zero probability of detecting the potential failure cause
4 (7 or 8) Close to zero probability of detecting potential failure cause
3 (4, 5 or 6) Not likely to detect potential failure cause
2 (2 or 3) Good chance of detecting potential failure cause
1 (1) Almost certain to identify potential failure cause
If the FMEA is being carried out at a 'project' level, then it can be beneficial to consider this value as 'reactability'. Will it be possible to react to the failure rapidly enough to reduce its impact sufficiently?
13. **Risk Priority Number (RPN)**
It is likely that the team will have identified many possible failure modes and effects. Each one needs to be assigned a 'Risk Priority Number' to enable the prioritization of mitigating action. The RPN is simply the product of the severity, occurrence and detection ratings:
RPN = Severity rating x Occurrence rating x Detection rating
- perhaps more easily remembered as:
RPN= S*O*D

The RPN value gives an indicator of the design risk and generally, the items with the highest RPN and severity ratings should be given first consideration.

14. **Recommended actions**
    Follow up is essential and actions to reduce the impact or likelihood are essential These actions should be specific and preferably measurable. Attention should be given to actions that address the root cause and not the symptoms.
15. **Responsibility**
    Finally, all actions should be clearly allocated (to an individual, department and/or organization) and a clear deadline given.
16. **Additional columns if wanted:**
    Some FMEA users add additional columns to record the actual actions taken or keep an update on the status of actions. It can also be a good idea to revise the RPN value following the corrective action. This enables full trace-ability between potential problems and the outcomes of actions.

Comments for FMEA and a variant process.

While systems modeling focuses, initially, on the overt customer needs of a product, methods are needed to identify the issues related to the expected quality of a specific product. The embodiment checklist presented previously provides a basic approach for focusing on expected quality.

FMEA is an analytical technique used by a product design team as a means to identify, define and eliminate, to the extent possible, known or potential failure modes of a product system. The technique should be used cooperatively with systems modeling to investigate and determine good choices for variables defining a product.

FMEA focuses on the entire product layout, not just on each subassembly, component, and interfacing system of a product. Must also be understood as a process. It entails the continuous application of design team tasks during a product's development. It also seeks to identify potential failure modes before a failure can occur in a product, not as a forensic tool for investigation a failure once it has occurred.

This analysis poses three basic questions in its pursuit of a quality product:

- What could fail or go wrong with each component of a product?.
- To what extent might it fail, and what are the potential hazards produced by the failure?
- What steps should be implemented to prevent the failures?

A systematic process provides the basis for answering the three basic FMEA questions. The proposed steps are (Otto & Wood, 2001):

List each subassembly and component number, along with the basic functions or function chains of the component.

Identify and list the potential failures for each product component. Simple prototype models and brainstorming techniques can aid in identifying potential failure modes. The checklist presented previously (Table 3.2) and the example failure modes (Table 3.3) should be used to check for typical problems with components and product systems. For any listed failure mode, the idea is that the failure could occur, but not that it will necessarily occur for the product under study.

List of Example Failure Modes

Corrosion	Leaking	Scoring
Fracture	Ingress	Radiation damage

Material Yield	Vibrations	Delamination
Electrical Short	Whirl	Erosion
Open Circuit	Sagging	Thermal shock
Buckling	Cracking	Thermal relaxation
Resonance	Stall	Bonding failure
Fatigue	Creep	Starved for lubrication
Deflections or deformations	Thermal expansion	Staining
Seizure	Oxidation	Inefficient
Burning	UV deterioration	Fretting
Misalignment	Acoustic noise	Thermal fatigue
Stripping	Scratching and hardness	Sticking
Wear	Unstable	Intermitent system operation
Binding	Loose fittings	Egress
Overshooting (Control)	Unbalanced	Surge
Ringing	Embrittlement	
Loose	Loosening	

Table D2. Abbreviated List of Example Failure Modes.

List possible potential causes or mechanisms of the failure modes.

List the potential effects of the failure, including impact on the environment, property, or hazards to human users.

Rate the likelihood of occurrence (O) of the failure. The ratings should be on a scale factor of 1-10, as given by:

1 No effect
2/3 Low (relative few failures)
4/5/6 Moderate (occasional failures)
7/8 High (repeated failures)
9/10 Very high (failure is almost inevitable)

Estimate the potential severity (S) of the failure and its effect. Again, a 1-10 scale should be used.

1 No effect
2 Very minor
3 Minor (affects very little of the system)
4/5/6 Moderate-most customers are annoyed
7/8 High (causes a loss of a primary function: customers are dissatisfied).
9/10 Very high and hazardous (product becomes inoperative; customers are angered; the failure may result unsafe operation and possible injury)

List current or expected design controls/tests for detecting (D) the failure before the product is released for production.

1	Almost certain
2	High
3	Moderate
4/5/6	Moderate-most customers are annoyed
7/8	Low
9/10	Very remote to absolute uncertainty

Calculate the Risk Priority Number (RPN). It prioritizes the relative importance of each failure mode and effect on a scale of 1-1000.

$$RPN = (S) \times (O) \times (D)$$

Small values represent that a failure that is highly unlike and unimportant.

Develop recommended actions for the failure modes, assign responsibilities to appropriate parties and team members, and set a schedule for implementing the actions. Corrective actions should be first develop for the highest ranked failure modes based on the RPN.

Implement the corrective actions, update the S-O-D ratings, and recalculate the RPN for the update design.

The results may be documented with the template provided in Table 3.4.

Product Name: ________ ____ System ____ Subsystem Name: ____ Component			Devel. Team: ____________________ ____________________				Page No. ___ of ___ FMEA Number ____ Date: __________		
Part # & Functions	Potential Failure Mode	Potential Effect(s) of failure	Severity (S)	Potential Cause(s)/ Mechanism(s) of Failure	Occurrence (O)	Current Design Controls	Detection (D)	Recommended Actions	RPN

Table D3. FMEA Template for Product Design and Development.

DFM and DFA Guidelines.

Designing for Manufacturing means designing for the minimization of production costs while maintaining the required quality of the product. (Pahl & Beitz, 1988).

By production, we refer to:

- Assembly, including transport of components;
- Quality control;
- Materials handling; and
- Operations planning.

The designer will accordingly do well to consult the Checklist (D1) under the headings "production", "quality control", "assembly" and "transport".

DFM is greatly facilitated if, from the earliest possible stage, the designer's decisions are backed up with data compiled by the standards department, the planning and estimating department, the purchasing department and the production manager.

DFM Guideline:

- *Appropriate overall layout design* which determines the production procedure, by the breakdown of the product in to assemblies and individual components (in-house or bought-out, new, repeat or standard). The appropriate subdivision of the overall layout can give rise to differential, integral, composite and/or building block methods of construction.
- *Appropriate form design of components*, which determines the production procedure, the manufacturing methods and the quality of components. The classifying criteria will be the process steps (PS) used in the manufacture of the component. In addition, we shall be assigning objectives- "reduction of cost" (C) and "improvement of quality" (Q) to the various design guidelines. The form design of components to be shaped by primary process must satisfy the demands and characteristics of the process used. (Figures D2 to D7)
- *Appropriate selection of materials*, which determines the production procedure, the manufacturing methods, the materials handling and quality control.
- *Appropriate use of standard and bought-out components,* which influence the production capacity, the storage and the costs.
- Appropriate documentation, which must be adapted to the production procedure, to the manufacturing methods and the quality control.

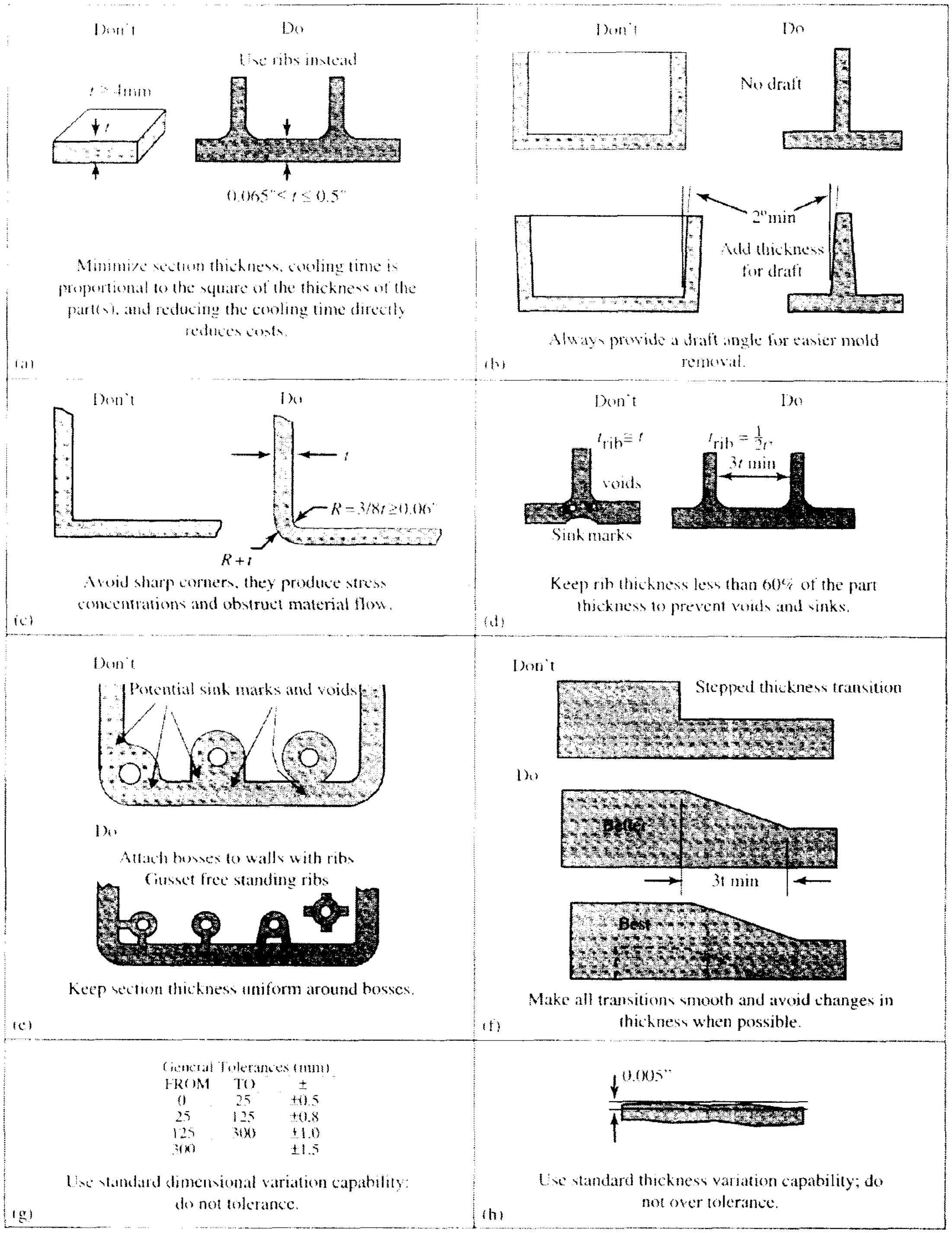


Figure D2. Injection-molded part design guidelines.

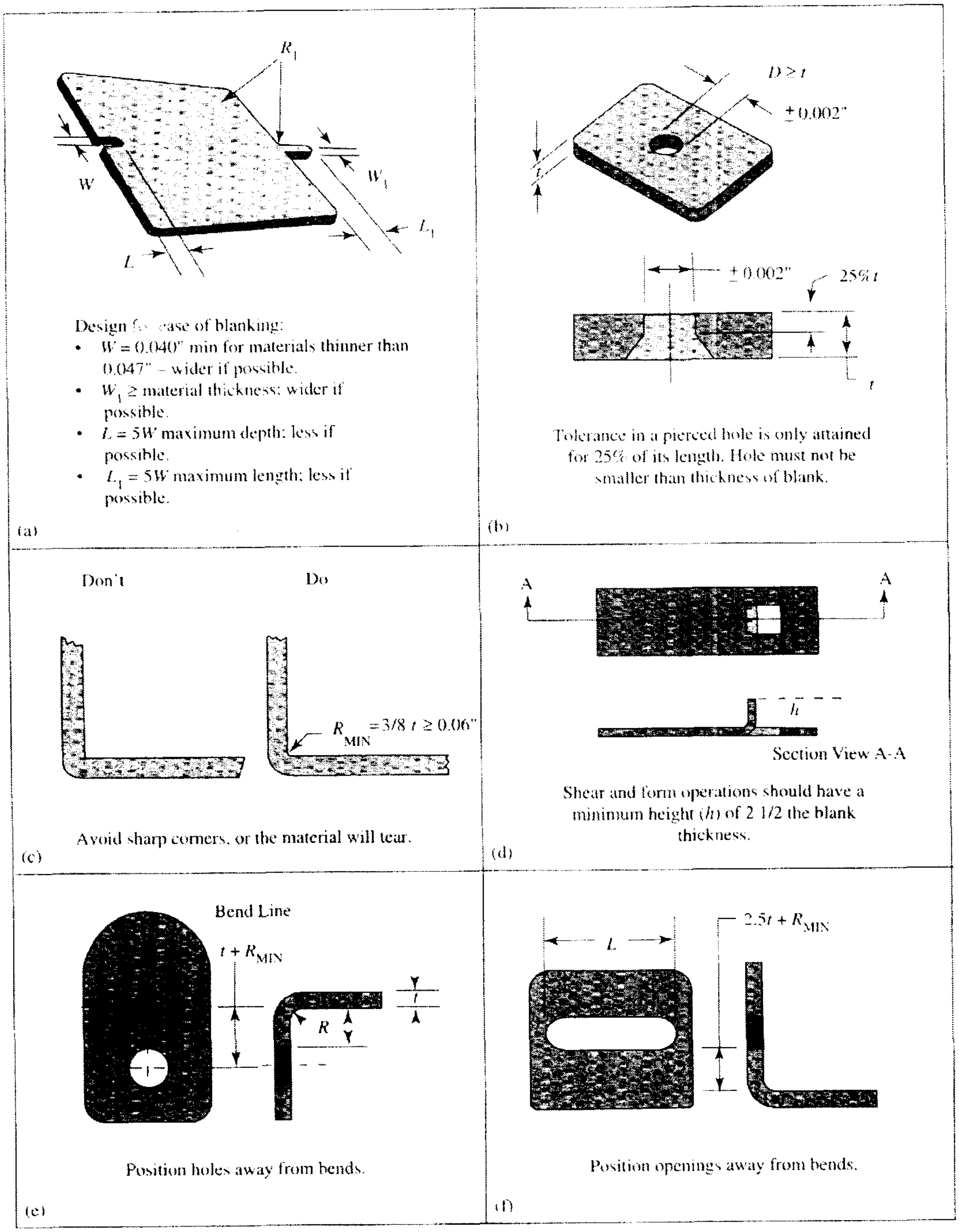


Figure D3. Sheet-formed part design guidelines.

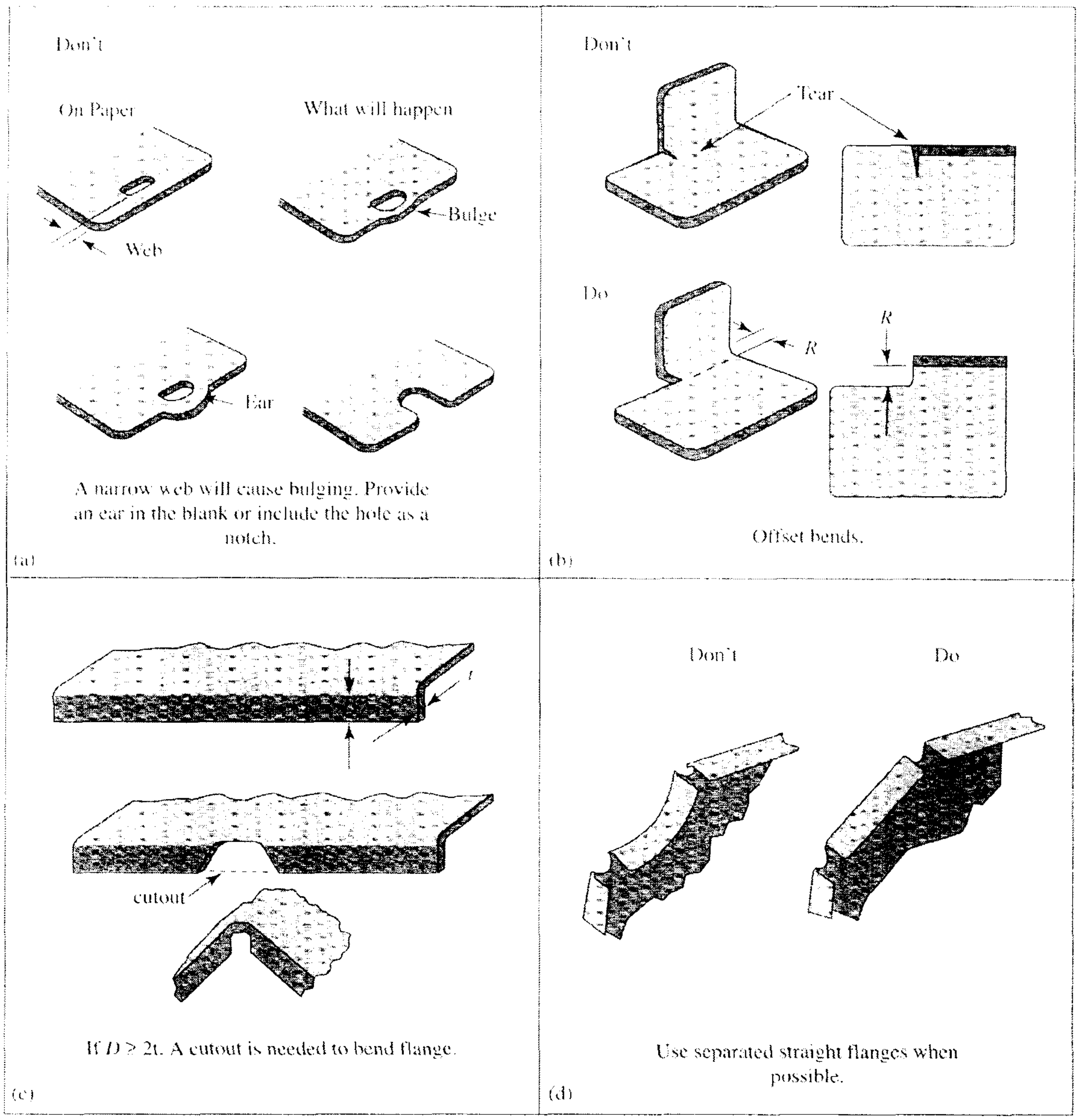


Figure D4. Sheet-formed part design guidelines (continued).

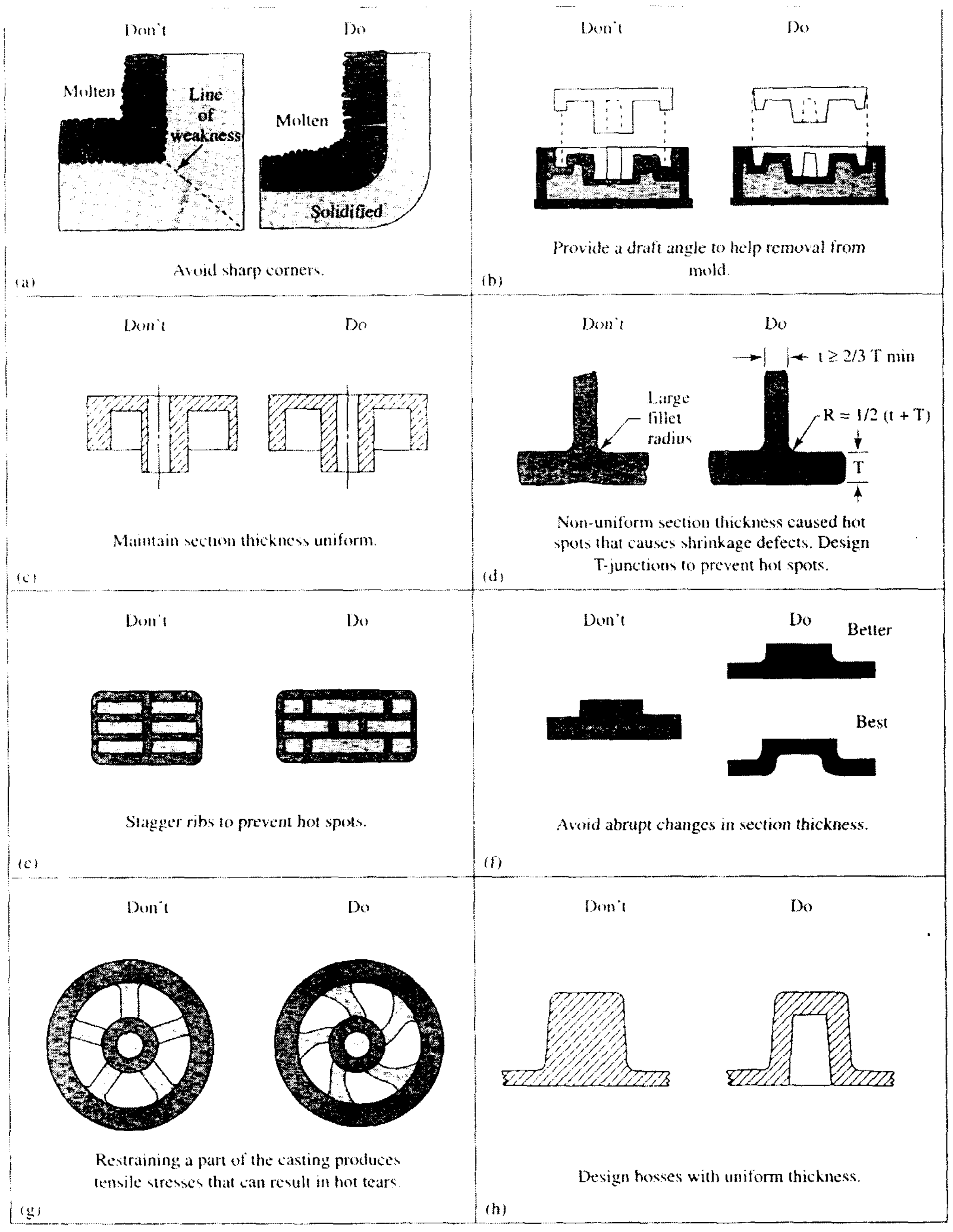


Figure D5. Cast part design guidelines.

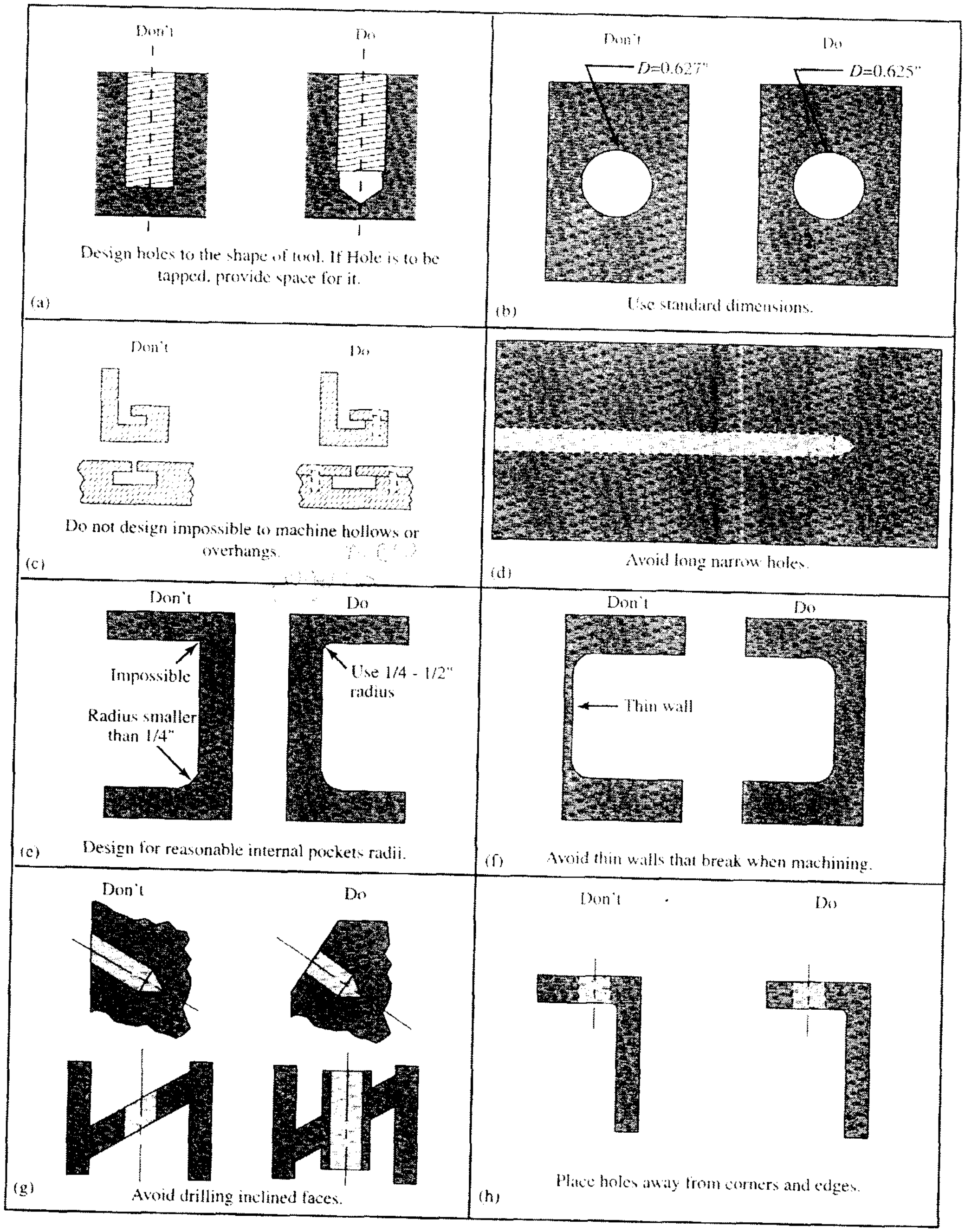


Figure D6. Machined part design guidelines.

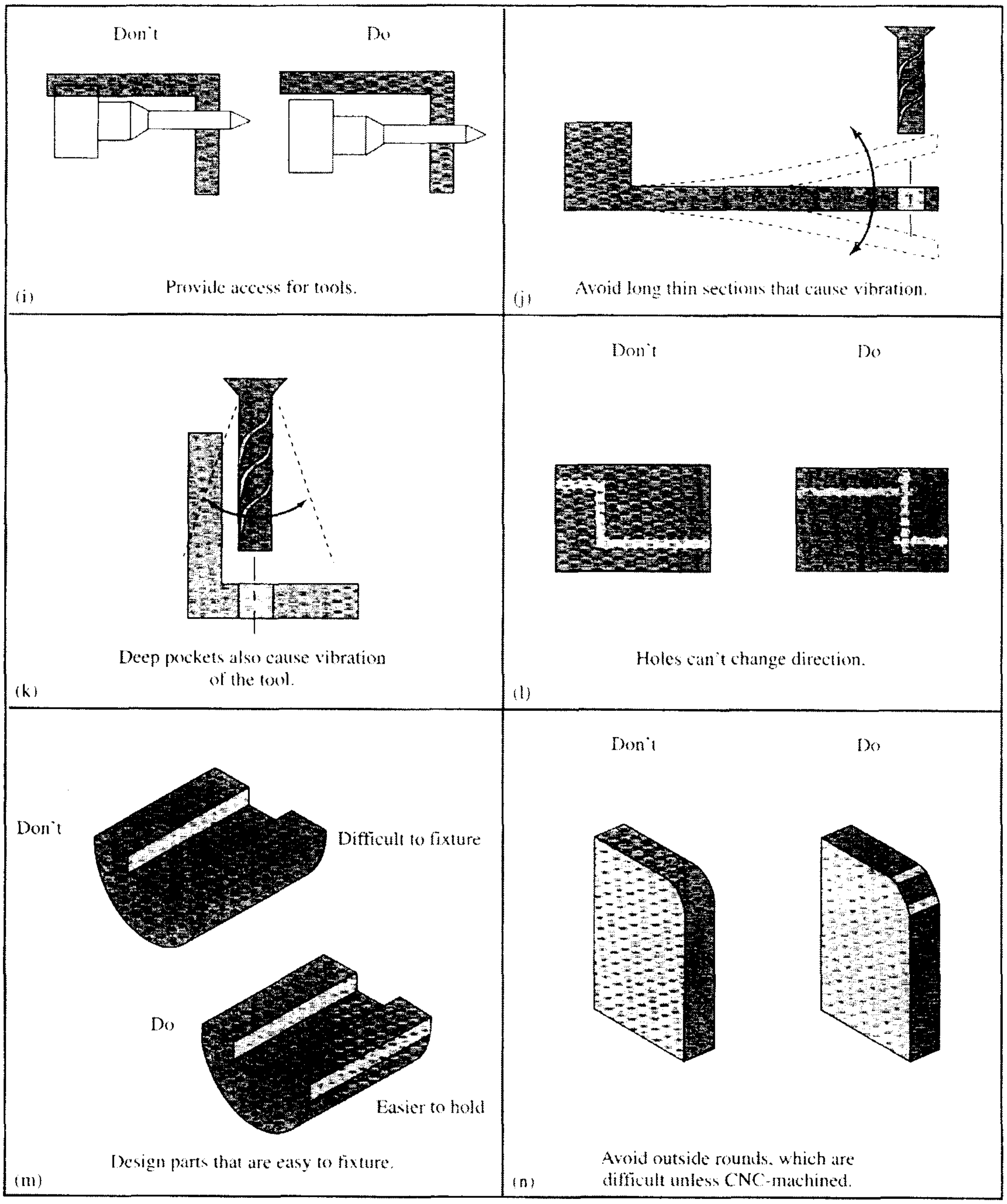


Figure D7. Machined part design guidelines (continued).

The Design for Assembly Guidelines are adapted from several authors such as Andreasen 1983, Baldwin 1966, Digital 1993, Huthwaite 1990, Iredale 1964, and Xerox 1986. If a concept is compatible with these guidelines, the design will fare well in the subsequent more detailed analysis.

1. *Minimize the part count by incorporating multiple functions into single parts (Iredale 1964).*
2. Modularize multiple parts into single subassemblies (Crow 1988).
3. Assemble in open space, not in confined spaces. Never bury important components (Tipping 1965)
4. Make parts to identify how to orient them for insertion. (Tipping 1965)
5. Standardize to reduce part variety (Tipping 1965)
6. Maximize piece symmetry (Iredale 1964, Paterson 1965)
7. Design in geometric or weight polar properties if nonsymmetric (Tipping 1965)
8. Eliminate tangly parts (Iredale 1964; Tipping 1965)
9. Color code parts that are different but shaped similarly.
10. Prevent nesting of parts (Iredale 1964, Tipping 1965)
11. Provide orienting features on nonsymmetries. (Iredale 1964, Tipping 1965)
12. Design the mating features for easy insertion. (Iredale 1964, Tipping 1965, Baldwin 1966)
13. Provide alignment features. (Baldwin 1966)
14. Insert new parts into an assembly from above. (Tipping 1965)
15. Insert from the same direction or very few. Never require the assembly to be turned over. (Tipping 1965)
16. Eliminate fasteners. (Iredale 1964)
17. Place fasteners away from obstructions.
18. Deep channels should be sufficiently wide to provide access to fastening tools. No channel is best.
19. Providing flats for uniform fastening and fastening ease.
20. Proper spacing ensures allowance for fastening tool.

Table D4. DFA Guidelines

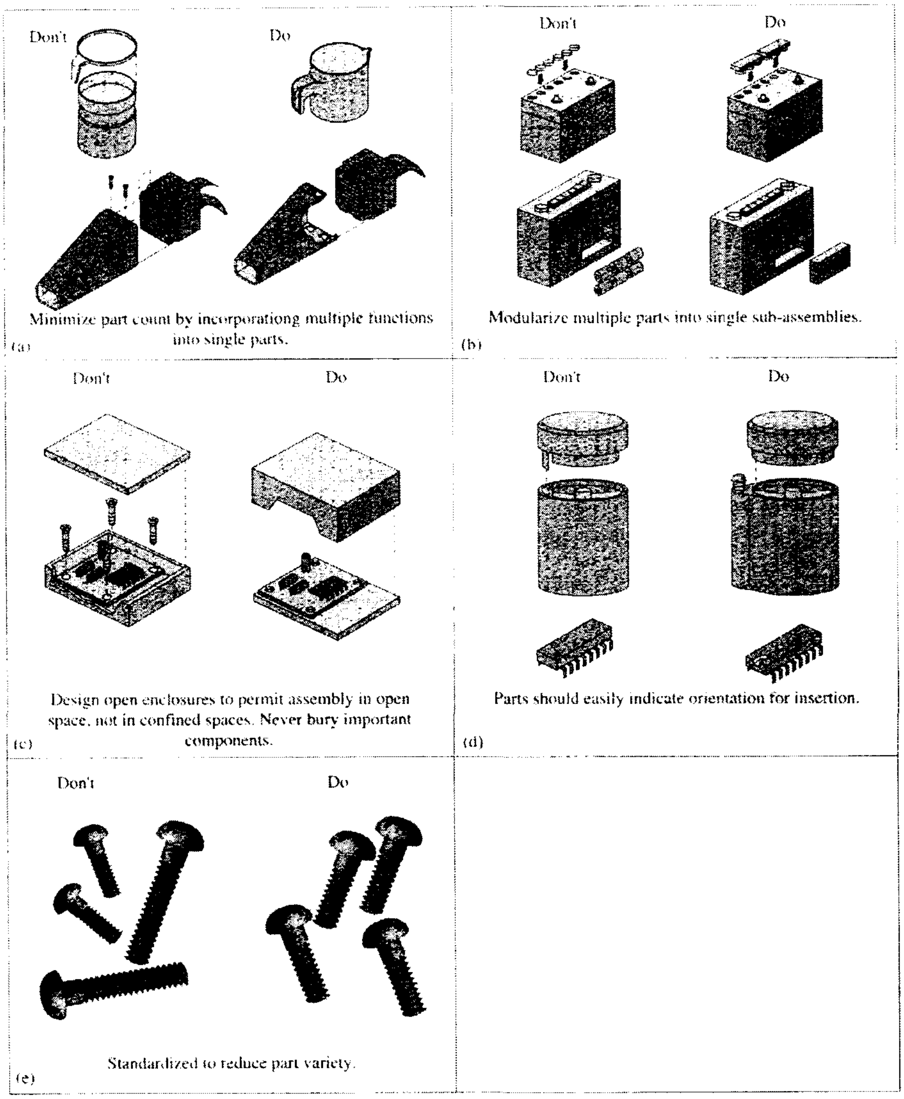


Figure D8. Design for assembly system Guidelines

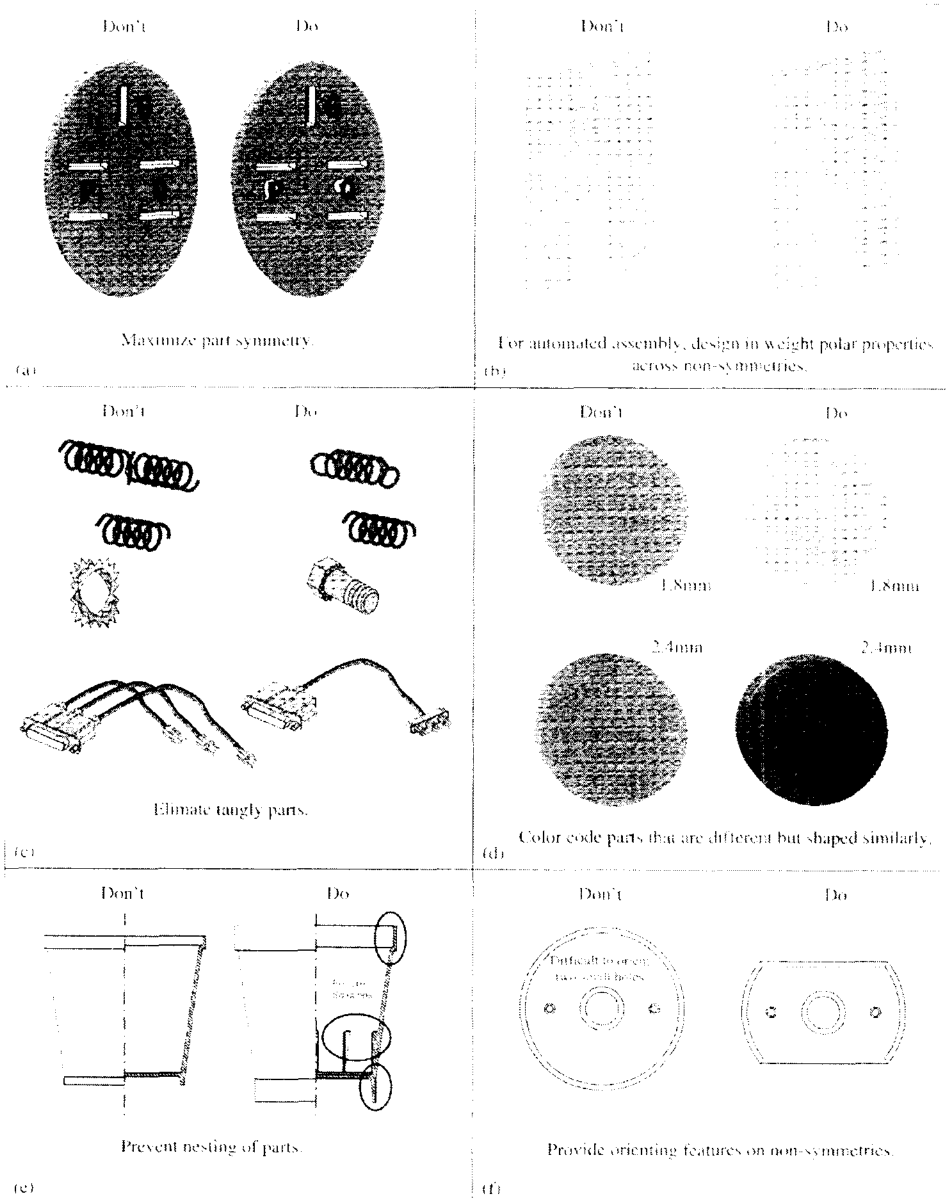


Figure D9. Design for assembly HANDLING Guidelines

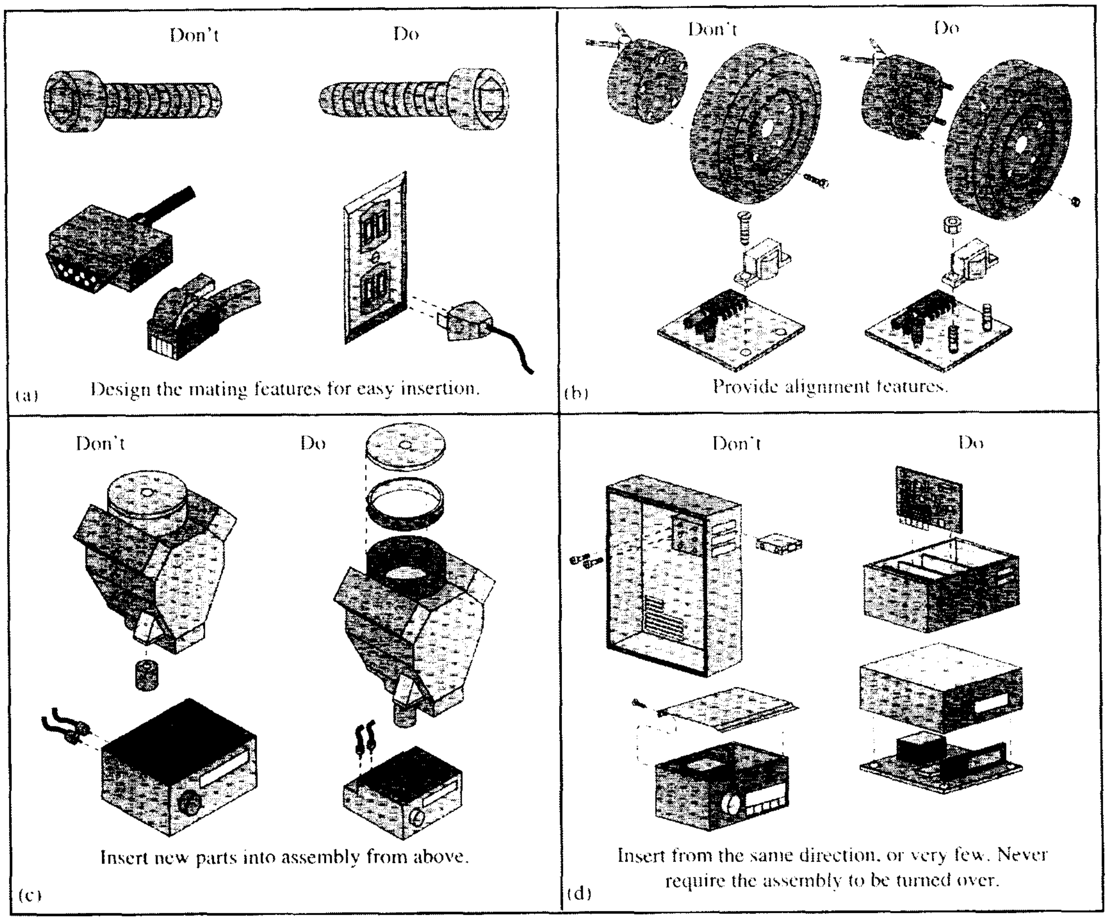


Figure D10. Design for assembly insertion design guidelines.

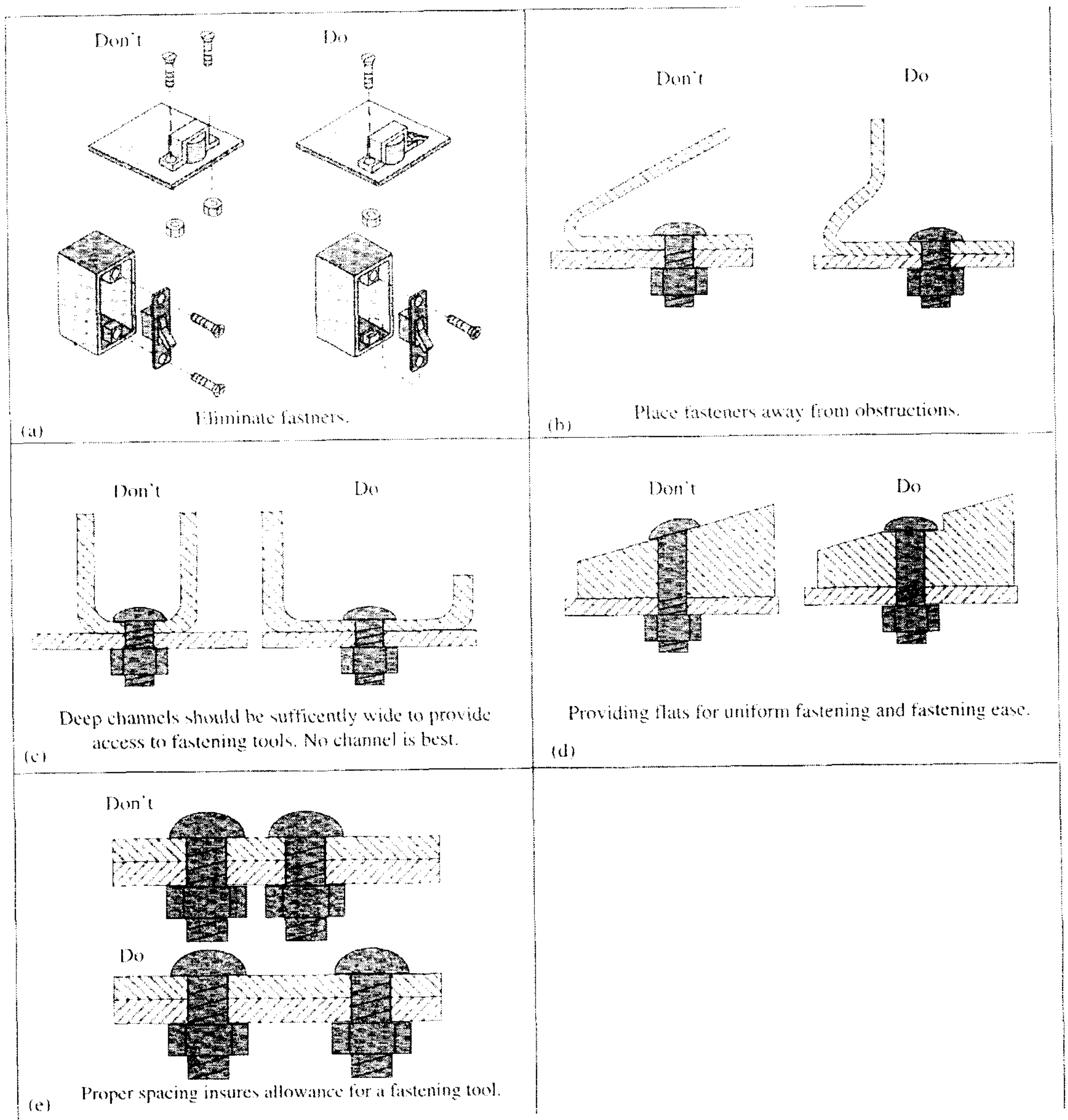


Figure D11. Joining design Guidelines

Theoretical minimum number of parts.

Assembly modules can always be defined; the module is simply a subassembly. The question is how to determine whether it is possible to combine parts into a larger, more complex part. A test of neighboring parts is proposed:

- Must the parts move relative to one another?
- Must the parts be electrically isolated?
- Must the parts be thermally isolated?
- Must the parts be of different materials?
- Does combining the parts prevent assembly of other parts?
- Will servicing be adversely affected?

If the answers are NO, then one should find a way to combine the two parts.

Variants Evaluation.

Similar to process selection, this process should be a team effort. Is a four-step process:

1. Define product function criteria
2. Define the importance of each criteria
3. Ranking the criteria
4. Evaluating the alternatives

Functions	Importance	Design Variants Alternative Blue	Alternative Green	Alternative Red	Alternative Orange
Total Weight	3	1	0	1	1
Dimensions	2	1	1	1	1
Air tightness	1	0	1	1	1
Stability	4	1	1	0	1
Noise level	4	1	-1	0	1
Material cost	5	-1	-1	-1	1
Production cost	5	1	0	-1	-1
....	....	....	....	....	....
....	....	....	....	....	....
Total +		5	3	3	6
Total -		1	2	2	1
Total		4	1	1	5
Weighed Total		13	-2	-4	14

Table D5. Variants Evaluation Example

Product function criteria.
The designer or the design team should choose the criteria for evaluate the alternatives. It has to be a very careful selection because on it depends the selection that is going to be made. Is recommended to follow the procedure described in the Forming Consensus on the Criteria step in the Selection process.

Define the importance of each criteria.
For each criteria it is very important to define a scale of importance, this will help designers to obtain a result weighed. This will help designers in focus on the criteria that is more important.

Ranking the criteria.
A team should consider each criterion once at a time and rank all the different alternatives on each criterion.
Rank the alternatives with a scale such as (-,s,+)

Evaluating the alternatives.
Once each criteria have an importance value, the alternatives should be evaluated using a (-1, 0, 1) scale on each criteria. Then add all the positives, all the negatives and obtain a final score. Using the importance value for each criterion, multiply for every alternative and obtain the final sum, the Weighed Total. Decide on the larger values.