POLITECNICO DI MILANO

DEPARTMENT OF MANAGEMENT, ECONOMICS AND INDUSTRIAL ENGINEERING

ROUGH PROCESS PLANNING FOR A SET-BASED CONCURRENT ENGINEERING DESIGN

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ABSTRACT

This dissertation examines the integration of Set-based concurrent engineering new product design approach and its requirements for rough production planning.

By delaying decisions, is achieved, and rework is eliminated. However there is no existing literature on a methodology for integrating design with manufacturing. According to many researches, the involvement of production or manufacturing function in early design process is of great importance. In fact, errors made during the early stages of design tend to contribute as high as 70% to the cost of production (Boothroyd, Bewhurst, & Knight, 1992) (Phal & Beitz, 1997). When Sobek et.al. 1999 devised the principle of set based concurrent engineering (SBCE), the interface between manufacturing planning and design process was highlighted (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999). SBCE methodology is proven to achieve lower time to markets, elimination of rework and development of successful products by considering sets of designs and converged gradually into one best design delaying decision making until more information is available. In particular, Principle 2 “integration by intersection” and principle 3 “Establish feasibility before commitment” address the communication and integration of design and manufacturing function to facilitate narrowing sets of design alternatives. However, the details and the levels of integration are not systematically investigated in their research. Indeed, it cannot give a concrete guideline and method to execute the principles. Such methods or guidelines will have dual purposes; designers able to narrow to optimal design alternatives taking manufacturing constraints and opportunities, and manufacturing will early be informed about the possible design alternatives so that manufacturing planning and execution follow smoothly.

Starting production planning after detail design will bring immense constraints and infeasibility from manufacturability perspective. That ultimately results in design rework and iteration which negatively affects time to market, cost and quality of the product given a certain process. In order to know and control the process cost from the beginning of the design, the manufacturing requirements of SBCE should be considered.

This thesis is an assessments of how companies with a Set-based concurrent engineering strategy for design prepare their production plan, paying much attention to the rough production plan, which is done during the early phases of design by analyzing a survey specially design for this purpose.

Key Words: Set-based Concurrent Engineering; Rough Process Plan; Manufacturing Process Selection.

1. Introduction

A new paradigm in engineering design, known as set-based concurrent engineering (SBCE), has been proposed which seems to offer advantages over more traditional techniques. Traditional methods of engineering design focus on setting requirements early, converging on a design concept rapidly, and then iterating over the design until it meets all specifications. In contrast, set-based methods delay fixing requirements and suggest that it is better to design a variety of concepts which would meet a range of requirements. Over time, as the customer's needs are better understood and the design problem itself becomes clearer, the range of designs is gradually narrowed, ultimately leading to one, globally optimal design. Set-based approaches to design seem to offer advantages over other methods in terms of improved design quality, reduced development risk, and shorter cycle times (Bernstein, 1998).

Conceptual Process Planning (CPP) is the activity of assessing the manufacturability and estimating the cost of conceptual design in the early product design stage. This activity aims at determining manufacturing processes, selecting resources and equipment, and estimating manufacturing costs and time. Conceptual process planning supports product design to optimize product form, configuration, and material selection to minimize the manufacturing cost (Song, 2000). CPP is done through five general steps; these are: *Matching* the design requirement and process attributes into the same 'language', *screening* through processes to eliminate those that cannot meet specifications, keeping a small subset of the original menu; *ranking* the surviving processes in order to identify those that have the greatest potential, gather *supporting information* about the top-ranked candidates to learn about its strengths, weaknesses, and history of use; and provide a *feedback* for future learning.

Even though there is a great number of literature related to SBCE and in CPP, and it is established that there is an important link with the communication with all departments involved, including manufacturing department; there is still a need for formal method/guidelines to align conceptual design and manufacturing planning to facilitate SBCE. Such methods or guidelines will have dual purposes; designers able to narrow to optimal design alternatives taking manufacturing constraints and opportunities, and manufacturing will early be informed about the possible design alternatives so that manufacturing planning and execution follow smoothly. And in sum, reduction in time to market, reduction in development and manufacturing cost, and quality improvements will be sought.

This thesis includes five chapter; Chapter I is for introduction and objectives, Chapter II talks about Set-Based Concurrent Engineering, Chapter III is about Design Processes and Manufacturing Plan; Chapter IV is Rough Process Plan; Chapter V is include the Industry Survey; then the last one Chapter VI is Conclusion.

1.1. Overview

This thesis study is divided into two main parts. At the first part of the study the main literature review about Set-based Concurrent Engineering (SBCE) methodology will be explained and rough process planning. The second part of the study includes an analysis of a survey sent to companies that operate in the automotive, aerospace and electro-domestic industries with the purpose of assessing the current state of their design process and their rough process planning.

Before to get in details; the scope, objectives of the study should be defined very well to be able to understand entire study.

1.2. Objective

The scope of this study is to understand the how the rough process planning is done in companies following set-based concurrent engineering principles. This objective is better understood if broken down into three sub-objectives:

Sub objective 1 - Assessment of presence of Set-Based concurrent engineering principles in the firm

Assess the methods and principles applied by companies when designing a new product, whether they use traditional design methods or pure set-based concurrent engineering methods; understanding how effective this method to the company; together with the tools used today by companies for this purpose.

Sub objective 2 – Assessment of integration the design to manufacture

If the companies operate using SBCE principles, to understand which are the manufacturing requirements for SBCE used by the company. If they don't, to understand whether or not the company has a rough process planning and which methods are used for it.

Sub objective 3 – Assessment of Manufacturing Process Product Preparation for Set-Based concurrent Engineering

Assess the rough process plan done by manufacturing companies, by identifying the methods used by companies in the following areas:

- Translation and matching design requirements with process attributes, listing which tools, methods and procedures are used.
- Screening of existing processes, discarding those that cannot perform the job.
- Ranking of possible processes and process chains is done and what elements are considered for this ranking.

- To understand if the company has a method of getting supporting information once the process chains have been reduced.

2. Set-based Concurrent Engineering

2.1. Chapter Introduction

It is impossible to define *Set-based concurrent engineering* (SBCE) without understanding where it came from. Set-based concurrent engineering is a new paradigm that fills the gaps left by its predecessor, point- based concurrent engineering (Bernstein, 1998). This section of the thesis is divided in three parts: the first one explains "traditional" design methods, while the second part introduces the main concepts of *set-based concurrent engineering*. The chapter closes explaining the benefits SBCE can bring to an enterprise.

2.2. Traditional design methods

In this section there are two traditional methods explained, both of which lead to the birth of Set-based concurrent engineering: Point-based approach and concurrent engineering.

2.2.1. Point-Based Approach

A Point-based design seeks to develop and select a single concept, i.e., a single *point* in the design space, as quickly as possible. Point-based design begins by defining the problem, and then generating many alternative solutions, preliminarily analyzing all solutions, and having engineers select the one with the most promise. Once one solution has been chosen, it is analyzed, evaluated, and modified until a satisfactory solution emerges. If the alternative is proven not to be feasible, then designers select another alternative and/or revise the problem definition, and begin the process again. The key point is that a *single* solution is synthesized first, then analyzed and changed accordingly-thus our term "point-based design." Figure 2.1 illustrates this point-based search process (Jeffrey K. Liker, 1996).

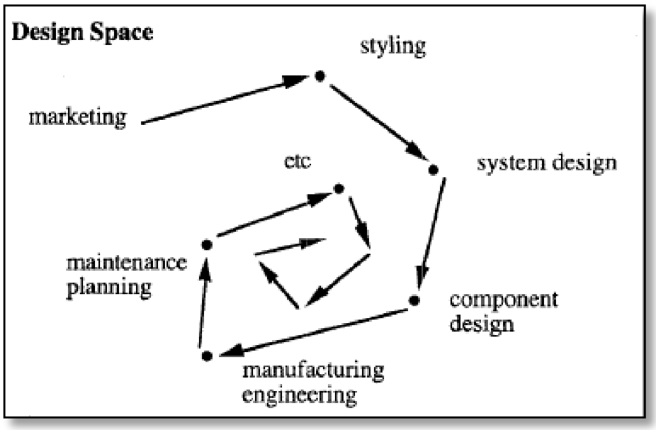


Figure 2.1. Point-based concurrent engineering (Jeffrey K. Liker, 1996).

In general, point-based strategies consist of four basic steps described in Figure 2.2 (Jeffrey K. Liker, 1996):

Problem definition	•Understand customer needs •Establish product requirements
Concept idea generation	•Usually during brainstorming sessions •A large number of ideas are brought
Select of a single solution	•Most promising solution is chosen •Through a preliminary analysis
Optimize selected concept	•The selected solution is analysis and modified •Until it meets customer requirements •It meets customer requirements = a solution is found •Throun away and repeat process starting from steps 1 or 2

Figure 2.2. Designing steps with a point-based approach.

The overall aim of these strategies is to identify the “best” solution to a design problem as early in the development process as possible, and to avoid wasting time considering other options. On the other hand, by selecting only one option when information is scarce the final solution might not be a global optimum. It also happens that the number of iterations around the spiral (see Figure 2.1) is generally limited by the available time and budget. There is a tendency to declare the design complete at the end of the scheduled time period, whether or not the design is optimal. Moreover, communication barriers were important players on the elongation of the design time, the problems with communication were so palpable that engineers often refer to throwing designs "over the wall" into the receiver (Rouse, 1989).

2.2.2. Concurrent Engineering

One step beyond point based design is what we today know as concurrent engineering. It is a variation of point based approach that involves the analysis in parallel of a specific design based on a request for analysis (Singer, Doerry, & Buckley, 2008).

Concurrent Engineering (CE) is an approach to product development in which teams work together from the requirements stage until production (Bernstein, 1998). Its main goal is to ensure that the requirements of all the stakeholders involved in the product development are met by keeping upstream activities from making choices that would increase the difficulty of downstream activities.

By identifying the problems that arise between various aspects of the design and production processes and based on the common point of view of people from different disciplines involved, it attempts to reduce the number of late changes, time-to market and cost as decisions at each stage of the product development (Liau, Young, & O'Grady, 1995).

2.3. Set-based Concurrent Engineering (SBCE)

A new paradigm in engineering design (SBCE) seems to offer advantages over more traditional techniques. As seen in previous sections, traditional methods of engineering design focus on setting requirements early, converging on a design concept rapidly, and then iterating over the design until it meets all specifications. In contrast, set-based methods delay fixing requirements and suggest that it is better to design a variety of concepts which would meet a range of requirements. (Bernstein, 1998)

Set-Based Concurrent Engineering (SBCE) was created by the Toyota production system (TPS), and it is referred as well as "The second Toyota paradox" following the first paradox which is its production system, that includes delivering just-in-time (Ward, Liker, Cristiano, & Sobeck, 1995). It is a technique used by Toyota engineers for the design of a new product, which different from traditional American way, decisions about details on the designs are delayed as much as possible while several possible solutions are explored (Ward, Liker, Cristiano, & Sobeck, 1995).

The Toyota processes produce world-class designs in a significantly shorter time than other automobile manufacturers.

Liker's findings while comparing Toyota with other American and Japanese automobile industries include the following:

- Teams define a broad sets of solutions (instead of one single solution) to allow concurrent design to begin
- These sets are retained for longer time, compared to the traditional design approaches, in order to gather more information and define tradeoffs,
- The sets are *gradually* narrowed, after extensive analysis of the set of solutions, until a more a single solution is revealed and refined. As the sets narrow, the level of detail (or design fidelity) increases, which provide more bases for better decisions about the future of the design.
- Once the team establishes a single solution for the design, it does not change unless it is absolutely necessary.

2.3.1. Differences between Point-Based, Set-Based and CE

Main differences between Set-based and point-based design resides on the timing and precision of specifications. Point-based design is based on the early specification of absolute design requirements leading to a selection of a single solution early in time so that the development of subsystems can proceed as early as possible, whereas set-based design approach requirements are represented as ranges and several solutions are proposed and gradually converged towards a final solution, giving more emphasis on analyzing possible solutions, which leads to greater knowledge on the design and improve the decision making process because it is now based on better information, eliminating the necessity of rework attached to its predecessor the point-based approach (Bernstein, 1998).

With a set-based approach, designs converge rather than evolve. Sets of possibilities are communicated, thus instead of carrying out a series of meetings in which a design is critiqued and modified several times as done in point-based design; designers, manufacturing representatives, supplier representatives, etc., bring to the table sets of possibilities and compare them to find intersections of feasibility. In the case of set-based approach, truly parallel design work is possible since decisions downstream are always compatible with those upstream. Trade-offs between alternatives from all functional perspectives is given greater consideration, and they are heard early in the process where decisions have the greatest impact. The process can be much quicker, and requires less frequent and prolonged communication, and less attention to design process structure (Jeffrey K. Liker, 1996). When using a set-based approach, flexibility to respond to a changing environment increases, because convergence to a final solution occurs closer to market introduction (Bernstein, 1998).

Compared to traditional design practice, SBCE casts a wider net at the start, and then more gradually eliminates weaker solutions. Design participants develop sets of solutions in parallel and relatively independently. As the design process progresses, they gradually narrow their respective sets of solutions based on additional feedback from product and manufacturing engineers, testing, customers, and others (Bernstein, 1998).

Finally, taking time up front to explore and document feasible solutions from design and manufacturing perspectives leads to gains in efficiency and product integration later in the development process and for subsequent development cycles.

Table 2.1. The comparison of Point-Based and Set-Based (Bernstein, 1998).

Task	Point-Based	Set-Based
Search: How to find solutions?	Iterate an existing idea by modifying it to achieve objectives and improve performance. Brainstorm new ideas.	Define a feasible design space, than constrict it by removing regions where solutions are proven to be inferior.
Communication: Which ideas are communicated?	Communicate the best idea.	Communicate sets of possibilities
Integration: How to integrate the system?	Provide teams design budgets and constraints. If a team can't meet budget or constraints, reallocate to other teams.	Look for intersections that meet total system requirements.
Selection: How to identify best idea?	Formal schemes for selecting the best alternative. Simulate or make prototypes to confirm that the solution works.	Design alternatives in parallel. Eliminate those proven inferior to others.
Optimization: How to optimize the design?	Analyze and test the design. Modify the design to achieve objectives and improve performance.	Design alternatives in parallel. Eliminate those proven inferior to others.
Specification: How to constrain others with your subsystem design?	Maximize constraints in specification to assure functionality and interface fit.	Use minimum constraints to allow optimization and mutual adjustment.
Decision Risk Control: How to minimize risk of "going the wrong path?"	Establish feedback channels. Communicate often. Respond quickly to changes.	Establish feasibility before commitment. Pursue options in parallel. Seek solutions robust to physical, market and design variations.
Risk Control: How to minimize the damage from unreliable communications; how to control communication?	Establish feedback channels. Communication often. Respond quickly. Review designs and manage information at transition points.	Stay within sets once committed. Manage uncertainty at process gates.

2.3.2. Principles of Set-Based Concurrent Engineering

Sobek summarizes the definition of set-based concurrent engineering (SBCE) as engineers and product designers "reasoning, developing, and communicating about sets of solutions in parallel and relatively independently" (Bernstein, 1998) and (Durward & Sobek, 1997). As shown in Figure 2.3, it begins by broadly considering sets of possible solutions and gradually narrowing the set of possibilities by converging them gradually to a final solution. The gradual elimination of weaker solutions, make finding the best or better solutions more likely (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999) because more time is available for the analysis of these solutions and decisions can be made based on more and better information.

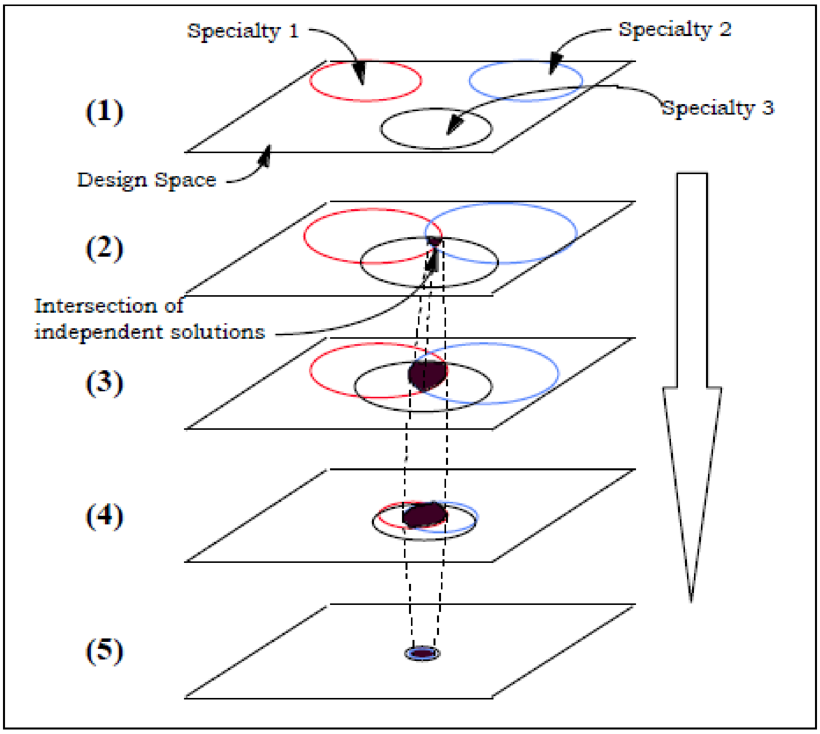


Figure 2.3. Set-based concurrent engineering design: Convergence of possible solutions (Bernstein, 1998).

A set-based concurrent engineering design process is identified by three main principles, which are shown in Figure 2.4. These principles create a framework in which design participants can work on pieces of the design in parallel yet knit them together into the system (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999). These principles turn around the two basic components of SBCE: the development of sets of designs, and the improvement of inter and intra team communications.

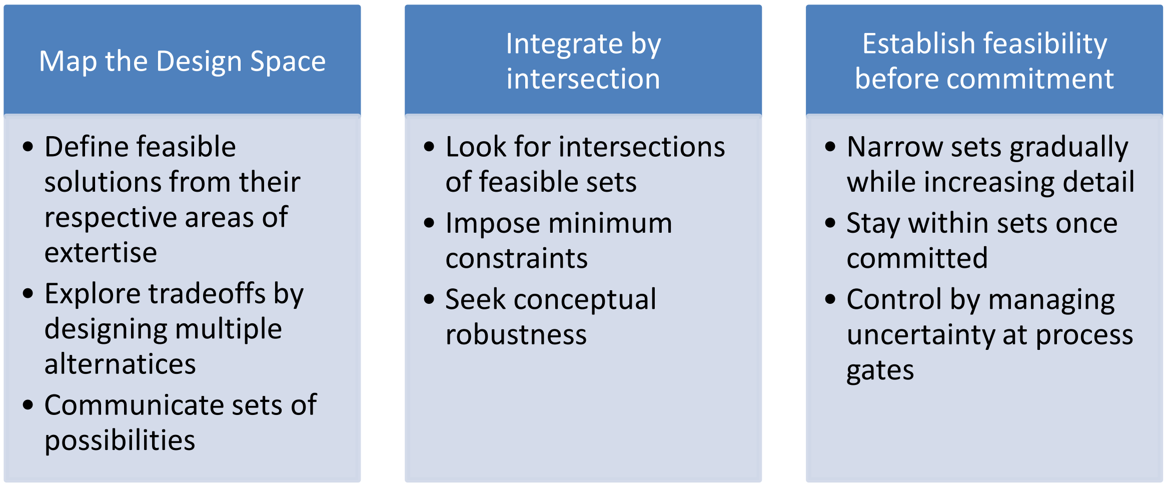


Figure 2.4. Set-based concurrent engineering principles (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

2.3.2.1. Map Design Space

To identify the set of alternatives or range of values to be carried forward, first the design possibilities have to be understood. All design contributors are free to develop their work, as long as they stay within the boundaries.

Define Feasible Solutions

Each functional department in parallel and relatively independently, determines the primary design constraints on its subsystem based on past experience, analysis, experimentation and testing, and other supporting information (Durward K. Sobek, 1996). By having all functional departments delivering their own ideas about solutions, a quality communication between upstream and downstream activities is ensured, because in this way what was previously considered as “implied information” is communicated in the form of a drawing, and misunderstandings are eliminated.

Every engineering function maintains checklist that details design guideline in several areas, such as functionality, manufacturability, government regulations, reliability and others. This documentation may also contain description of what can and cannot be economically produced along with solutions to past problems, information on how to accommodate new production methods like new automation, suggestion to improve quality, reduce cost, and enhance manufacturability (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

Explore Tradeoffs by Designing Multiple Alternatives

Toyota and supplier engineers explore trade-offs by designing and prototyping or simulating alternative systems and subsystems. Often trade-off curve that establishes a relationship between two or more parameters is more useful than trade-off data on two or three alternatives. Whenever possible, engineers abstract from prototype data to establish mathematical relationship between design parameters and performance outcomes or use test data from a number of test pieces and interpolate relationships (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

The "explore trade-offs by designing multiple alternatives" principle is also seen in Toyota's supplier relations (called "design-in"). Toyota gathers ideas and information on trade-offs from its supply base before making basic decision on who will supply the part. After supplier selection, design and price negotiations continue (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

Communicate Sets of Possibilities

Toyota engineers communicate about sets of ideas and regions of the design space, not about one idea at a time. If the feasible regions outline sets of possibilities, and trade-offs help one understand the implications of choosing an alternative over another, then communicating sets enables functions to understand the feasible regions of others. An excellent solution from one perspective may be a poor solution from another, making it suboptimal for the overall system (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

The most straightforward of sets are discrete alternatives, lists of ideas, drawings and models. Sets might also be bounded intervals for parameters or open-ended intervals. Other ways to communicate information about sets of alternatives may include trade-off curves, nomograms, performance charts, and best estimates with "design tolerances" (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

2.3.2.2. Integrate by Intersection

This section is looking for solutions within the intersections of sets or intervals and smoothly refines the set by eliminating ideas not feasible from the manufacturing perspective.

Look For Intersections of Feasible Sets

Having communicated the possibilities, teams can look for the intersections of different functions where feasible regions overlap. Organizations that do not communicate sets and therefore cannot look for intersections often wind up trying to marry independently optimized components. Toyota, on the other hand, looks for solutions that optimize total system performance (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

Impose Minimum Constraints

Toyota often imposes constraints needed at the time, ensuring flexibility for further exploration or adjustments that improve integration. "Make each decision in its time" reflects Toyota's thinking more than the U.S. practice, which seems to be "make decisions as early as possible to avoid confusion" (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

Seek Conceptual Robustness

Taguchi popularized the concept of robust design that is designs which are functional regardless of physical variations such as wear, manufacturing variations, and weather. Recently robustness to market variations has also increased in popularity. Strategies such as short development cycles, manufacturing flexibility and standardization help get a product idea to the market faster and thereby decrease design susceptibility to changes in market demand or competition. The last principle embodies these two thrusts and extends it to include robustness against design uncertainty: create designs that work regardless of what the rest of the team decides to do. If one function can create a design that works well with all the possibilities in another function's set, it can proceed with further development without waiting for information from that function. Such "conceptually robust" (Chang, et al., 1994) strategies can collapse development time significantly while providing other benefits such as ease of module upgrades and serviceability (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

2.3.2.3. Establish Feasibility before Commitment

Toyota's entire set-based development process might be viewed as a way to ensure that designs are feasible before committing to them (Toyota's conservatism is well known in the industry). By exploring multiple designs in parallel, and only gradually converging on a single one, Toyota avoids late problems (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

Narrow Sets Gradually While Increasing Detail

As the set grows smaller, the resolution of each idea or design grows sharper. In this way, the design team more fully understands the relevant space of considerations before committing to a design. Functions narrow their respective sets in parallel, communicating throughout to ensure that each function converges to a solution that integrates with the overall system. Eliminating ideas in stages allows participants time to consider the most important alternatives more fully, and gives them time to react and to influence one another's narrowing process (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

Stay within Sets Once Committed

The value of communicating about sets is limited if a team member jumps to a solution outside the originally communicated set. Participants must stay within the narrowing funnel so other team members know that they can proceed with further design work without concern for changes that causes rework. This approach can be followed only if design teams maintain robust sets that contain at least on workable solution. If a new solution does not work by a specified cut-off date, the team resorts to the back-up solution (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

Control by Managing Uncertainty at Process Gates

US companies view design processes as networks of tasks, and control them by timing the information hand-offs between the tasks (as in the familiar PERT chart). But Toyota views its process as a continuous flow, with information exchanges as needed.

Toyota manages this process through a series of gates, each of which is tied to an integrating event that brings all the pieces together, e.g., a vehicle prototype. Toyota controls the level of uncertainty at these gates, reducing it with each successive gate. Uncertainty includes both the size of the set still under consideration, and the depth of knowledge acquired--have we proven feasibility. Each area of the vehicle has different uncertainty requirements at different stages in the process (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

This approach appears to provide much better control over the process than the standard US approach. The control may contribute to the rigidity of Toyota's development schedules (Toyota people say, "Sometimes they move the due dates up, but never back"). In the US system, tasks hand-off partial solutions to each other, knowing that changes will result from later events. It is therefore difficult to evaluate the quality of the information being transferred, and managers frequently complain that the gates are not taken seriously. At Toyota, though, each gate obliges every function to report, in effect, "We know that a good solution lies within the set of possibilities defined here." Thus managers can more accurately determine development status (Durward K. Sobek, 1996).

2.4. Benefits of SBCE

When engineers look at the cost of a project most try to predict the final cost of a product and match that to a budget, but towards the end of the cycle very little can be done to control costs, and normally costs increases due to changes to optimize the design. As shown on Figure 2.5, 70% manufacturing cost and time of products are already committed during the conceptual phases

(Boothroyd, Bewhurst, & Knight, 1992), (Phal & Beitz, 1997). One issue a design program has is that the program does not incur major portions of the total cost of the product until very late in the development cycle while the program committed to these costs very early in the program.

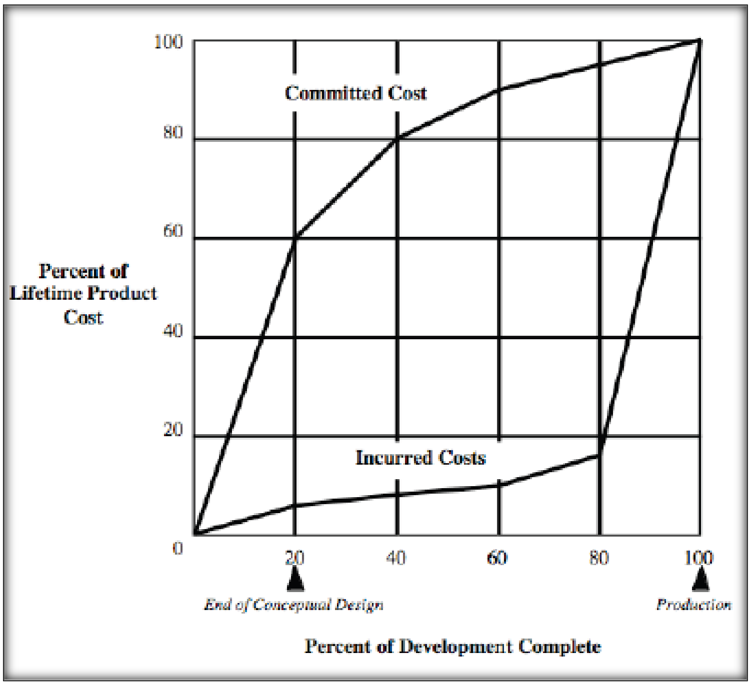


Figure 2.5. Design committed and incurred Cost (Bernstein, 1998).

As you can see in Figure 2.6, in any design, knowledge increases over time (Bernstein, 1998). Early in the design process engineers and managers know very little due to the fact that the details concerning the design are neither well defined, nor developed nor understood. Consequently, decisions during the early stages of product development are made with incomplete data. As the design evolves over time the engineers, managers and customer better understand, due to analysis and experience, the product and the requirements that are driving the product design (Bernstein, 1998). By developing, analyzing and converging sets of concepts, SBCE provides better controls for committed costs from the beginning of design, providing an important effect on evolution of design knowledge.

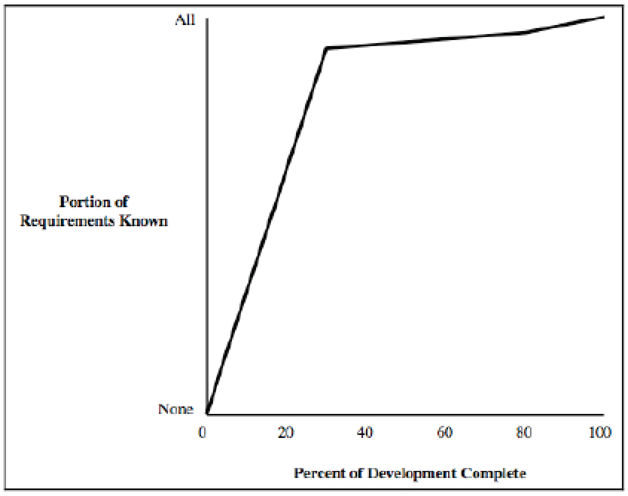


Figure 2.6. Evolution of design knowledge (Bernstein, 1998).

All stakeholders have the greatest impact on any design during the initial stages of the design process. At this stage, the design and its requirements are a blank canvas and any decision made obviously has an impact on the final product performance and cost. As the design matures, stakeholders' ability to impact the design diminishes because the design becomes more locked in (as represented by the Committed Cost curve) and any major change, cost prohibitive. As stated earlier, one of the goals to use SBCE is the delay of critical decisions to the latest point possible. By delaying decisions, one can improve the design by delaying the commitment of cost until later in the design process and until such time that our information is much better. By delaying the cost commitment also the time is increased in which stakeholders can influence a design. This can be seen in Figure 2.7.

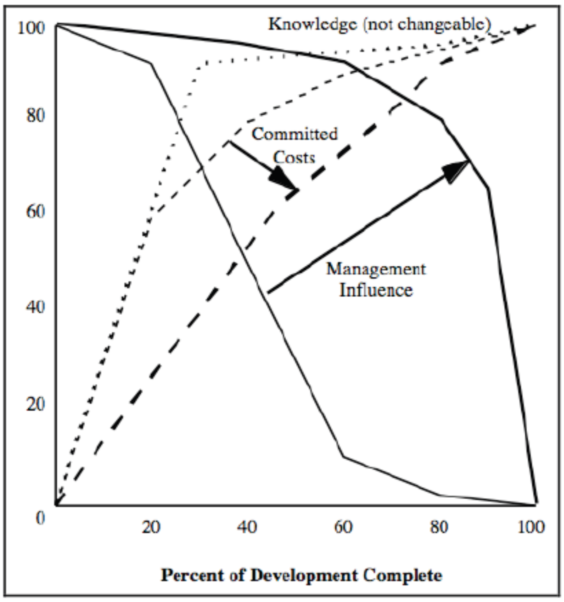


Figure 2.7. Advancing product development practices (Bernstein, 1998).

3. The Design Process and to Manufacturing Process Planning

3.1. Chapter Introduction

The increasing challenge of competing in the global rival market environment is forcing organizations to reconsider and often revise their business development strategies (such as innovation, operation and marketing strategy) in order to improve competitive advantage (Rasli, 2011).

Manufacturing competitiveness means sustained growth and earnings through building customer loyalty by creating high value products in a very dynamic global market. In order to remain competitive, companies are compelled to produce low-cost and high-quality products in nowadays highly competitive environment. The new product design and development task is a highly iterative process which involves a substantial heuristic knowledge component (practical knowledge) about areas of customer requirements, product design specifications, production and tooling requirements, etc. Product designers are required to possess a high standard of specific knowledge and experience because design decisions require intensive knowledge and interaction between different parameters. Product design does not result from a sole quantitative analysis but comes within a range of design procedures and decision makings (Yang, 2008). Figure 3.1 represents the decision phases of design and manufacturing.

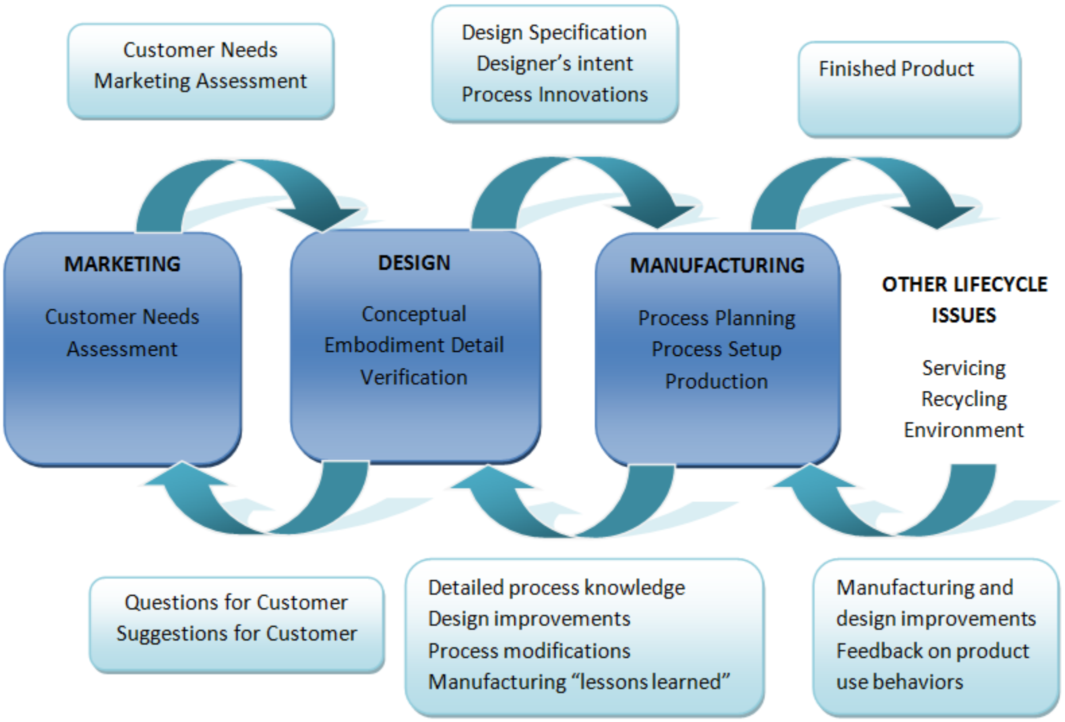


Figure 3. 1. The main phases of design and manufacturing (Herrmann, et al., 2004)

The product improvement starts with marketing research. The most important resource is the results of the questionnaires which are done normally by the customer. The results are assessed and the product requirements should form the design and manufacturing goals of the company.

Design department has three parts: Conceptual – Embodiment - Detailed design. Conceptual design translates the product requirements into the workable concepts but at a low level of detail. Embodiment design uses the result of conceptual design level to a level of detail where it can be implemented. The last part is detailed design which completes all details of an embodiment design for production to take a place (Herrmann, et al., 2004).

The detailed design is sent to manufacturing department. The first phase is process planning, then process set up and the last one is production.

3.2. Stages of Design

From the conception of an idea, several steps are needed in order for that idea to become an actual product. In Figure 3.2 the phases of product development are shown. This idea needs first to be expressed in terms of the expected detailed 'functionality' for the product-to-be, then these functionalities need to be translated into certain engineering requirements and just then the concept design starts.

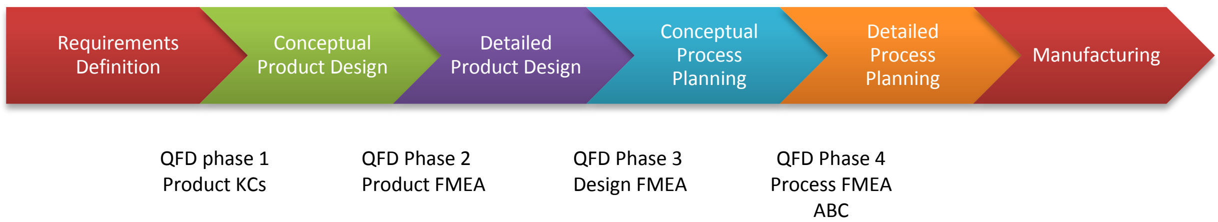


Figure 3. 2. Product development phases (Alaa Hassan, 2010).

Product design begins with a need and ends with detailed drawings and all the accompanying information necessary for manufacturing the product (Sharma & Gao, 1997). Much research has been devoted to the theory of design, in most literatures it is described as a complex iterative process and in most studies it is divided into two, three or four stages, begin four the most common. Extensive comparisons of the various systematic modern design methods can be found in literature (Sharma & Gao, 1997) and (Phal & Beitz, 1997). As an instructional approach, we present them in two stages, mostly by combining together the three first because they are all characterized by the fact that, because of uncertainty, the provide very limited information about the design.

The new design of process starts as a result of market and customer needs. The companies have to keep abreast of all the latest developments in market and consider about the demands of customer which they concern high quality and short deliver times. In this situation companies have to react quickly and economically to customer demands.

For the purpose of this thesis, we will show design can be divided as follows:

1. Early design stages (a.k.a. progressive design): where the designs are still being explored and compared. The design data provided at this stage is mainly characterized for being incomplete and abstract.
    a. Design Specifications: where the customer needs are analyzed and translated to functional requirements. Different tools can be used at this stage, QFD phase 1 is one of the most used.
    b. Conceptual product design: It is generally the stage where the design's basic function, geometry and material are least tentatively specified. This stage is explained more in depth in the following section.
    c. Preliminary design (or embodiment, or fundamental design)
2. Detailed design: where the design selected during the early stages is refined.

3.3. Conceptual Product Design

Early design begins with the initial discussions of a product's functionality, and ends when its basic function, geometry and material have been at least tentatively specified. Although, conceptual design has the greatest potential impact on the product's long term success, it remains poorly understood and supported (S. D. Kleban, 2001). According to Kleban et al., characteristics of early design include:

- **Teams are only partially formed.** As a rule, small teams of designers and engineers perform early product design. Manufacturing process engineers, reliability engineers, testing people and similar specialists typically join the team as the project moves into later stages.

- **Early design teams are closely coupled.** Classical project management and planning is based on a well-structured series of activities specified in a work breakdown structure. In contrast, early design seems to take place in small, tightly coupled teams, whose organization and interactions are not well structured.

- **Early design decisions have greater impact on the overall project and product than decisions made later in the life cycle.** Because little has been decided about the product's form and function in early design, each decision has tremendous leverage in reducing the range of possible product designs and manufacturing options.

- **Much information that is important in early design tends to resist formalization.** Because so little is known about the product in early design, and because so many possibilities remain open to the design team, the processes and information used in early design resist formal characterization and offer little structure for coordinating group activity. Because later stages of design have gathered more information, projects have both greater need and ability to use formal design representations and the infrastructure that goes with them. In early design, people tend to rely more on ad hoc representations (sketches, short memos, etc.) and communication (e-mail, hallway conversations, etc.) It is important to develop flexible tools that capture the decision-making process during conceptual design.

- **There are few tools to support conceptual design.** Product design typically begins with a general, often ill defined, set of requirements, and proceeds at a conceptual level until the rudiments of functionality, geometry, material and usability have been articulated. At this point, projects enter a detailed design phase, where all team members agree on the artifact's basic shape and function, and work to refine this design.

- **Early design synthesizes multiple points of view**. Before product design can move into the detailed phases, the design and engineering team must address a wide variety of issues in at least a high-level manner. Making early decisions on issues as diverse as geometry, function, material, manufacturing processes and product maintenance is more than a problem of gathering large amounts of information; it also requires a synthesis of different points of view. Early designers should evaluate all effects of such decisions.

- **Early design is opportunistic.** Unlike later phases of design, decisions made in early design often effect radical changes in a product's geometry, material or function. Humans tend to respond to the under constrained nature of early design by working at a high level of abstraction, and focusing on what they perceive to be important issues. This gives early design an opportunistic flavor: designers seem to move unpredictably from one issue to another, one day emphasizing functional constraints, the next day focusing on material, etc (S. D. Kleban, 2001).

All these characteristics have an important task to make a good start point of the product development process. According to the output of early design phase the detailed design is started.

4. Rough Process Planning

4.1. Chapter Introduction

Traditionally the selection of material and manufacturing process are done at the detail design phase, when the design is almost finished and some part have already been created. The critical parameters of material and production processes are not defined until the very last phase which forces the designers to make compromises to overcome critical issues. Companies want to know which the critical design parameters are in earlier time not in the detail design stage to avoid later costly impacts on the design. Changing the design towards the end of the design phases causes companies to spend even more time and money. Figure 4.1 shows the costs incurred and committed at different stages of the design. As a solution of this problem; the conceptual process planning was born. "An early integration of design, planning, and process seems necessary, since most of the cost comes from the product design phase. Design for manufacturing is but one step toward integrated concepts" (W. Eversheim, 2000) and (Lenau, 1996).

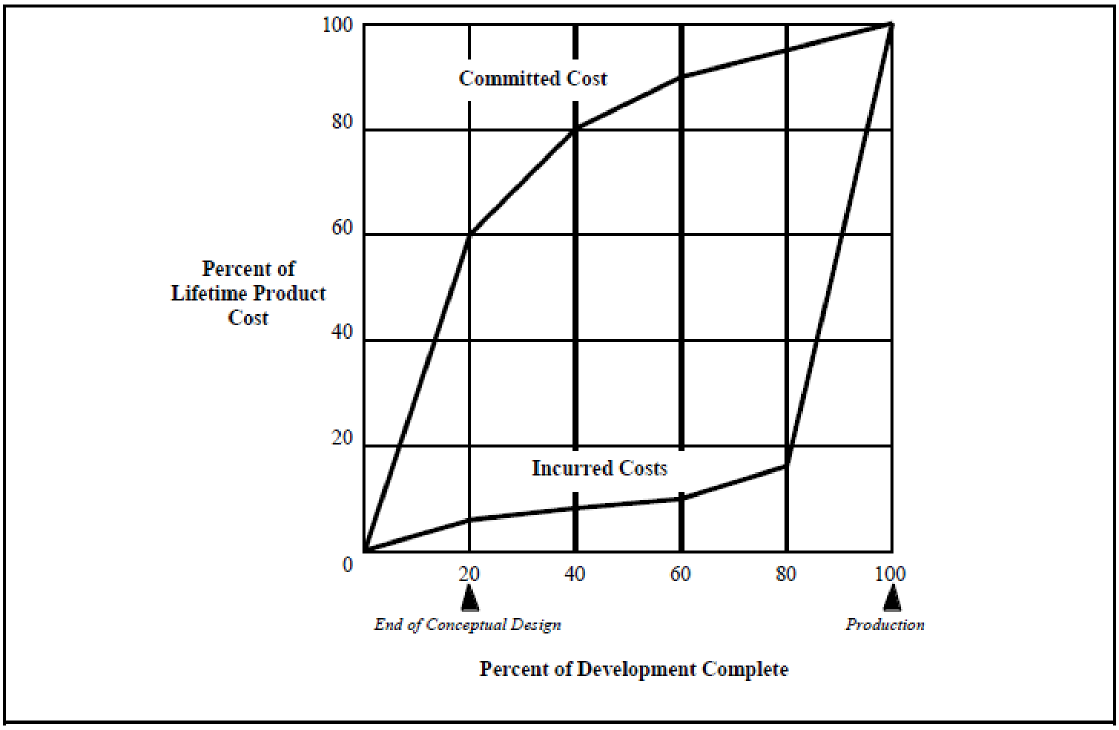


Figure 4. 1. Designing Costs. Even when the majority of designing costs are not incurred until late in the project, costs are commited to the product's lifecycle very early (Bernstein, 1998).

Spending more time on analysis and evaluation during conceptual design has the potential of reducing the overall time-to-market by reducing the number of design changes (Giachetti, 1998) and

(Boothroyd, Bewhurst, & Knight, 1992). The problem is that this phase is characterized by imprecision1. Most decisions can only be made when more information about design parameters and features are known and usually, at this stage, designers are pressured to optimize an inferior alternative rather than making larger modifications to the product specification.

Toyota's Set-based concurrent engineering paradigm is again applied on the material and process selection stage during the concept design stage. In order to optimize and make sure the best alternative is chosen, a set of possible materials-to-be-used and processes-to-be-used should be listed. These, as the design gets more specific, can be optimized and tuned in order to assure that the optimal alternative is chosen.

Conceptual Process Planning (CPP) is the activity of assessing the manufacturability and estimating the cost of conceptual design in the early product design stage. This activity aims at determining manufacturing processes, selecting resources and equipment, and estimating manufacturing costs and time. Conceptual process planning supports product design to optimize product form, configuration, and material selection to minimize the manufacturing cost (Song, 2000). Figure 4.2 shows a basic model of CPP.

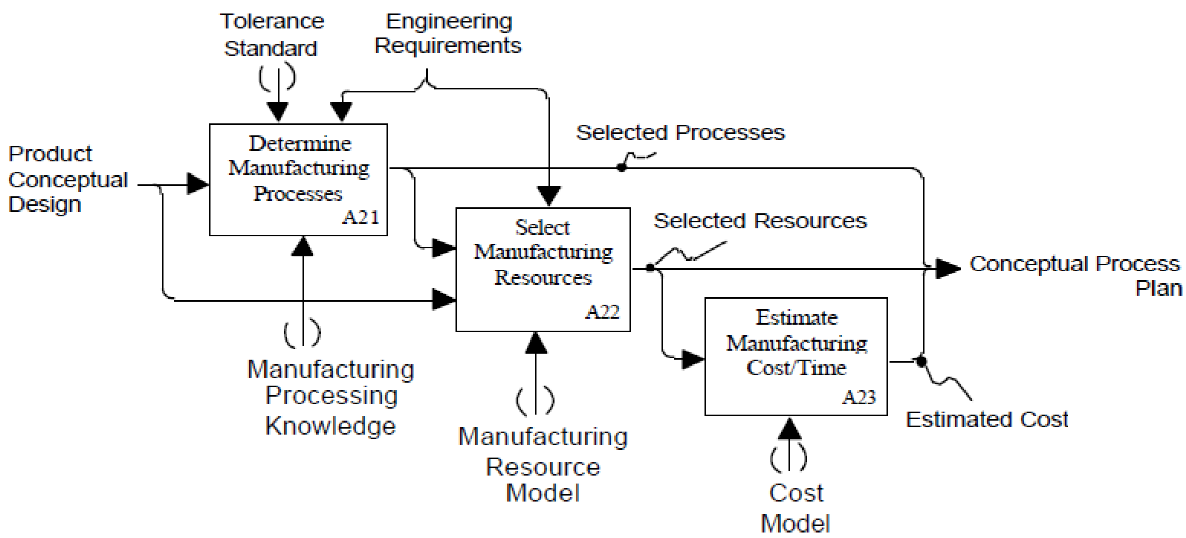


Figure 4. 2. Conceptual Process Planning Activity Model (Song, 2000).

After conceptual design, conceptual process planning starts, in Figure 4.3 the relation between conceptual design and conceptual process planning is shown. From conceptual design, data such as form, function, features, product quantity, and form properties (tolerances, surface conditions), are

[1] Imprecision refers to a vague and incomplete description of design requirements and design parameters.

sent to a conceptual process planner. These data describe the product and the reasoning behind certain design decisions, also referred as design rationale. They are sent to conceptual process planning as messages. The outputs from conceptual process planning, including manufacturing processes, equipment, and cost, are the manufacturability data. These manufacturing data are also captured in the messages and sent back to the conceptual design tools and designers. Designers receive the feedback of feasible manufacturing process(es), required resources, and estimated cost and redesign as necessary for better products (Song, 2000).

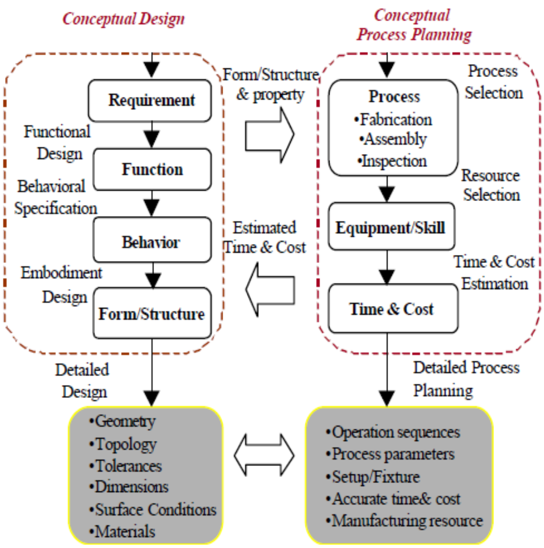


Figure 4. 3. Design and Process Planning (Song, 2000).

Conceptual Process Planning helps to move the decisions on materials and manufacturing processes to the formative stages of the design process. It has three main phases:

1- Determine Manufacturing Processes
2- Select Manufacturing Resources
3- Estimate Manufacturing Cost

Determining the proper manufacturing processes is based on the characteristics, properties and quantity of the product to be produced. The tolerance requirements of the design should be considered during the determination of manufacturing processes by the designer: tight tolerances usually require high precision machinery and skilled workers, thus, tolerances further narrow down the choice of manufacturing processes.

Selection of manufacturing resources is the second step of CPP. The resources of the system (machines, machines tools and fixtures, and labor skills) are selected.

The last phase of CPP is the estimation of manufacturing cost based on the selected manufacturing processes and the use of selected manufacturing resources. Manufacturing cost covers material, purchased parts, labor, tooling, capital and overhead.

Conceptual design defines the functions of products according to engineering requirements. The material, form, product configuration, features, tolerance requirements, quantity, and date of delivery are defined based on product functional requirements and transferred to the conceptual process planning software. The selection of process and resources, and the cost estimation are done by software. These results are sent to back conceptual design to decrease the cost and increase the manufacturability of design by designers.

4.2. Determination of Manufacturing Process at Conceptual Design Phase

4.2.1. Processes

A process is a method of shaping, joining, or finishing a material (Ashby M. , 1999). The choice, for a given component, depends on the design requirements (material of which of the material which is to be made, on its size, shape, and precision, and the batch size).

Each process is characterized by a set of attributes: the materials it can handle set of shapes it can make, precision, complexity and size of the piece.

4.2.1.2. Classification of processes

The kingdom of processes is classified according on what it does. There are three families: Shaping, Joining, and Finishing. Within the Shaping family, primary and secondary processes exist. Figure 4.4 shows a general classification of processes.

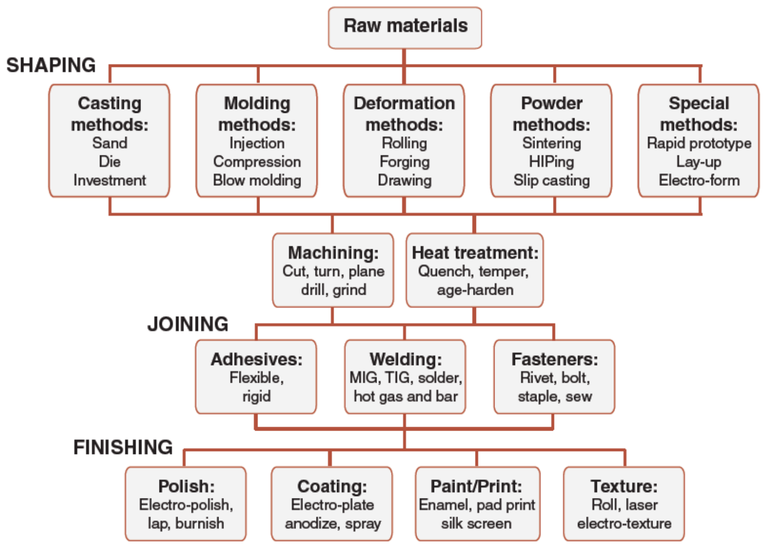


Figure 4. 4. Classification of processes (Ashby, et al., 2009).

Within these kingdoms, a hierarchical classification exists. Figure 4.5 shows an example of how the Shaping family is classified into class and members, where each member is entitled to a set of attributes that describe that specific process.

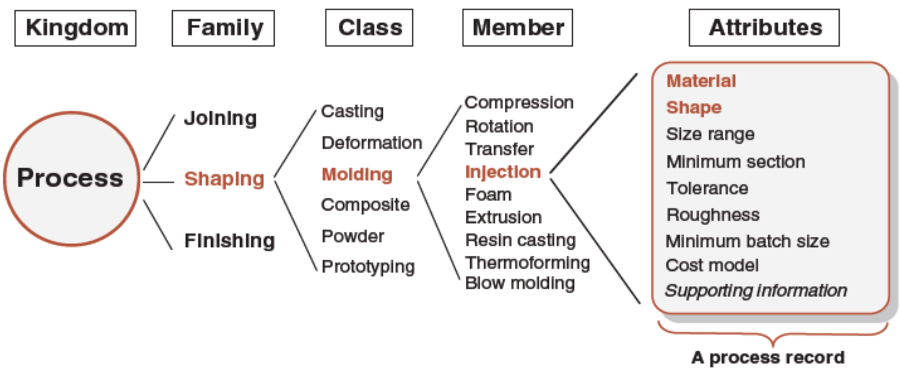


Figure 4. 5. The taxonomy of the kingdom of processes, with the shaping family expanded (Ashby, et al., 2009).

The kingdom of processes into three families: shaping, joining and finishing; each family contains many classes, some examples inside the shaping family casting, deformation, molding, composite, powder, and machining. Each class can be as well subdivided into members: casting contains sand casting, die casting, and investment casting for instance; while molding contains injection molding, extrusion, blow molting, among others. Each member subsequently has a number of attributes assigned to it (Esawi & Ashby, Computer-based selection of manufacturing processes: methods, software and case studies, 1998) & (Ashby M. , 1999).

An attribute is a particular subset of materials, sizes, shapes, tolerances, complexity among others in which the process member can be applied to. These attributes are recorded into a computer database, several can be found in the market, together with general information about the process, such as a schematic diagram of the process, a description of how it works, and typical uses and notes on its characteristics.

4.2.1.2. Process Selection

Selecting the right process and optimizing the design to suit the process selected involves a series of decisions which exert considerable influence on the quality and cost of components and assemblies (Swift & Booker, 2003). In the literature (M.F. Ashby, 2004), is written that selection strategy has three components:

- The formulation of constraints that must be satisfied if the material is to fill the desired function;
- The formulation of a performance metric or value function to measure how well a material matches a set of requirements;
- A search procedure for exploring solution-space, identifying materials that meet the constraints and ranking them by their ability to meet the requirements.

The goal of process selection is to identify systematically the match between the requirements of the design and the capabilities of the processes (Shercliff & Lovatt, 2001). There are four main approaches, developed through time, for determining a process plan for a new design at the conceptual phase. These are shown in Figure 4.6.

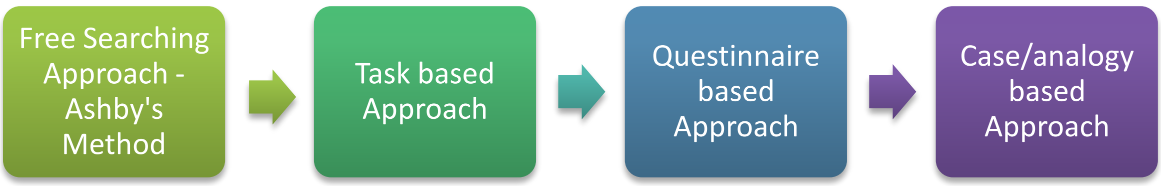


Figure 4. 6. The literature approaches for selection strategies.

All four approaches agree that the manufacturing process product preparation is an activity that includes five steps: of matching, screening, ranking, fine-tuning and providing feedback about possible processes that can be used on a specific design.

In this chapter the details and evolution of methods, procedures and tools are described.

4.2.1.3. Selection Strategies

In any approach, the goal of Process selection is to identify systematically the match between the requirements of the design and the capabilities of the processes.

As mentioned before, process selection has five phases; match design requirements with process attributes, process screening, process ranking and partial selection, fine tuning and supporting information for designers, summarized in Figure 4.7 (M.F. Ashby, 2004).

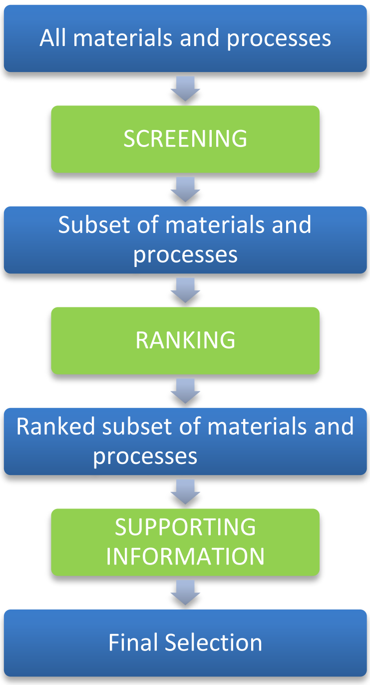


Figure 4. 7. Process Selection Phases (M.F. Ashby, 2004).

1. A **translating** method from design requirements into material and process attributes.
2. A procedure for **screening** out those processes that cannot meet specifications, keeping a small subset of the original menu.
3. A scheme for **ranking** the surviving materials and processes, identifying those that have the greatest potential.
4. A method for fine-tuning and gathering **supporting information** about the top-ranked candidates, giving as much background information about their strengths, weaknesses, history of use and future potential as possible.
5. A formal **feedback** method to increase the knowledge of the organization and progressively reduce time to market of new products through time.

4.2.1.4. Ashby's Approach

Ashby's method is based on free searching and quantitative analysis which offers great freedom of application; and it has the ability to reveal solutions that are new and innovative. However it needs detailed inputs in a form that can be analyzed by standard engineering methods (M.F. Ashby, 2004).

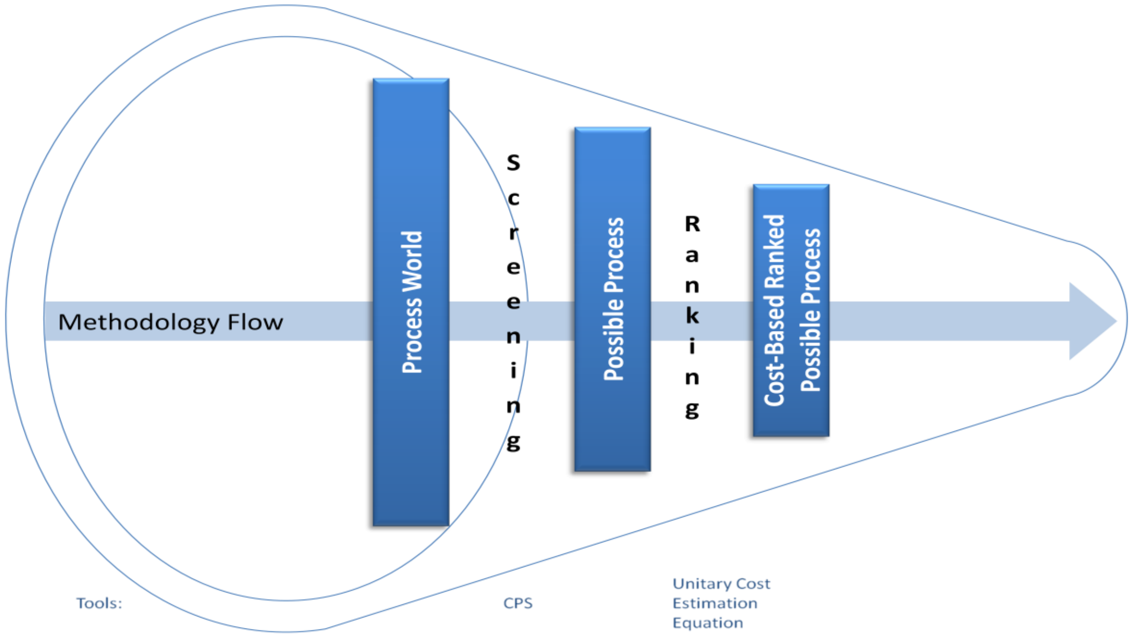


Figure 4. 8. Ashby's approach.

Ashby's approach recommends using multiple and compatibility charts, which process capabilities and design constraints are mapped to screen incapable process options. The complex matching and screening is done by Cambridge Engineering Selector (CES) web-based software. The processes that remained after screening are then ranked based almost always considering an estimate of the production's unitary costs (Esawi & Ashby, Cost estimates to guide pre-selection of processes, 2003).

Process Selection

Process selection is the action of matching process attributes to the design requirements (Esawi & Ashby, Computer-based selection of manufacturing processes: methods, software and case studies, 1998). It is an iterative procedure. The first iteration gives one or more possible process-routes. The design must then be rethought to adapt it, as far as possible, to ease of manufacture by the most promising route. The final choice is based on a comparison of process-cost. When selecting processes, the basic assumption is "all processes are candidates until shown otherwise."

According to Ashby, there are three main steps to follow when selecting a process: first, the design requirements need to be expressed in terms of constraints, meaning that the functionality and drawings need to be translated into the same terms used in processing; then, according to these constraints, a general screening of all available processes is performed with the goal of eliminating from the lists those processes that cannot meet the constraints. Finally, all capable processes need to be ranked, mainly according to economic criteria (Ashby, et al., 2009).

Expression of Design Requirements

The design requirements are expressed as constraints on material, shape, size, tolerance, roughness, and other process related parameter. For instance constraints in materials, or material groups to be used, maximum or minimum size of the piece, tolerances, roughness and other process-related parameters.

The steps of Ashby's method to translate of process requirements are:

- **Defining design function:** What must the process do? (Shape? Join? Finish?)
- **Defining constraints:** What material, shape, size, precision, etc. must it provide?
- **Defining objectives:** What is to be maximized or minimized? (Cost? Time? Quality?)
- **Free Variables:** Choice of process and process chain options.

Screening

Once the constraints are well defined, a screening of all processes is done. The goal of the activity is to drop out processes that cannot meet these minimum requirements, and keep on a list all processes that are able to perform the job. The screening process can be very complex due to the number of available processes and materials; therefore, the use of databases and computer software is highly recommended.

A typical three stage screening takes the form of Figure 4.9, where the attributes of processes are plotted as selection charts, created by the software. The attributes specified by the designer are plotted as selection boxes on the charts. The software then retrieves the subset of processes which meet all the required attributes. Any 'class' or 'numeric' attribute can be chosen. For example, in Figure 4.9, the left-hand chart selects a process of a given type ('shaping', for example) which offers a tolerance better than T1 mm. The second specializes this to those which can shape a chosen class of materials ('thermoplastic polymers', for instance) with a mass between S1 and S2 kg. The third isolates the subset of these which are able to create a given shape (such as 'three-dimensional solid, parallel features') and with a minimum section thickness as small as X1 mm. Further stages can be added. The number of stages depends on the number of attributes defined, and it is all up to the user. The selection is made by placing a selection box on to each chart, identifying the range of tolerance, size, quality and so forth, specified by the design. The effect is to eliminate the processes which cannot meet the specifications (Esawi & Ashby, Computer-based selection of manufacturing processes: methods, software and case studies, 1998).

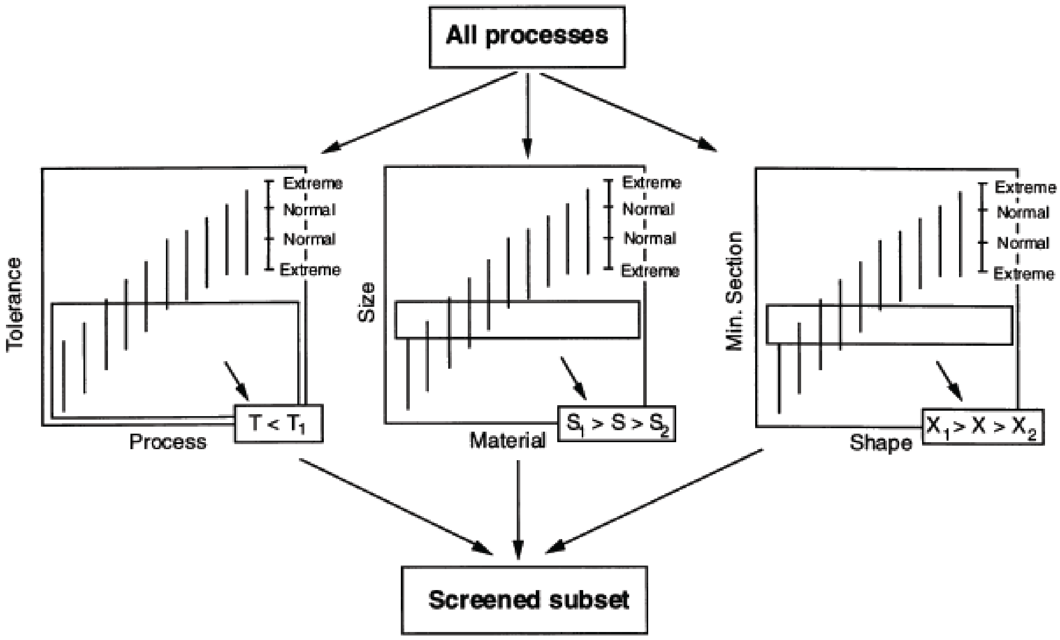


Figure 4. 9. A typical computer-based screening process (Ashby, et al., 2009).

Ranking

The processes that remained after screening are then ranked based almost always considering an estimate of the production's unitary costs (Esawi & Ashby, Cost estimates to guide pre-selection of processes, 2003). In order to estimate unitary costs, a batch size, or a set of possible batch sizes, should be defined. Different processes are suitable for different batch sizes.

These costs can be estimated considering three variables: the first describe the *consumables* (materials used per unit mass of product), the second uses the allocation fraction *tooling cost* to each unit of output, and the third measures the contribution of the time dependent *overhead cost*.

$$C_u = \left[\frac{m \cdot C_m}{1-f} + C_w\right] + \left[\frac{C_T}{n} + \left\{Int\left(\frac{n}{n_t} + 0.51\right)\right\}\right] + \left[\frac{1}{m} \cdot \left(\frac{C_c}{L \cdot t_{wo}} + C_{oh}\right)\right]$$

Equation 4. 1: Unitary cost estimation equation, used by Ashby (Ashby, et al., 2009).

Where C_m is the material used per unit produced; C_w is the cost of other consumables used such as energy; f is the fraction of material which appears as scrap, C_T is the total cost of tooling, n is the batch size, n_t is the number of units that the set of tooling can make before it has to be replaced. The term in curly brackets simply increment the tooling costs by that of one tool set every time $n > n_t$. Cc is the capital cost of equipment, *L* is the machines load factor, t_{ow} is the capital write-off time, C_{OH} is the overhead rate, and *m* is the rate of production.

4.2.1.5. Task Based Approach

Task based approach is developed as an improvement of Ashby's method, which proved to have limitations such as:

- The selection can only be based on parameters that relate process and design independently, where a number of issues arise when several important selection issues associate the combination of processes and design.
- There are poor considerations of material-related detail attributes.

A task-base methodology involves the consideration of attributes of the material, design and process which are relevant to the task in hand. Here, a Task is defined as a subset of processes applied to a subset of materials.

Theoretically task based approach improvement is on the determination of the detailed combinations of process that are both technically viable and cost effective. It also gives some idea of the necessary processing conditions and material specification for the given combinations in order to minimize productions trials (Lovatt & Shercliff, 1998).

The base assumption for task based approach is before selecting the processes; the design should be at a stage where the process and materials should be chosen from a specific set. There are three aspects addressed when selecting a process chain: performance, processability and cost. *Performance* shows; the component must be left with a satisfactory set of engineering and material performance characteristics after processing. *Processability* means; the process is able to modify, form or join the material in the required manner repeatedly and reliably. Processing the material in a given way must be reasonably economic (Lovatt & Shercliff, 1998).

The methodology, as shown in Figure 4.10, consists in two macro phases; the first one is called 'preliminaries,' which regards to the preparation process before the actual searching for a process chain; and the second phase where a procedure for selecting the process chains is described. These phases are described in the subsequent sections. According the literature Lovatt & Shercliff there are some constraints of task-based approach:

- Process chaining need to be considered directly.

- The selection is for one operation in one component (even when the process/machine will be used for other components in its life, the economic analysis should not consider this).
- Do not consider cost savings quantitatively (can be considered qualitatively).

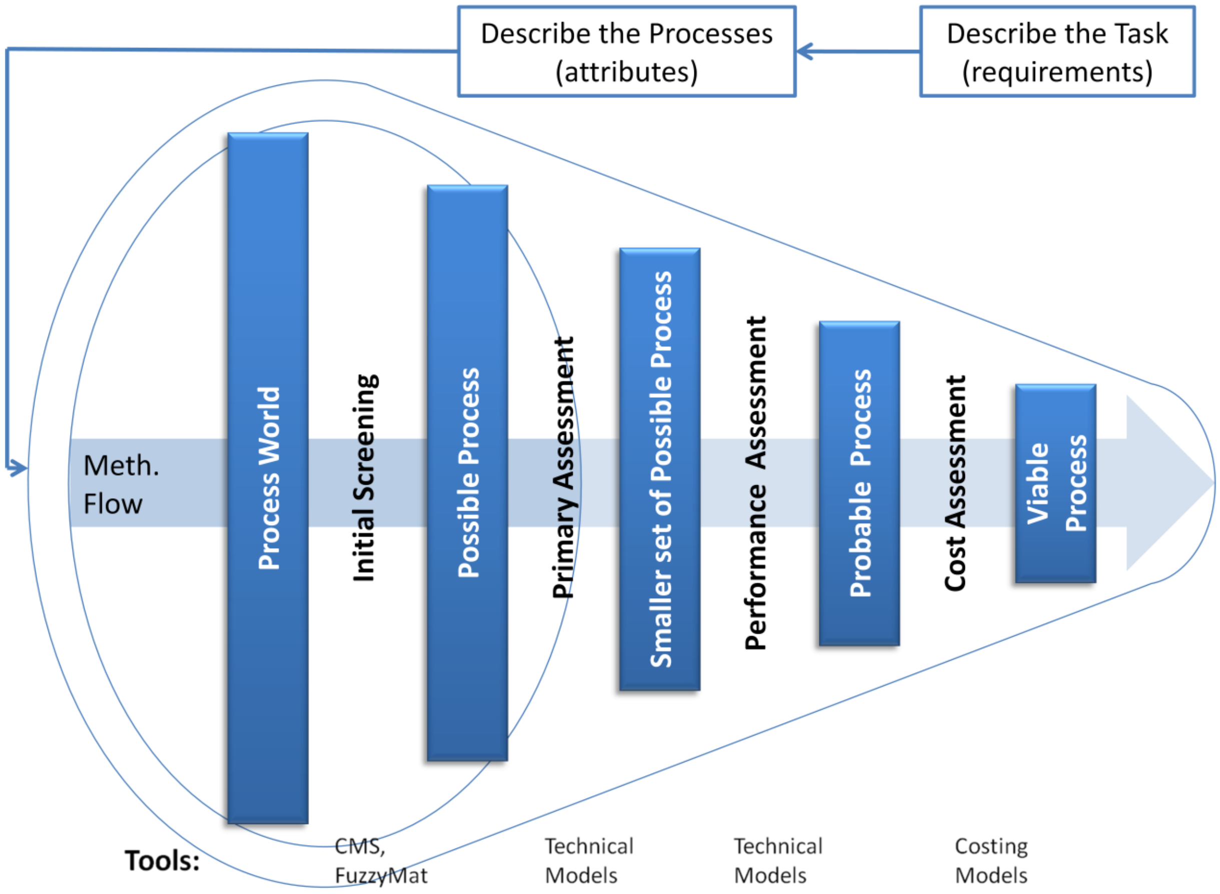


Figure 4. 10. . General Scheme for Task Based Selection Method.

Phase 1 – Preliminaries

This phase is to outline the task in detail, *specifying requirements and attributes* that will be used as inputs to the selection together with the results that will be needed.

Describing a task: the requirements

The first step is to specify details such as:

- The set of materials and processes that the procedure is to be created for;
- To what extent co-selection with material will take place;
- The scope of the design and manufacturing issues the procedure should consider; and
- The level of detail required of the results.

Specifying the task in some detail at the outset constraints the problem to facilitate decision-making and also clearly defines the assumptions that have been made in approaching those decisions.

Lovatt recommends dividing the requirements in three broad categories:

Design-related: Specifications found in the drawings such as size, shape or surface finish.

Production-related: Details required for the shop floor such as batch size, production rate.

Processing-related: In-process faults that may be reduced or eliminated at the design and production planning stage. These will generally be quite process specific, such as hot tearing for a casting (Lovatt & Shercliff, 1998).

Describing a task: the attributes

Attributes are parameters that describe a process and its capabilities in order to allow direct, objective comparisons to be made.

In order to simplify the determination of the most appropriate attributes, it is useful to split them into three classes: material-related, design-related and manufacturing-related. These classes are summarized in Table 4.1 (Lovatt & Shercliff, 1998).

Table 4. 1. Three classes of process attribute (Lovatt & Shercliff, 1998).

Class of Attribute	Type	Question to be asked	Other aspects	Examples
Material Related	Compatibility	Can I use this material with this process?		
Design Related	Primary	Could I ever make the design this way?	Generally geometrical attributes	Thickness of material at a desired speed for cutting, complexity of shape, overall size of casting process
	Processability	What problems can I expect?	List only problems related to poor design	Filling for casting, hot cracking for welding
	Quality	Can I achieve this specification?	Refers to quality after processing (include attributes addressed to performance requirements)	
Manufacturing Related	Cost	What is it likely to cost?	Include direct and indirect costs	
	Parameters	What parameters should I use?	Indicate operating conditions within which it is viable	Specifying arc voltage, current and traverse speed for MIG welding
	Indirect	What else might I need to consider?	Think of attributes related to the process but independent to the design & the actual processing that can affect the process	Machine size, the degree of flexibility of the process, the need for training and the type of production the process is usually used for

Attribute types: Some attributes may depend on the specific design, or may be influenced by some of the manufacturing parameters. Three types of process attribute can be identified, each implying different complexity in data storage: single values, ranges and functions.

- Single Values: usually for data that is specified qualitatively. It is useful to rank qualitative measures in such a way that they can be compared in order. i.e: for surface finish use "poor", "good" or "excellent."
- Ranges: state minimum and maximum possible values gathered from
  - empirical data from reference books;
  - data gathered from company data sheets and in-house knowledge; and
  - data inferred from generic process models.
- Functions: state, when existing, correlation between different attributes of a certain process. i.e: weld hardness in given steel depends on the speed and power used and the thickness welded.

Single values and ranges allow a quick, rough check to be made whereas functions allow a more accurate assessment at the expense of increased complexity. The type of attribute to use depends on the level of detail required, and the nature of the data available (Lovatt & Shercliff, 1998).

Phase 2 – Creating the Selection Procedure

This phase is to specify the relevant process attributes that will be used to describe the process in sufficient detail for selection to take place. It consists of 4 stages; three for technical evolution (initial screening, primary assessment and performance assessment) and one for economic evolution.

Initial Screening

It aims at eliminating quickly all processes that are clearly not viable, by matching requirements to a corresponding process attribute on a one to one basis. In principle, screening can take place for most requirements (with the probable exception of those related to in process quality), ranging from a design requirement (such as depth of a cut) to a manufacturing requirement (such as maximum size of machine). For many of the requirement attribute matches, there will be a clear yes no result. It is very similar to Ashby Cambridge Process Selector, with the difference that this last one has the limitation that attributes are predominantly design-related. For a deeper screening it is also necessary to establish material and manufacturing related attributes (Lovatt & Shercliff, 1998).

Primary Assessment

After the initial screening, some of the remaining processes might still not be viable due to interrelations between requirements and attributes. Reduce the options that remained after initial screening into a **smaller set of possible** processes, by assessing whether if they can achieve the basic production criteria when the primary technical requirements are considered.

Primary assessment aims to account for such correlations by the incorporation of models in Figure 4.11. The output of a model at this stage may include valid combinations of production attributes for the possible processes.

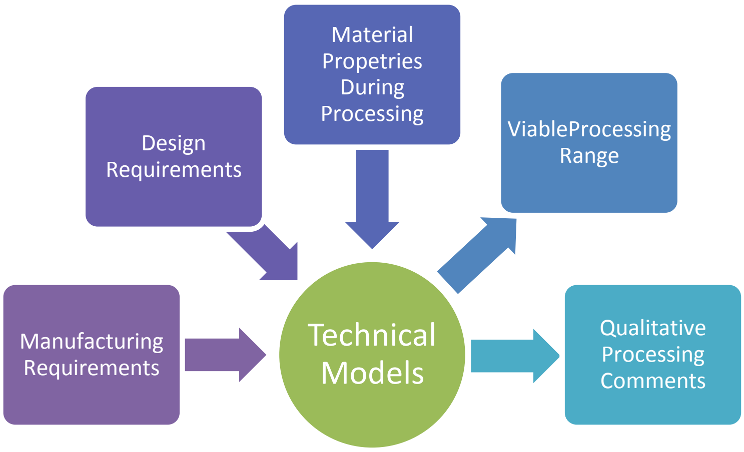


Figure 4. 11. Primary Assessment (Lovatt & Shercliff, 1998).

Performance Assessment

In order to leave only the **probable** processes, this stage removes all the remaining combinations that would encounter processability problems, or could not form the component to the specified performance requirements. Achieving a robust performance assessment frequently requires knowledge of production parameters which were determined in the previous stage. In addition, this stage should aim to refine the parameters to a level suitable for guiding production trials.

After the primary assessment stage, there is a reduced set of processes that should be able to form the component. It now becomes feasible to assess whether the performance requirements for the component can also be achieved. This involves examining both the processability of the design with the various process/material combinations, and the resulting engineering performance of the component. The interaction between parameters and requirements is now even more apparent, and at this stage it is likely that co-selection with material will be important. Accounting for these interactions will ideally involve the use of models in a similar manner to that detailed for the primary assessment but now, in addition, models involving microstructure and properties will usually be required, shown in Figure 4.12.

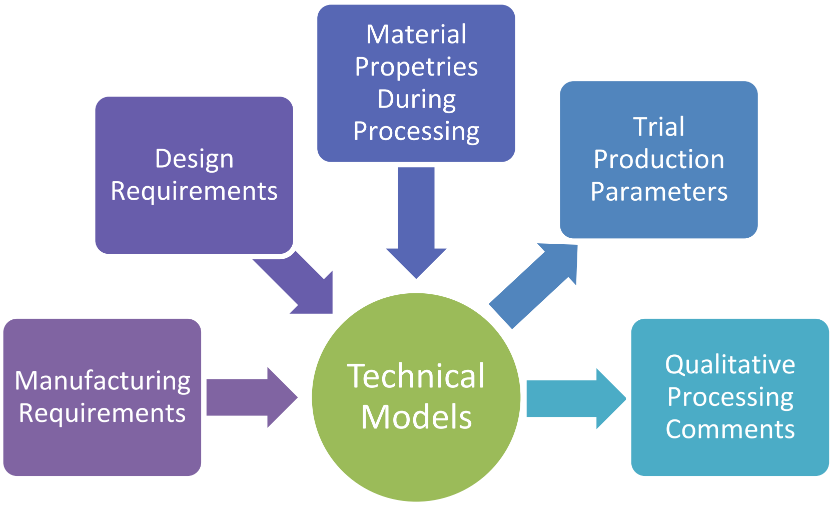


Figure 4. 12. Performance Assessment (Lovatt & Shercliff, 1998).

Economic Evaluation

The aim of the economic Evaluation is to reject processes that will clearly not be **viable** economically, rather than to try to produce an accurate costing. As a result, the only cost elements important at this stage are:

- Investment: one-time costs incurred to begin production, for example installation of equipment, and training.
- Operational: Day to day costs such as labor, consumables, power, maintenance and repairs.
- Overhead: includes costs that are not possible to track directly to the production, for example depreciation of equipment, heating and lighting, etc.

The relative proportion of these three groups depends on the type of production to be undertaken (mass, batch or one-off) as well as the particular process and component (Lovatt & Shercliff, 1998).

4.2.1.6. Modeling Tools used in Task-Based Process selection

This includes all types of technical modeling from empirical methods through knowledge-based systems to detailed physically-based modeling, and a variety of approaches to cost modeling.

Modeling should reduce the number of independent variables, or at least identify how they couple and vary. A good modeling practice is to maintain the process selection simple, it is also important to take full account of the uncertainties in the assumptions and the input data, and tests their effect on the output by sensitivity analysis (Lovatt & Shercliff, 1998).

Technical Modeling

Process modeling can contribute to the technical evaluation by introducing some predictive capability. A model may be a simulation at some level of abstraction of the process itself, or a critical part of it. Another important application of modeling is to describe the industrial tests which are commonly the basis for empirical rules for material behavior under 'standard' conditions.

According to Lovatt; models can be implemented in numerous ways, ranging from empirical to mathematically-encoded physical relationships:

- *Empirical Relationships*: empirical relationships for specific processing situations, often represented in the form of simple equations or visualizations.
- *Expert systems*: Embed rules gathered from experts which can subsequently be followed to outline solutions for new problems.
- Process charts: A series of bar charts indicating the valid process parameter ranges are often useful at the preliminary stages of selection (e.i. the process selection charts proposed by Ashby). It is also useful to define operating regions on two-dimensional charts with a different parameters or combination of parameters on each axis which help to reveal couplings between process parameters in a visual way.
- *Dimensional analysis*: This type of analysis can be useful when the process parameters are known, but their functional relationship is complex or unclear. It is particularly powerful for scaling between different conditions or materials, so that results from existing experiments can be extrapolated to provide predictions for new processing conditions. Dimensional analysis can also be used to reduce the number of parameters to be considered which therefore simplifies graphical mapping onto process charts.
- *Advanced statistical techniques*: An increasingly popular technique used for modeling deterministic problems where the physical behavior is complex is to use neural networks or other advanced statistical techniques. These methods are best applied when there is a large amount of empirical data available, but no obvious means of extracting quantitative predictions from it.
- *Physical Models*: There are two types of physical models that can be used: (1) *Constitutive modeling*: describes the material transport in the process using fluid-flow and plasticity, and to predict important characteristics such as temperature history using heat flow theory; and (2) *Micro structural modeling*: which predicts the behavior during processing (Lovatt & Shercliff, 1998).

Cost Modeling

- *Direct Cost Estimation*: the most basic relationship for costing purposes is the estimate for the direct process cost per part as a function of batch size and production rate. It comprises contributions from material, time-dependent overheads such as labour costs, and fixed costs such as capital:

Equation 4. 2. Direct cost estimation (Lovatt & Shercliff, 1998).

$$C_p = C_m + \frac{C_c}{n} + \frac{\dot{C}_L}{\dot{n}}$$

Where:

C_m is the cost of material per part

C_c is the capital cost

n is the total batch size

$\dot{C}_L$ is the labor rate

$\dot{n}$ is the production rate.

The main problem with this cost equation is that it does not take into account any influence that various characteristics of the design may have on cost.

- *Activity-Based Costing*: Although ABC is, strictly speaking, too detailed in scope for a costing system to be used during selection, some of the ideas it presents can be utilized. The ability to place costs on specific activities suggests a consistent method for comparing processes (this is especially useful for processes that are competitive in economic terms). In addition, it provides a metric for improvements by identifying the activities which are the dominant cost-drivers.
- *Technical cost modeling*: Standard ABC only employs simple constant. Monetary rates for allocating costs to activities. It would be useful if the effect of changing design or production requirements on a processing activity cost could be readily determined. This becomes possible if a combination of physical modeling and cost modeling is used, a technique known as Technical Cost Modeling (TCM) (Lovatt & Shercliff, 1998).

4.2.1.7. Questionnaire Based Approach

In principle, questionnaire-based approach is to present the expert with a comprehensive set of specific questions and solicit from the answers and the further questions that follow from those answers and the spectrum of answers to these, and the further questions until an unqualified answer is reached. Also therein lies its challenge: there has to be a definitive answer to every question, and further questions following from every answer until the end is reached; nothing can be left hanging. (M.F. Ashby, 2004).

Questionnaires guide the uninformed user through a more or less structured set of decisions, using built-in expertise to compensate for the lack of it in the user, particularly for secondary processes applied to components (such as joining and surface treatments) (C. LeBacq, 2002) and (Brechet, Bassetti, Landru, & Salvo, 2001). Questionnaires to guide selection of processes are constructed by documenting the ways in which experts do it (M.F. Ashby, 2004).

The questionnaire-based approach follows the steps described in Figure 4.13. The selection procedure relies on the transcription of technical requirements for a given joining problem into answers to a predefined questionnaire. When the first questionnaire is answered, for a given set of requirements, the user ends with a list of processes that are 'technically admissible'. Each of these processes may be characterized by three evaluations represented by marks between 0 and 10 (C. LeBacq, 2002): (1) a *technical evaluation* which represents the degree of agreement with the requirements expressed by the answers to the questionnaire; (2) a *local evaluation* which represents the current ability of the company to use the process; and (3) a *reputation evaluation* which indicates the perception of this process in the industrial field of the application (C. LeBacq, 2002).

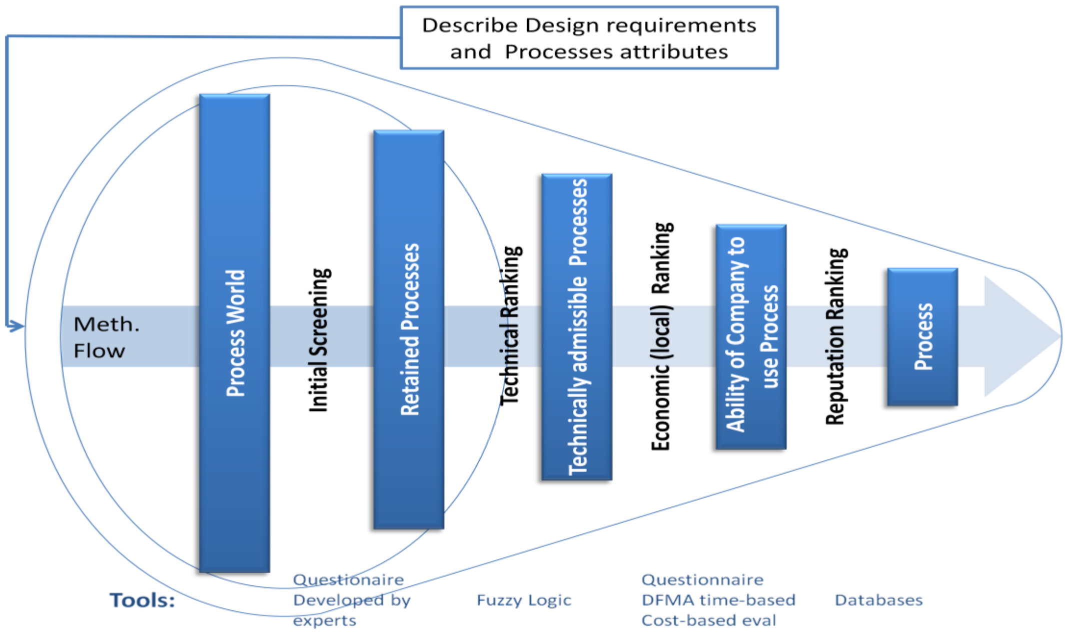


Figure 4. 13. Questionnare-based approach.

Technical ranking

The technical evaluation compares the answers to this questionnaire with information concerning each process, materials, and joint geometry stored in databases. The multi criteria evaluation is performed using a fuzzy logic algorithm, giving a numeric and qualitative evaluation of all feasible solution (called objective mark). Designers can change the importance of the different criteria that the ranking is based on.

Economic ranking (local evaluation)

Another questionnaire concerning the existence, availability, possibility to invest on equipments and skills is provided to evaluate the top options. A DFMA time based or cost based evaluations tools can be used for calculating the estimations.

Reputation ranking

The final ranking is concerning with the current industry acceptance and familiarity of process options. A data base is provided for different industrial sector

The important point is that, for the given selection problem, the data must be relevant, discriminating and available. The user is free to answer as many of the questions as he/she considers relevant for the design in hand the benefit of the questionnaire is that important criteria are not inadvertently overlooked (C. LeBacq, 2002).

4.2.1.8. Case/Analogy Based Approach

Case/analogy based approach is the last one for selection process; inductive reasoning has its foundations in previous experience. The inputs are design requirements expressed as a set of problem features; the transfer function exploits knowledge of other solved problems that have one or more features in common with the new problem, allowing new, potential solutions ('hypotheses') to be synthesized and tested for their ability to meet the design requirements (M.F. Ashby, 2004).

The use of analogy-based selection is clarified on Figure 4.14.The new problem is analyzed and its features identified. The cases are searched with features in common with the new problem. The new problem is tackled and (with luck) solved by adapting and combining elements of the selected 'cases' to meet the new need (M.F. Ashby, 2004).

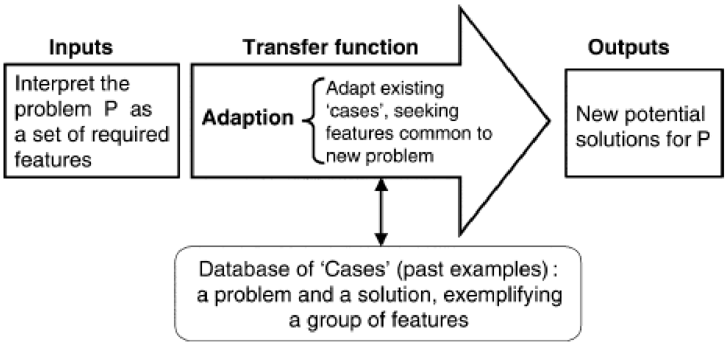


Figure 4. 14. Selection methodology by analogy based approach (M.F. Ashby, 2004).

4.2.1.9. Summary Selection Process Approaches

This part; the process selection procedures is figured for a wide range of manufacturing tasks. It is planned to provide more detailed selection information than is possible at the preliminary stages of design. Each approach has its own strengths and weaknesses. In Table4.2 the comparison is done for each approach according to the steps of selection process.

Table 4. 2. The Comparison of Process Selection Approaches

Approaches / Steps	Ashby's Method	Task Based Approach	Questionnaire Based Approach	Case/analogy Based Approach
Translation of Design Requirements	Requirements are expressed as constraints on material, shape, size, tolerance, roughness, and other process related parameters.	Claims that selection can only be based on parameters that relate process and design independently, where a number of issues arise when several important selection issues associate the combination of processes and design. It also claims that there is a poor consideration of material related detailed attributes.	Claims that Ashby's method is not well discriminating for secondary processes, where functional aspects are important, e.g. joining, finishing processes and finite life design. Expert based sequential questionnaire are provided to match between design requirements with joining process attributes. Geometry-Material-Function-Production condition.	Design requirements are expressed as a set of problem features.
Process Screening	Using multiple and step by step compatibility charts, process capabilities and design constraints are mapped to screen incapable process options. The CES web-based software makes complex matching and screening.	Similar to Ashby's	A transcription of technical requirements derived from the filled questionnaire appears in the same format as the database (that have process capabilities for process/material/geometry).	A library of previously solved problems or cases If appropriate indexing (word) for the cases' feature is given, the new problem will have the ability to be matched with the existing cases.
Process Ranking	Using economic batch size (used as screening as well) And, "Rough cost modeling" (material, capital, time, energy, and information costing	**Primary Assessment** Double check to be sure that remaining processes are possible considering interrelations between requirements and attributes. Use Technical Models **Performance Assessment** Select processes that ensure the performance required by the design. Tool: Technical Models **Economic Evaluation** Select processes that are economically viable. Tool: Cost models	**Technical ranking** Using fuzzy logic a comparison between difference processes can be made. The ranking gives numeric and qualitative evaluation of all feasible solution, and designers can change the importance of the different criteria that the ranking is based on. This option gives to have "effective ranking". **Economic ranking (local evaluation)** Another questionnaire concerning the existence, availability, possibility to invest on equipments and skills is provided to evaluate the top options. DFMA time based or cost based evaluations are also possible though for secondary process **Reputation ranking** The final ranking is concerning with the current industry acceptance and familiarity of process options. A data base is provided for different industrial sector	There is no formal method to select the best material or process option but similar method to others should be used.
Supporting Information	Case histories, documented, experiences, examples of related past products, handbooks.	Not formalized	Local evaluation and reputational evaluation are more of fine tuning than evaluation for optimality.	

4.2.2. Rough Process Selection Planning Tools

The process of product development is leaded not very systematically because of a lack of communication between the different functions involved in product development. Managers need a set of practical tools and methods which ensure a better understanding of customers' needs and requirements, as well as procedures and processes to enhance communication by focusing on the voice of the customer within a product development project.

In order to perform parallel design and planning, a large number of methods and tools have been developed (W. Eversheim, 2000):

- Quality Function Deployment (Akao, 1998),
- Design for Manufacture and Assembly (Boothroyd & Dewhurst, Adecade of DFMAResearch. Conference Proceedings, 1994),
- Failure Mode and Effects Analysis (VDA, 1986), and
- Computer-Aided Simulation (Winner, Pennell, Bertrand, & Slusarczuk, 1988).

A quality/cost-based conceptual process planning (QCCPP) enables designers to optimize manufacturing process plan concerning with resource determination in order to improve product quality/cost ratio. This approach uses Quality Function Deployment (QFD) and Failure Mode and Effects Analysis (FMEA) tools to determine manufacturing resources with appropriate process capability to produce product characteristics. Then, it uses ABC (Activity-Based Costing) method to roughly estimate manufacturing cost (Alaa Hassan, 2010).

4.2.2.1. Quality Function Deployment (QFD)

Concurrent Engineering supports the early involvement of all business functions in product design and development decisions. Increasingly, CE integrates the fuzzy front end of marketing into the detailed design of the product. One Japanese design and development methodology that aids in this effort is quality function deployment (QFD). The QFD methodology provides a structured framework for concurrent engineering that ensures that the "voice of the customer" is incorporated into all phases of product development (John J. Cristiano, 2001).

The implementation of QFD results in many significant improvements in the product design and development process. These include;

- Reduced product development cycle.

- Reduction of problem/redesign “spikes” during production start-up.
- Improved product quality.
- Increased customer satisfaction.

Figure 4.15 illustrates the “typical” effect that QFD is reported to have on product design and development processes (John J. Cristiano, 2001).

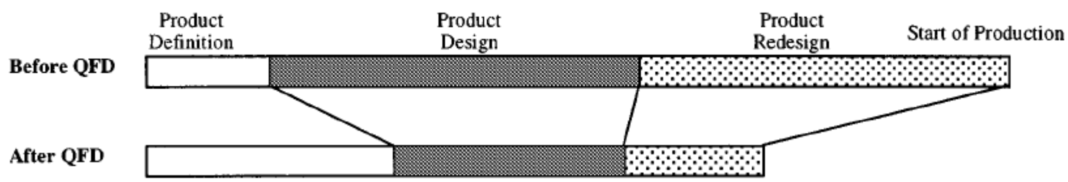


Figure 4. 15. Effect of QFD on product development lead time (John J. Cristiano, 2001).

QFD helps a company to make key trade-offs between what the customers want and what the company can afford to build. The product development process can be outlined in a step-by-step approach. Usually seven steps can be discerned, these are shown in Figure 4.16 (Hauser, 1993) and (Hauser & Clausing, The House of Quality, 1998).

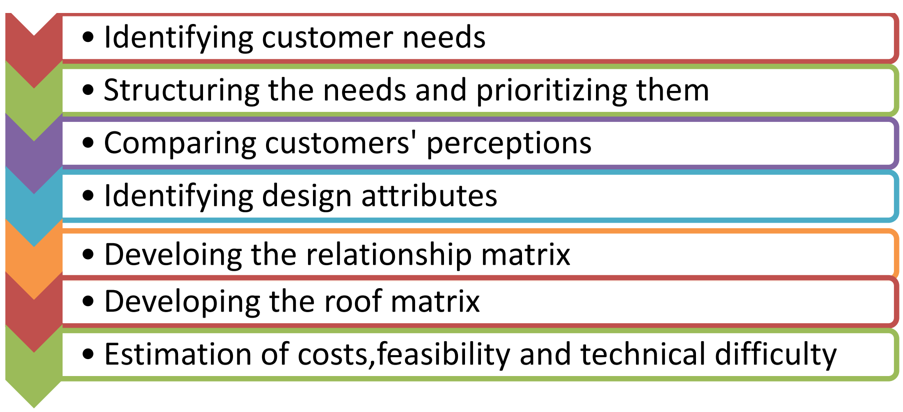


Figure 4. 16. QFD steps

- *Identifying customer needs*: The first step is to identify customer needs, which usually are determined by personal interviews and/or focus groups. It is very important to discover not only articulated needs but also exciting needs or unarticulated needs which, if they are fulfilled, delight and surprise the customer.
- *Structuring the needs and prioritizing them:* Customer needs should be structured into a hierarchy of basic requirements, one-dimensional requirements and attractive requirements,

which means assessing their strategic importance. Basic requirements have to be fulfilled; a product should be competitive with one-dimensional requirements and stand out regarding attractive requirements. To increase customer satisfaction, those product attributes should be improved which have a more than proportional effect on customer satisfaction, i.e. attractive requirements. To make effective improvements in terms of increasing the level of customer satisfaction it is necessary to know how the quality of competitive products is perceived by the customers.

- *Comparing customers' perceptions:* In order to know whether an improvement of certain product attributes leads to a competitive advantage it is necessary to compare the customers' perceived product quality with that of products of competitors. This evaluation should be based on scientific market research.
- *Identifying design attributes:* In this step the product development team translates customer needs into engineering concerns. The question is: How can we change the product? The team has to identify those design attributes which fulfill customers' needs.
- *Developing the relationship matrix:* The product development team has to judge how strongly the different design attributes influence individual customer needs. The influence should be measured for the following reasons (Govers, 1994): first, to determine priorities and directions for improvements to the design attributes; second, to provide an objective means of ensuring that customer requirements have been met; and third, to provide targets for further detailed development.
- *Developing the roof matrix:* The roof matrix should quantify the physical relationships between the design attributes. Sometimes the improvement of one design attribute leads to a degradation of other design attributes. The roof matrix is very helpful when trade-offs have to be made.
- *Estimation of costs, feasibility and technical difficulty:* The product development team should try to quantify costs, feasibility and technical difficulty of each design attribute, which is necessary if reasonable choices are to be made (Kurt Matzler, 1998).

Phases of QFD

QFD consists in a set of matrixes that relates the Voice of the Customer (VOC) to the product's technical requirements, component requirements, process control plans, and manufacturing operations. These series of matrixes, which are called House of Quality (HOQ) shown in Figure 4.17, that guide the product team's activities by providing standard documentation during the product and process development.

There are four phases of QFD; product planning, product design, process planning and process control planning.

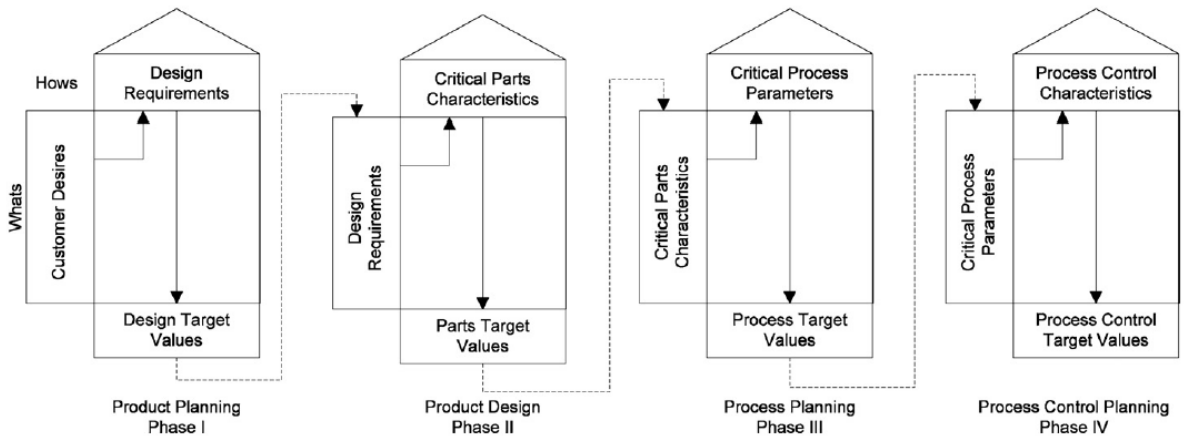


Figure 4. 17. House of Quality and Four phases of QFD

QFD Phase I is Product Planning; which is done before conceptual product design for transfer the requirements definition of customer to design requirements. The steps to build first phase are the following (Brun, 2010-11):

- Identify customer needs
- Define the priorities of the needs
- Translate customer needs into technical requirements
- Relate the customer needs to the technical requirements
- Define interrelationships between the technical requirements
- Conduct an evaluation of the competitors' products or services
- Select critical technical requirements to be deployed in the design and production process

QFD Phase II is Product Phase; which is done between Conceptual Product Design and Detailed Product Design is similar to the first house but applies to subsystems and components. This matrix identifies how critical requirements are implemented by the parts or subsystems of the product and define the technical requirements that implement the product's characteristics (Brun, 2010-11).

Third QFD phase is Process Planning; which is done between Detailed Product Design and Conceptual Process Planning. The design team translates technical specifications of each component into manufacturing process of the components and defines the process specifications (Brun, 2010-11).

The last phase is Process Control Planning which is done before Detailed Process Planning. In this phase the design team defines, on the basis of the process's control point, the control plan. A control point forms the basis for a quality control plan delivering those critical characteristics that are crucial to achieving customer satisfaction (Brun, 2010-11).

4.2.2.2. Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis is an important method of preventive quality and reliability assurance. It involves the investigation and assessment of all causes and effects of all possible failure modes on system in the earliest time (Alaa Hassan, 2010).

FMEA consists of:

- Identifying the ways in which a *failure* can occur
- Establishing the causes of the *failures*
- Evaluating the effects of the *failures* (dissatisfaction, potential injury, safety issue, etc.)
- Estimating the criticality of each *failure* so as to individuate those that are more critical and that must have to be eliminated

A general improvement of safety, reliability and quality is achieved by the implementation of FMEA to the system. The other advantages of FMEA are (Cwielong, 2003);

- Assistance in the selection of design and development alternatives with high reliability potential during the early phase of development.
- Consideration of all possible failure modes of the product and their effects on meeting customer requirements.
- Provision of a list of potential failures and identification of the relative severity of their effects and impacts.
- Description of all improvements resulting from any corrective actions taken.
- Creation of a basis for additional test programs during development and manufacturing.

- Collection of historical information for future reference to aid in the analysis possible failure modes for consideration in intended product or process changes.
- Implementation of adequate defect prevention measures conducted by the responsible department or person.

Types of FMEA

FMEA can be classified into two main types design and process FMEA. Design FMEA deals with design activities, such as product design, machine or tooling design, and process FMEA is used to solve problems due to manufacturing processes (Alaa Hassan, 2010).

Design FMEA deals with products in a stage during detailed design before conceptual process planning. The main aim is to discover design deficiencies prior to turning it into physical goods. The benefits of Design FMEA are;

- Establishment of a priority for design improvement actions
- Information for product design verification and testing
- Identification of potential safety concerns as well as critical and significant characteristics
- Evaluation of design alternatives and requirements
- Discovery of product failures early in the product development process

Process FMEA analyzes the production and manufacturing processes before detail process planning is started. The benefits of Process FMEA are;

- Identification of process deficiencies and conduction of prioritized corrective action plan
- Assistance in manufacturing and assembly analysis
- Support with development of control plans
- Documentation of the rationale for changes

Application Methodology of FMEA

Failure mode and effect analysis requires a cross-functional team which is formed by specialists from various functions (e.g., design, process, production and quality) to thoroughly examine and quantify the relationships among failure modes, effects, causes, current controls, and recommended actions (Yang, 2008).

Each failure mode will be assessed in three parameters; severity, likelihood of **occurrence**, and difficulty of **detection** of the failure mode. A typical evaluation system gives a number between 1 and 10 (with 1 being the best and 10 being the worst case) for each of the three parameters. By multiplying the values for severity (S), occurrence (O), and detectability (D), the team obtains **a risk priority number** (RPN), which is RPN = S x O x D. These risk priority numbers helps the team to identify the parts or processes that need the priority actions for improvement. Depending on the company policy, different criteria are used to trigger the improvement actions (Yang, 2008).

The steps of FMEA method to fill the form are shown in Figure 4.18;

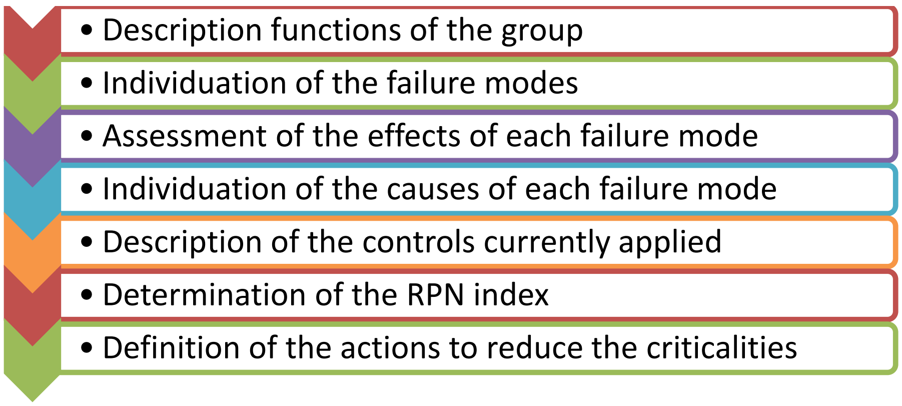


Figure 4. 18. FMEA steps (Brun, 2010-11).

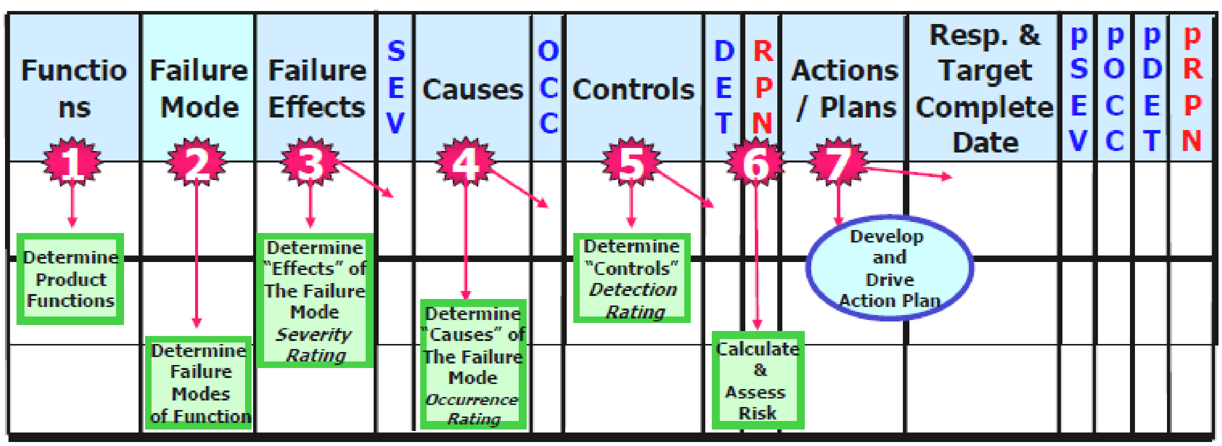


Figure 4. 19. The steps of FMEA on form (Brun, 2010-11)

As shown in Figure 4.19, the first step is determination of the product function by describing what the system or component is designed to do. Then failure modes are determined in which a system, subsystem or component could potentially fail to meet design intent. It can be the answer of the question; "How could this design fail to meet each customer requirement?" gives failure modes. After the failure; their effects which can be perceived by customer are defined in terms of customer experienced. It can be the answer of the questions; “What would be the result of this failure? or “If failure occurs then what are the consequences?”. The next step is severity is ranked and the assessment of the seriousness of the effects is done. (Severity = 10 indicates that the effect is very serious and is worse than Severity = 1.) After severity; each cause should be listed as concisely and completely as possible so efforts can be aimed at pertinent causes. Then to remove or control the causes; occurrence rating is done; in the way Occurrence = 10 indicates that the likelihood of occurrence is very high and is worse than Occurrence = 1.

Confidence Current Design Controls will detect cause and subsequent failure mode prior to production, and/or will prevent the cause from occurring. If there are more than one control, rate each and select the lowest for the detection rating. There are 3 types of control;

- Prevention from occurring or reduction of rate
- Detect cause mechanism and lead to corrective actions
- Detect the failure mode, leading to corrective actions

After control; detection ranking is done which value is assigned to each of the detective controls. Detection = 10 indicates that the failure is not likely to be detected before it reaches the end user and is worse than Detection = 1.

The next step is calculation of risk priority number (RPN) that multiplication of severity, occurrence and detection ratings.

- The RPN is a measure of design risk.
- The RPN will be between "1" and "1000"
- For high RPNs, the team must undertake efforts to reduce this calculated risk through corrective actions
- RPN is used to prioritize concerns/actions

To reduce the ranking the new tasks should be recommended, generally design revision is the solution for reduction in the severity rankings. The responsibility and targets should be described in recommended actions; and all of them must have a person assigned responsibility for completion of the action. Person listed as responsible for an action must also be listed as a team member also there must be a completion date accompanying each recommended action (Brun, 2010-11).

4.2.2.3. The relation between QFD and FMEA

Chin et al used a method for utilizing a hybrid quality planning approach plans for translating customer requirements into design requirements. They used a hybrid between FMEA and QFD. The process FMEA, which is more of a production oriented problem solving technique focusing on process quality, accounts for incorporating the process failure knowledge involved in the similar or the historical component to the QFD for process planning. As shown in Figure 4.20, most quality characteristics in the process FMEA should be included in the QFD (Kwai-Sang, 2003).

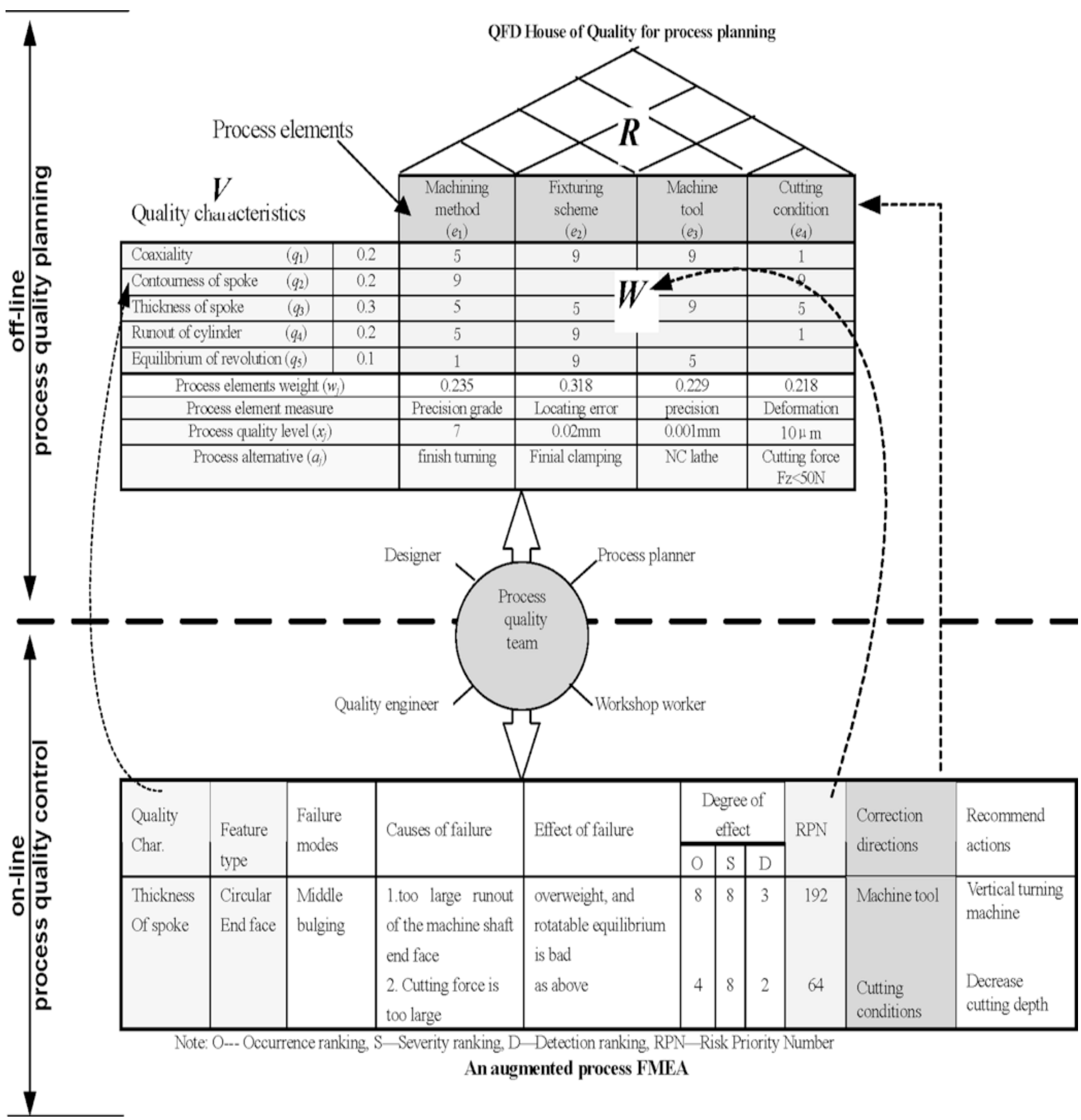


Figure 4. 20. An illustration for process planning for quality with a hybrid approach of a combined QFD with a process FMEA (Kwai-Sang, 2003).

During the process planning for quality, a process quality team (consisting of designer, process planner, quality engineer and workshop people) should be organized. In the off-line process planning for quality, based on the team's experience and knowledge, the QFD addresses additive and positive quality with a planning perspective, and establishes the house of quality (HOQ), and translates the quality characteristics into a set of process elements and their target levels (Kwai-Sang, 2003). A process element is a phase that significantly influences quality characteristics. Process elements generally cover the machining method, the machine tool, the assembly tool, the fixturing scheme, the tool path mode, the cutting condition, the work piece structure, etc. The capability of each process element is measured by one or more quality measures or indicators. For examples, ''precision level'' for the machining method, and ''deformation'' and ''locating error'' for the fixturing scheme are quality measures of process elements. Such indicators should be selected in accordance with the features of the component and its manufacturing processes (Kwai-Sang, 2003).

The correction directions in the FMEA are useful for determining appropriate process elements, while the risk priority number (RPN) values are applicable in determining relationships between the quality characteristics and the process elements in HOQ. Therefore, with the teamwork of the process quality team as an enabler, the QFD and the process FMEA can be combined as a hybrid approach to effectively plan the process quality. QFD acts as the guardian to the voice of the designer (the internal customer of process planning) from the perspective of positive quality, while the process FMEA acts as the guardian to the voice of engineers (the quality engineer and the workshop people, etc.) from the perspective of negative quality. Combining these two quality tools could facilitate tackling the issues of the planning of process quality (Kwai-Sang, 2003).

4.3. Manufacturing Requirements for SBCE

SBCE helps to control the project cost from beginning of the design, it provides a significant effect on evolution of design knowledge from the early stage of the design phase, as well. What can be done to apply the SBCE methodology to product development process? The answer for this question gives us the manufacturing requirements for SBCE:

The exploration, from design and manufacturing perspective, of *sets of possible design solutions,* these sets might include several discrete design options or a range of parameter values (Jeffrey K. Liker, 1996). As the design progresses, they gradually narrow their respective sets of solutions based on additional information from development, testing, the customer and other participants' sets (Sobek, Ward, & Liker, Toyota's Principles of Set-Based Concurrent Engineering, 1999).

Communication about sets of possible solutions should be done early, based on preliminary information of concept sets, such as range of values; in this way, instead of carrying out a series of meetings in which a design is critiqued and modified several times (as done in point-based design), designers, manufacturing representatives, supplier representatives, etc., bring to the table sets of possibilities and compare them to find intersections of feasibility. In the case of set-based approach, truly parallel design work is possible since decisions downstream are always compatible with those upstream (Jeffrey K. Liker, 1996).

Enforce *ranges or minimum constraints* to allow optimization and mutual adjustment. When requirements are given as ranges or as minimum constraints, the parameters are specified as being allowed to be "no less than x and no greater than y" (Jeffrey K. Liker, 1996). The goal of incorporating minimum constraints or ranges is to add some flexibility in the design process, giving more room for adjustments as engineers become more informed about what is possible (Bernstein, 1998).

Narrow sets gradually while increasing details until an optimal design and manufacturing system are found. Since SBCE design approach requirements are represented as ranges and several solutions are proposed and gradually converged towards a final solution, giving more emphasis on analyzing possible solutions, leadings to greater knowledge on the design and improve the decision making process because it is now based on better information, eliminating the necessity of rework attached to its predecessor the point-based approach (Bernstein, 1998).

4.4. Implications on Rough Manufacturing Planning

- Rough manufacturing process plan should start early in the design phases
- Design requirements will be described as ranges or as minimum/maximum constraints
- Different process plans will be feasible at early stages of design and they will be gradually narrowed down. By having information about possible process plans, more information about the design (including estimated costs) is available, leading to better decisions when reducing the set of possible solutions.

5. Industry Survey

5.1. Chapter Introduction

This chapter aims at providing an overview of the objectives and methodologies used to complete the research done for this dissertation.

5.2. Questionnaire Delivery and Analysis Methodology

In order to fulfill the objectives of this thesis, a questionnaire was developed based on knowledge obtained from literature written on the topic. The most important topics were discussed on previous chapters of this thesis. This questionnaire was revised and approved by Endris Kerga, our thesis supervisor and sent to over one hundred companies including Ford, Cummins, Bosch, Black and Decker, and Whirpool, Chico-Artsana among others. All these companies operated in the automotive, aerospace or electro-domestic industries, with on-site design and manufacturing capabilities. They were mostly medium to large sized, with predominance on medium-sized companies.

Of all the companies contacted, only three replied all the questions through a link provided with the survey in an online format. Four of the questions of the survey were taken from a previous survey done by the ingenieria gestionale department at the Politecnico di Milano. These questions were answered by eleven more companies and the results were added to the ones of this survey.

The main objective of the survey was to understand the current state of companies regarding the [1] utilization of SBCE design approach, [2] the interaction between the design and manufacturing departments in companies, with special attention to those implementing SBCE principles, and [3] understand how is the rough production planning done.

The following sub-section explains the design and goals of each question.

5.3. Survey Creation Methodology

This survey was intentionally divided into three parts to fulfill all three objectives. These parts are:

- Part 1 - Assessment of presence of Set-Based Concurrent Engineering principles in the firm
- Part 2 – Assessment of integration of design and manufacturing
- Part 3 – Assessment of Manufacturing Process Product Preparation

The following sub-sections include first a general description of the section, followed by an explanation of the intention of each of the questions.

Part 1 - Assessment of presence of Set-Based Concurrent Engineering principles in the firm

The aim of the first part of this survey is to assess the methods and principle applied by companies when designing a new product, whether they use traditional design methods or pure set-based concurrent engineering methods; understanding how effective this method to the company. Answers will give us as well information about the tools used and their performance.

This part contains 10 questions where the use of SBCE principles is tested together with some tools that work hand by hand with these principles. Each question's purpose is explained below:

Q1. 1: How do you gather the necessary information to define the value of the product?

- The chief engineer is present during the design activity. This person is an expert engineer as well as an expert user and understands in depth what does and doesn't add value to the customer.
- Information about valued elements is gathered by conducting interviews to users (or expert users) while using existing products and indirectly asking them about the value of new features that the new product will contain.
- Information about valued elements is gathered from direct surveys to customers.
- Information about valued elements is gathered by collecting ideas from multidisciplinary teams inside the company.
- Information about valued elements comes from knowledge acquired from previous experience, and resides in the mind of key personnel.

Results for Q1.1 are shown below:

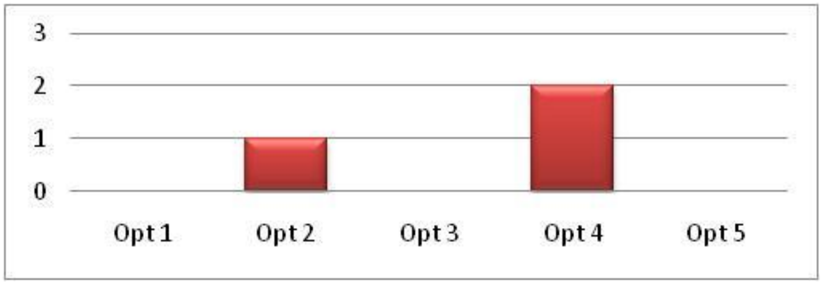


Figure 5. 1 Answer of Q1.1

One of SBCE principles is "Map the design space", this includes the deep understanding of what adds value to the customer. A technique used by Toyota is the presence of a chief engineer, a very experienced engineer as well as an expert user. This person is involved throughout the design process. Other effective methods for deeply understanding what customer values include performing high quality market research about the product and by including the ideas of experts in multiple disciplines inside and outside the company. This question is intended to learn company's way to define the value of product and how much contributions they consider during product development process: if they take care also customer ideas or they create the ideas only inside the company and experience.

On Figure 5.1 the answers for Q1.1 show that the companies interviewed collect information mostly from inside sources followed by studies conducted to expert users. Although there is no evidence of presence of a chief engineer, the importance given to understanding what is valued by the market is very high. Option 2 is usually effective for benchmarking analyses and very useful to understand the gap between perceived values against the value offered by products in the market. Option 4, internal brainstorming, is useful for understanding a new need although it needs to be validated with from the customer point of view.

Q1.2: In what terms do you usually specify design requirements?

- Ranges
- Minumums and maximums
- Numerical quantity
- qualitiative description (example: enough or not enough)

Results for Q1.2 are shown below:

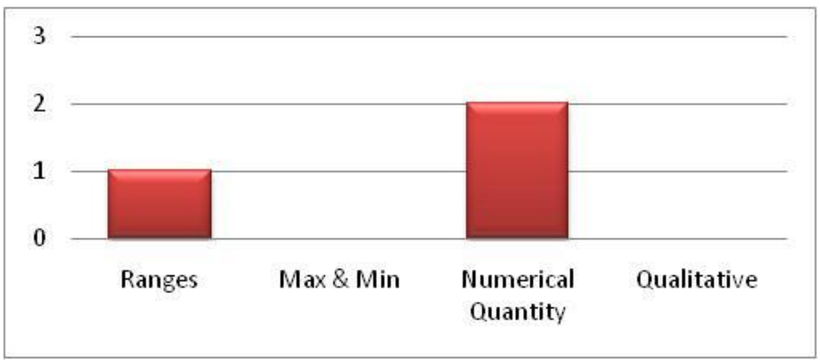


Figure 5. 2 Answer of Q1.2

SBCE is based on the development of sets of concepts to be evaluated and gradually narrowed down. Providing design requirements as ranges or as minimum and maximum constraints is what enables the creation of different sets. An absolute number is given as a requirement limits the design to very few possible solutions eliminating the possibility of exploring tradeoffs.

Only one of the respondents follows SBCE principle that states that design requirements should be expressed in ranges or maximum and minimum limits. Most of the companies specify their design requirements as absolute numbers.

Q1.3: Which of the following statements better fit your concept idea generation process:

- Each functional department in parallel and relatively independently determines the primary design constraints on its subsystem based on experience, analysis, experimentation and testing, and outside information.

- Concept ideas are generated and collected from brainstorming techniques done by key personnel.

Results for Q1.3 are shown below:

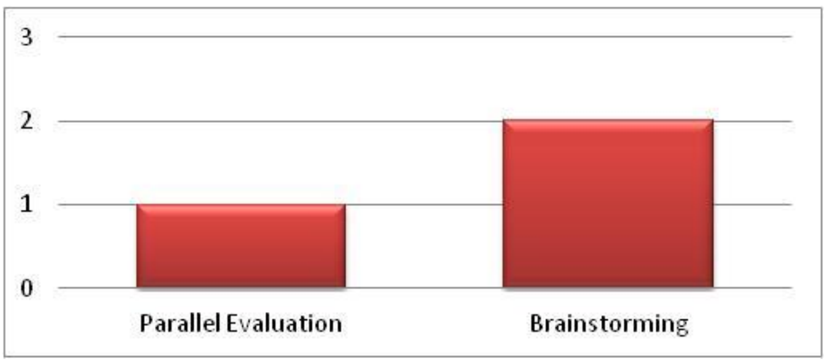


Figure 5. 3 Answer of Q1.3

Bernstein suggested in his studies that one of the biggest problems with point-based approach and with traditional concurrent engineering was the lack of transmission of tacit knowledge between functional departments. In SBCE, different concepts are created in parallel and relatively independent by each functional department and then presented to the rest of the team and together look for the intersections of all concepts. In this way it is ensured that the constraints of each department are communicated to the rest.

Q1.3 determines the way companies generate concept ideas, once the minimum requirements are established, either in parallel (described above), or as a brainstorming done by key personnel. The result shows that most companies interviewed still generate ideas using brainstorming techniques, without considering the advantage of the communication benefits that exists by developing several concepts in parallel.

Q1.4: Which of the following options better fit the way concepts are analyzed in your company?

- We create a matrix in which we compare what the customer values and what we need to do to create that value; then rank them according to their importance.
- We list all ways of making possible what the customer values, asses all causes and effects of these ways, and list possible failure modes; ranking them based on the probability of occurrence, detection difficulty and severity of the failure.
- We list all ways of making possible what the customer values and rank them according to apparent simplicity.

Results for Q1.4 are shown below:

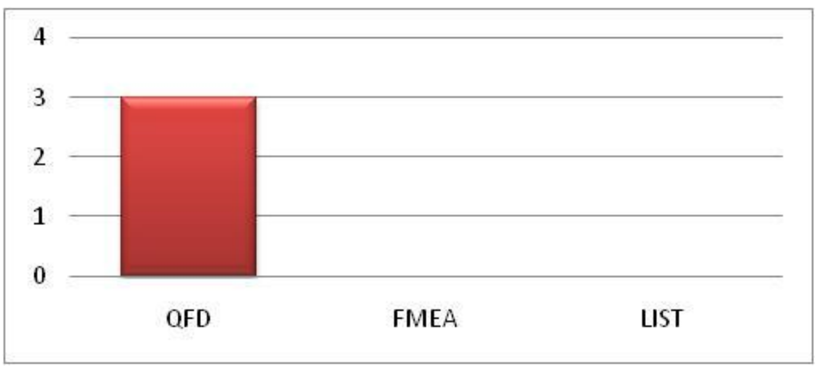


Figure 5. 4 Answer of Q1.4

This question is asked to learn if company use tools which help to be sure about what the customers' need like QFD and FMEA. These tools are useful to define design requirements from customer and enhance communication of customer's values/needs, improve the product quality, among others.

All companies interviewed responded that they use QFD method without evidence of use of FMEA techniques.

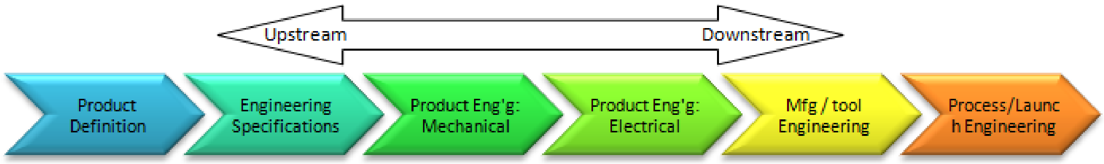


Figure 5. 5 An example of an engineering division with its department. The starter department is the upstream and the receiver is the downstream.

Q1.5: According to the figure above, choose the statement that better fit the way you transmit design information between departments:

- Functional requirements are frozen and transmitted from the upstream department to the downstream department when the upstream activity is in process.

- Functional requirements are transmitted from the upstream department to the downstream department as a set of possible solutions allowing downstream activities to begin developing their set of feasible designs at the same time as upstream activities are developing.

- Conservative assumptions about functional requirements are done by the upstream and transmitted to the downstream department to allow them to start with their activities. Sometimes overdesign occurs because as the design progresses, the conservative assumptions where not conservative enough.

Results for Q1.5 are shown below:

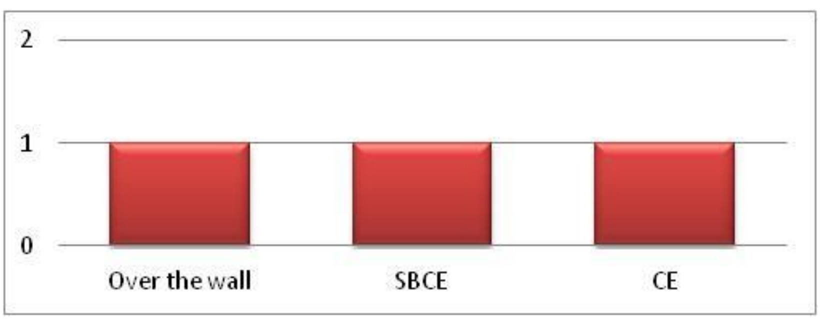


Figure 5. 6 Answer of Q1.5

On SBCE, the communication between departments is done using sets of designs, instead of a single design. By doing so, the risk of rework is reduced to minimum because all departments have information about the limits of the design and are aware of the current state of the design and have on hand all information currently available. This question intends to understand the communication methods used by the companies in their concept design process.

According to responds for Q1.5 that there is no a clear consensus on the methods used when communicating between departments.

Q1.6: How do you select the design concept to be developed? Please select one option.

- We only produce one concept design for each product.
- We identify multiple design concepts and select the one that better fit the functional requirements.
- We identify multiple design concepts and select the one that has the lowest development costs.
- We identify multiple design concepts and eliminate them gradually as more information becomes available with the advancement of the design.

Results for Q1.6 are shown below:

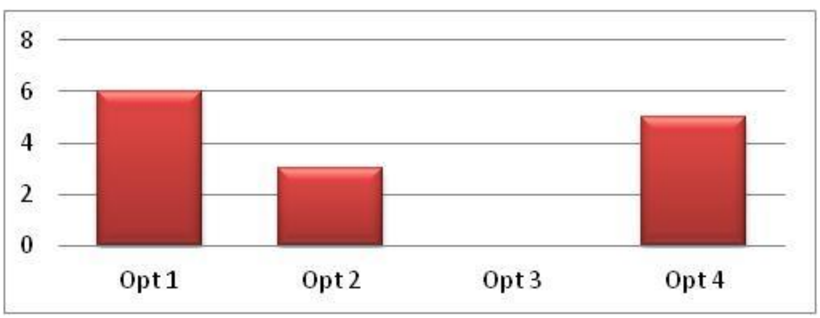
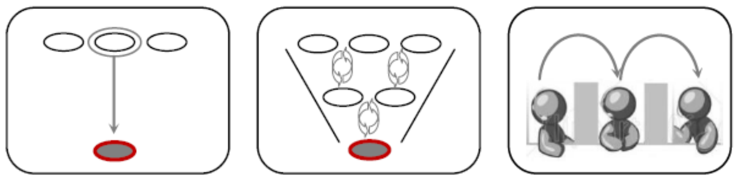


Figure 5. 7 Answer of Q1.6

The main principle of SBCE, different from point-based and CE, is that the company works on sets of design concepts at the same time and gradually eliminates them as more information is available. The two questions above (Q1.5 and Q1.6) give us information about the main principle of SBCE: the number of concepts evaluated and how gradual they are eliminated.

On Q1.6 we can see that 64% of the companies still use the point-based approach were “the one best option” is selected when designing concept products, while 36% are already designing sets f concepts and narrowing them out as more information is available.

Q1.7: From de diagrams below, can you indicate what method(s) of concept development do you currently follow and rate its effectiveness?



Concurrent Eng *Set-Based Concurrent Eng* *Sequential Manner*

Method	**Frequency of use**			**Effectiveness**		
	Never	*Sometimes*	*Always*	*Not Effective*	*Somewhat Effective*	*Very Effective*
Concurrent Engineering						
Set-Based Concurrent Eng.						
Sequential Manner						

Results for Q1.7 are shown below:

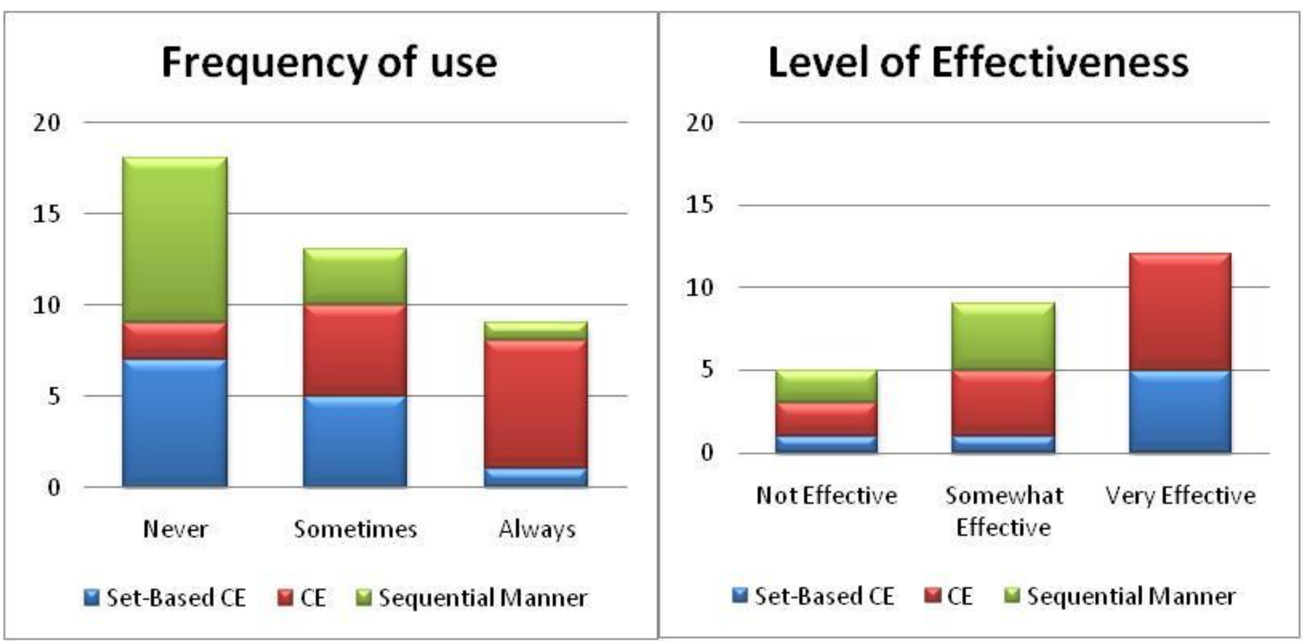


Figure 5. 8 Answer of Q1.7

Question 1.7 gives information about the frequency of use of the provided design methods (Concurrent Engineering, Set-based concurrent engineering and point-based concurrent engineering) for concept development on the evaluated companies and the feeling of how efficient they are for their operations.

Figure5.8 shows clearly that companies interviewed use SBCE method either never or sometimes; however when used, it was considered very effective for their operations. With this answers we can state that, even though the approach is considered to be very effective, SBCE is not embedded in company's culture.

Q1.8: Which ways do you use most to communicate information about sets of alternatives, and how efficient do you asses them?

Communication Way	Usage			Effectiveness		
	Never	*Sometimes*	*Always*	*Not Effective*	*Somewhat Effective*	*Very Effective*
List of ideas						
Drawings						
Models						
Trade-off curves						
Performance Chart						
Other:_______________						

Results for Q1.8 are shown below:

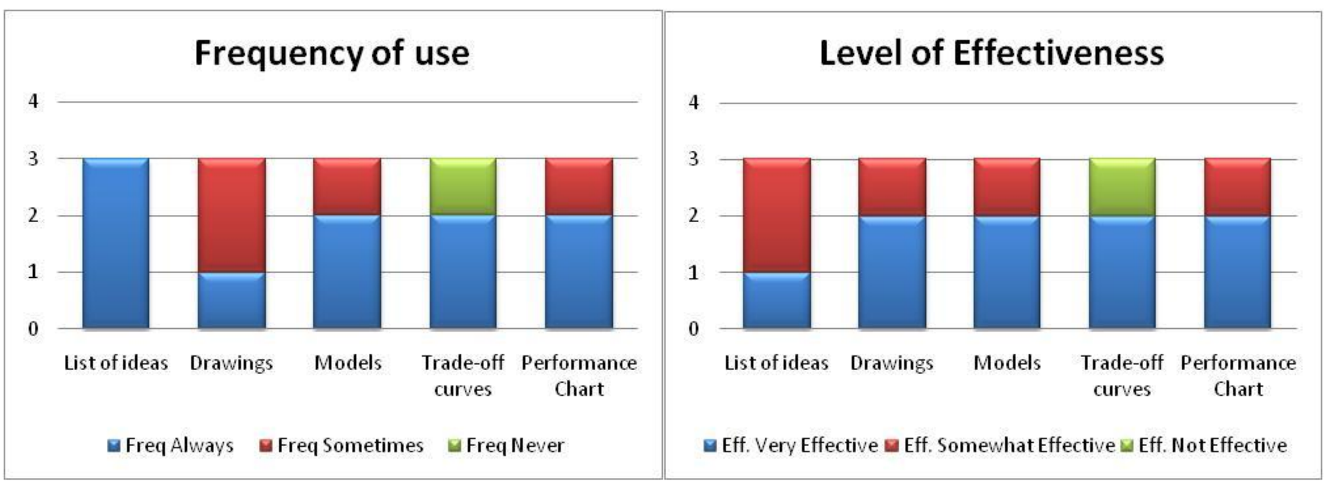


Figure 5. 9 Answer of Q1.8

Quality communication among departments is a vital in a SBCE environment; in fact, the only way to effectively concur tasks is by having open and effective communication methods. Since the SBCE suggests working simultaneously; it is important for all departments to be aware about the other teams work. To assess the methods of communication between functional departments in the companies evaluated, this question takes place. Some communication methods used by design departments are listed above, together with an additional space for companies to add methods of their own. The question asks about the frequency of use and the effectiveness for company's communication ways.

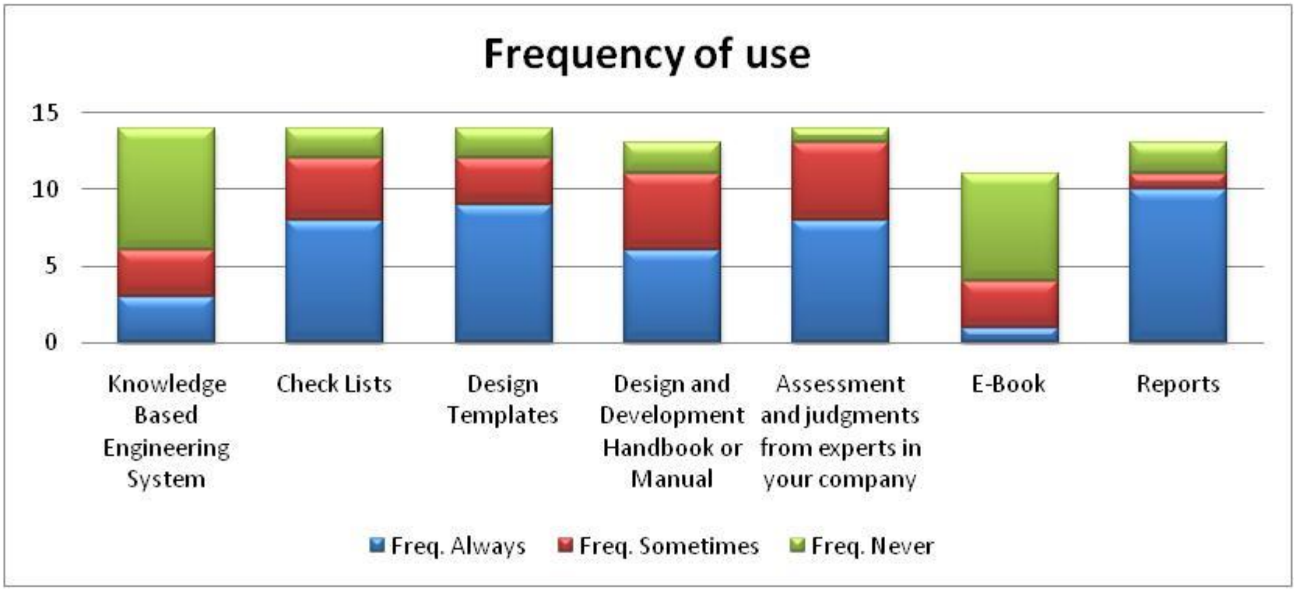
The most used method is list of ideas, although it is stated that it is not as effective as other listed methods. Trade-off curves on the other hand, is a SBCE repeatedly mentioned method, and according to this survey, it is sometimes used and qualified mostly as 'very effective'.

In summary, the most effective methods found in the survey are those that contain more information than just a list of ideas. These methods (drawings, models, trade-off curves and performance charts) usually explain designs in more detail.

Q1.9: What technologies or functions are used in your company to realize that captured knowledge is re-used and shared during the concept development and how frequently it is used? In addition, do you think the knowledge content of the provided technologies is adequate in supporting decisions taking in an efficient way?

Technologies and Functions	**Usage**			**Effectiveness**		
	Never	*Sometimes*	*Always*	*Not Effective*	*Somewhat Effective*	*Very Effective*
Knowledge Based Engineering System						
Check Lists						
Design Templates						
Design and Development Handbook or Manual						
Assessment and judgments from experts in your company						
E-Book						
Reports						

Results for Q1.9 are shown below:



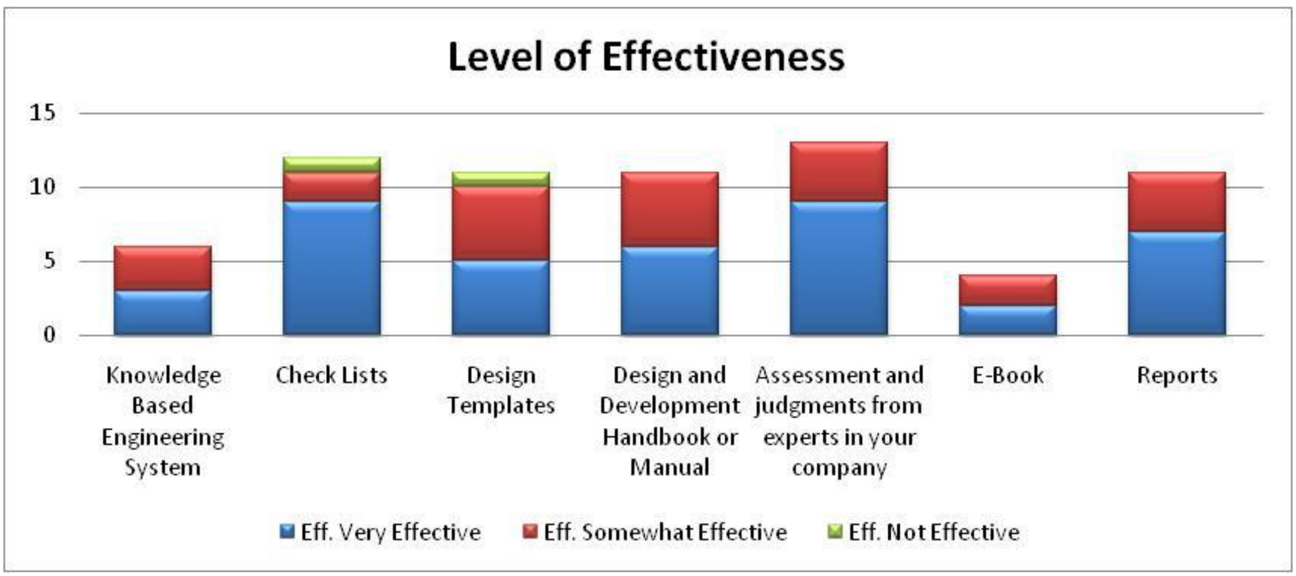


Figure 5. 10 Answer of Q1.9

In Q1.9 it is asked about the technologies and functions used by companies for reusing and sharing knowledge during future product development process, like Knowledge Based Engineering System, Check Lists, Design standards, Judgment from Experts, and others.

The most used sources of knowledge include assessment and judgments from experts, design templates, check lists and reports according to the answer of Q1.9. The most effective knowledge sources for companies during the development of new products are the assessment and judgments from experts in the mater together with check lists.

Q1.10: From your experience, how important do you assess the following sources of knowledge? (Select one each marking with an 'X').

Sources of Knowledge	**Importance**			
	Not Important	*Important*	*Very Important*	*Essential for competitive advantage*
Design Rules:				
Heuristic rules (company design its own rules)				
Published rules (e.g. from books)				
Rules from suppliers (e.g. material provider)				
Design Standards				
Capability of current resources				
Capability of current process				
Previous projects				
Tacit Knowledge (Expertise of engineers)				

Results for Q1.10 are shown below:

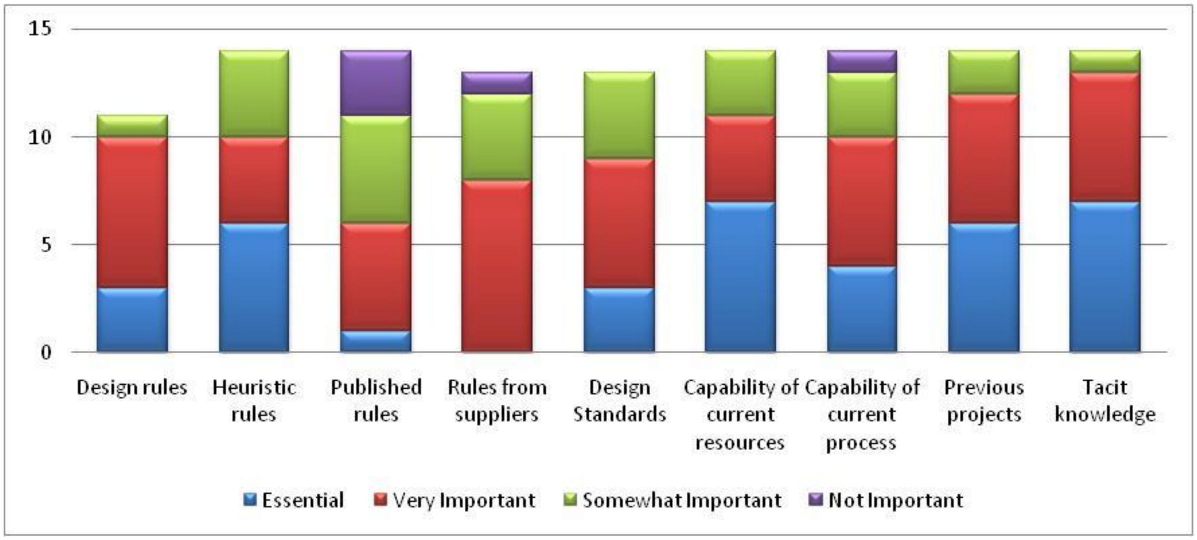


Figure 5. 11 Answer of Q1.10

The last two questions are about the role of knowledge and knowledge management within the company. Knowledge can be captured, formally represented and re-used to support engineering decisions in product design and development. Q1.10 investigates how companies capture knowledge, considering the sources of knowledge and the formal initiatives, software and mechanisms used for it.

The most prevalent method to re-use and diffuse knowledge is not a defined and structured one, but it is based on people's expertise. Check lists and reports are used by the majority of companies and their effectiveness is good. Other methods widely used are tacit knowledge, capability of resources, heuristic rules.

Part 2 – Assessment of integration of design and manufacturing

This second part of the survey contains three questions and aims at understanding the way the design departments interact with the production departments in a company, by questioning about whether or not the companies perform conceptual process planning, a requirement for SBCE manufacturing rough production planning; starting with understanding when is the communication process started, how is design information transmitted from the design department to the manufacturing department and why is that companies communicate in this manner. The purpose of each question is explained below:

Q2.1: In which phase of the design are manufacturing processes first thought of? Phases are explained in the drawing just below the answers.

- During the requirements definitions phase
- At conceptual product design phase
- At detailed product design phase

Figure 5. 12. Phases of design.

Results for Q2.1 are shown below:

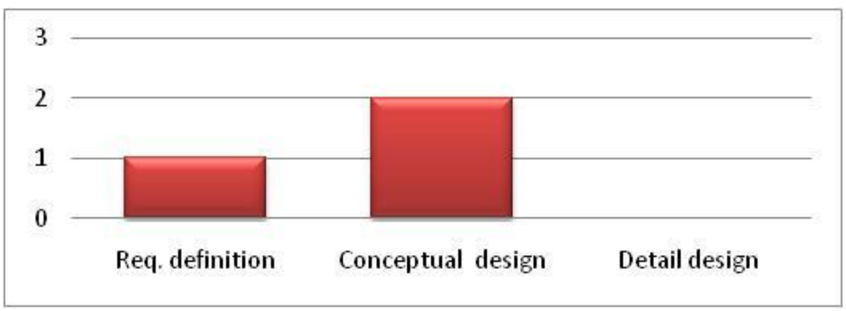


Figure 5. 13 Answer of Q2.1

Manufacturing requirements for SBCE include the start of communications between design and manufacturing departments early during the design phase, specifically during conceptual product design since it is the phase where some information is available for manufacturing process searching. With the traditional methods, communication between these two departments starts during the detailed product design stage, limiting the information provided by rough process planning (estimated costs, quality and time of unitary production). This information is essential for narrowing down the set of possible solutions that exist during the conceptual product design phase and avoiding design errors. Errors made during the early stages of design tend to contribute up to 70% of production costs (Boothroyd, Bewhurst, &

Knight, 1992). Q2.1 is design to understand when communications are started, whereas Q2.2 asks for the reasons the company has for doing so.

The answers from companies reflect the importance taken by them about the involvement of the production department during the conceptual product design phase. While one of the companies involves the production department even earlier, during the requirements definition phase.

Q2.2: For the company, what is the importance of including manufacturing process assesment at this stage (stage selected in Q2.1)?

- There is more informantion at this time and there is no need for rework.
- Estimation of costs, time and other variables can be done earlier in time.
- Some design and production problems can be avoided earlier earlier in the lifecyle of the product.
- Production planning can be started earlier.
- There is more time to improve the quality of production.

Results for Q2.2 are shown below:

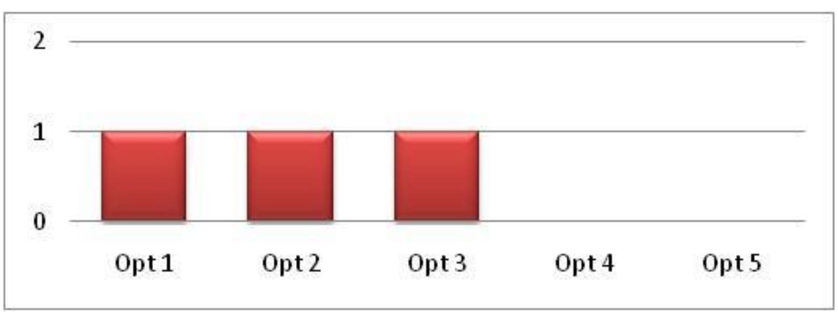


Figure 5. 14 Answer of Q2.2

This question shows that the companies prefer the early involvement of the manufacturing department in design because of a variety of reasons that are mainly related to preparing information about production early in time to better control costs and prevent future problems in production.

Q2.3: When communicating your designs to manufacturing...

- Designs are first communicated to manufacturing as a single draw or sketch.
- Designs are first communicated to manufacturing as a single draw or sketch + a verbal description indicating how the shape might change.
- A number of drawings or sketches are sent to manufacturing illustrating possible shapes..

Results for Q2.3 are shown below:

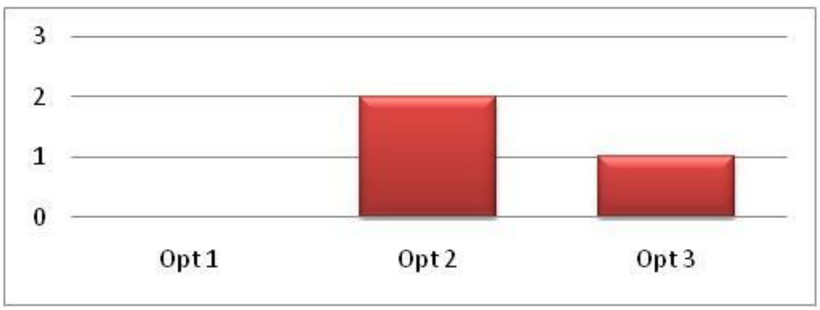


Figure 5. 15 Answer of Q2.3

Manufacturing requirements for SBCE includes the early communication of sets of concept designs to the manufacturing department to start the rough process planning. Although companies support the importance of providing complete information to the manufacturing departments, only one of them practices communicating the design information by using sets of drawings with all possible design shapes.

Part 3 – Assessment of Manufacturing Process Product Preparation

This final part is a 5-question survey that aims at understanding how is the rough process plan done, by identifying the methods used by companies in the following areas:

- Translation and matching design requirements with process attributes, listing which tools, methods and procedures are used.

- Screening of existing processes, discarding those that cannot perform the job.
- Ranking of possible processes and process chains is done and what elements are considered for this ranking.
- To understand if the company has a method of getting supporting information once the process chains have been reduced.

Q3.1: How do you obtain information about existing processes?

- We buy/rent a database in the market from a company that provides these services.
- We have recorded all processes we think we can possibly use in a database of our own.
- We have experts on the matter in our company, they provide the information.
- All manufacturing process information needed comes from books and manuals we own.

Results for Q3.1 are shown below:

Figure 5. 16 Answer of Q3.1

Design requirements have to be translated to the process attributes to have the same structure and language. The process attributes and design requirements should be expressed as constraints on material, shape, tolerance, roughness and other process related parameters. It can be done by using databases either experts or manual books. This question is asked to learn which way company use for matching the process attributes with design requirements.

According to the results we can state that companies that answered the survey generally do matching using knowledge from inside the company, either from own databases or from process experts; or by hiring expert consulting services.

Q3.2: The methods used by your company to screen the existing processes is more similar to which of the following statements?

- Process experts design questionnaries guiding the user with data that is relevant, discriminating and available. The benefit of the questionnaire is that important criteria are not inadvertently overlooked.
- The designer specifies the design requirements as input on our software, the software then retrives the subset of processes which meet all the required attributes.

Results for Q3.2 are shown below:

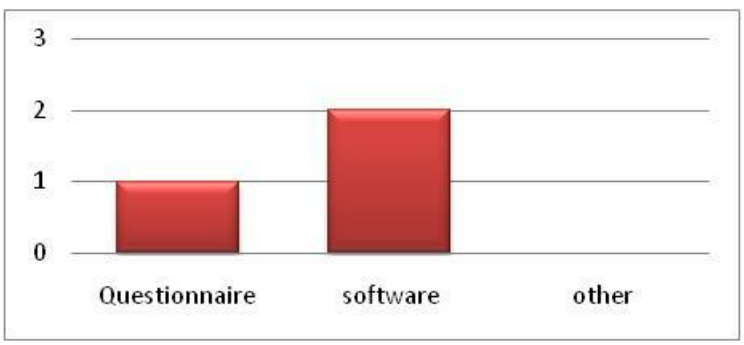


Figure 5. 17 Answer of Q3.2

Starting from all existing processes, selection aims to separate those processes that are suitable for the design in question from the ones that cannot do the job. In the literature there are two ways for selecting processes: one is the use of software, such as CPS[2], for free searching and selection of processes, and the other is the use of questionnaires prepared by experts that guide the user.

As seen in the survey answers, most companies use software that aids on the selection of such processes.

[2] CPS stands for Cambridge Process Selector

Q3.3: How is the outcome of the screening process? Once all processes are screened, the results are displayed:

- In absolute values, for example as a direct 'yes, it matches' or 'no, it does not match'.
- By giving a number (for example from 0 to 1) to represent the approximate degree to which it matches.

Results for Q3.3 are shown below:

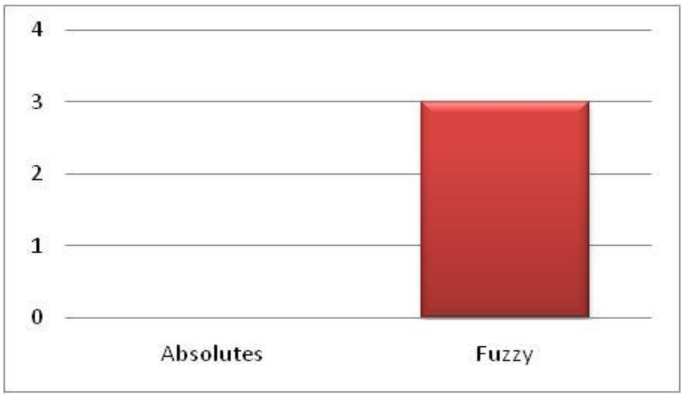
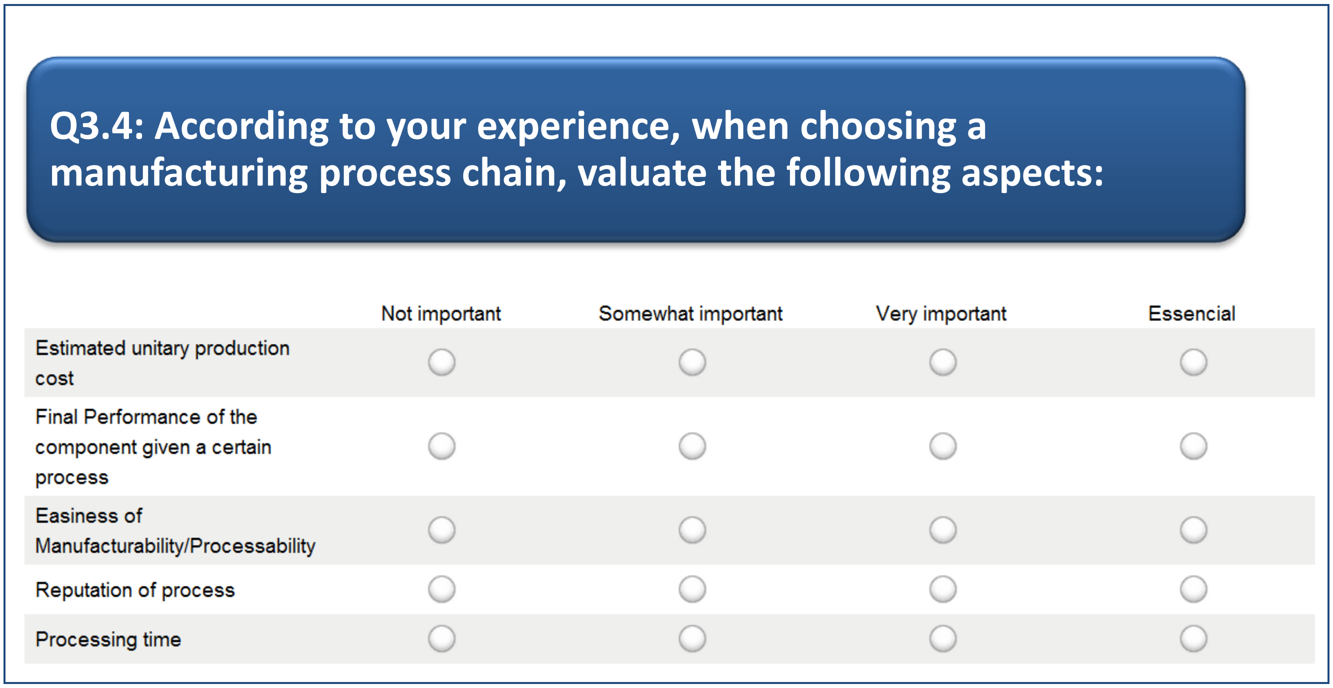


Figure 5. 18 Answer of Q3.2

The previous two questions are intended to understand the nature of the screening process in the companies. Q3.2 aims that the determining which process approach is currently used by companies, whereas Q3.3 aims at understanding how the results are displayed.

All interviewed companies, after screening through existing processes, select the possible processes defining, with a number, the degree of compatibility of the processes with the specific design.



Q3.4: According to your experience, when choosing a manufacturing process chain, valuate the following aspects:

	Not important	Somewhat important	Very important	Essencial
Estimated unitary production cost	○	○	○	○
Final Performance of the component given a certain process	○	○	○	○
Easiness of Manufacturability/Processability	○	○	○	○
Reputation of process	○	○	○	○
Processing time	○	○	○	○

Results for Q3.4 are shown below:

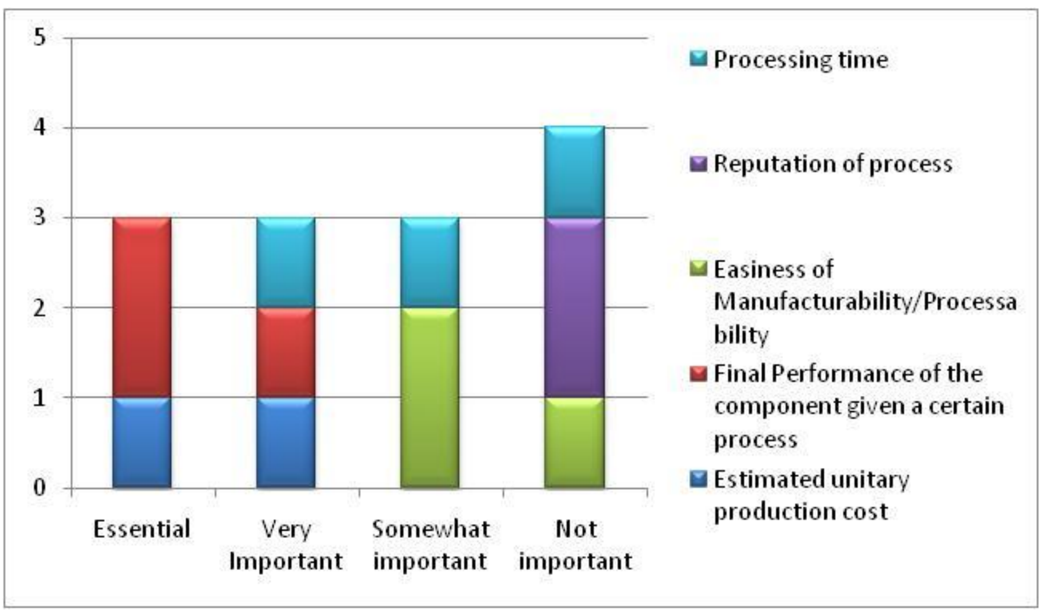
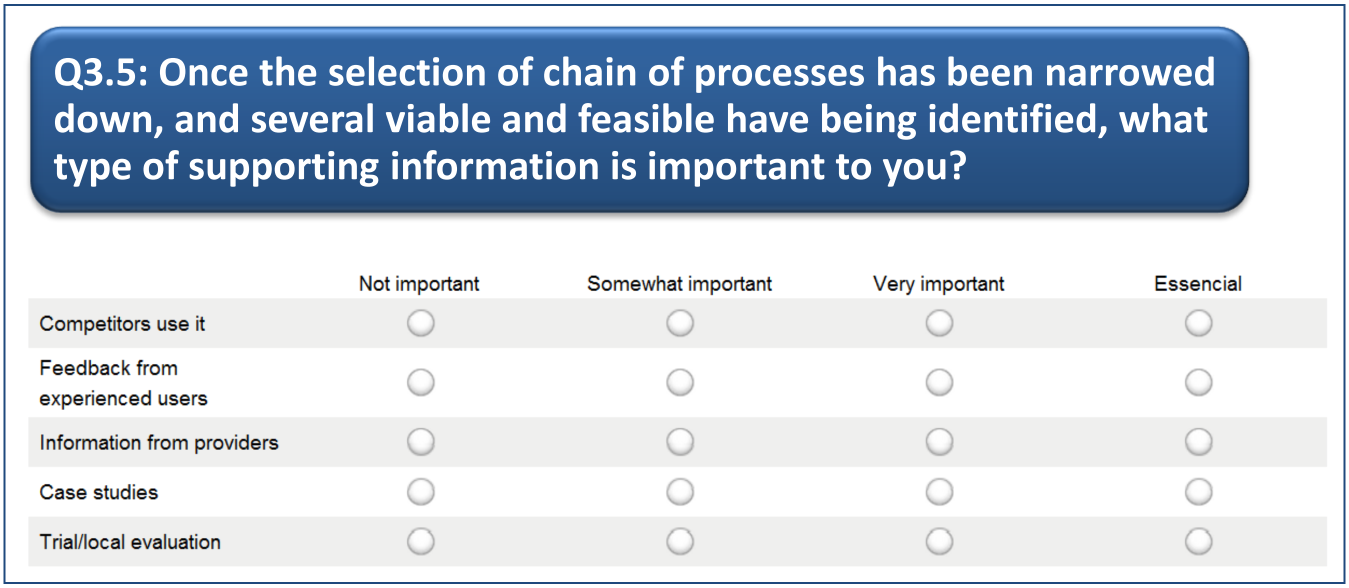


Figure 5. 19 Answer of Q3.4

This question is intended to understand which are the preferred factors used by companies when ranking possible processes. Answers to this survey show that 'final performance of the component' followed by the 'estimated unitary cost of production' are the two factors that weight the most when ranking a group of possible processes. Processing time and reputation of the process are the least considered by them.



Q3.5: Once the selection of chain of processes has been narrowed down, and several viable and feasible have being identified, what type of supporting information is important to you?

	Not important	Somewhat important	Very important	Essencial
Competitors use it	○	○	○	○
Feedback from experienced users	○	○	○	○
Information from providers	○	○	○	○
Case studies	○	○	○	○
Trial/local evaluation	○	○	○	○

Results for Q3.5 are shown below:

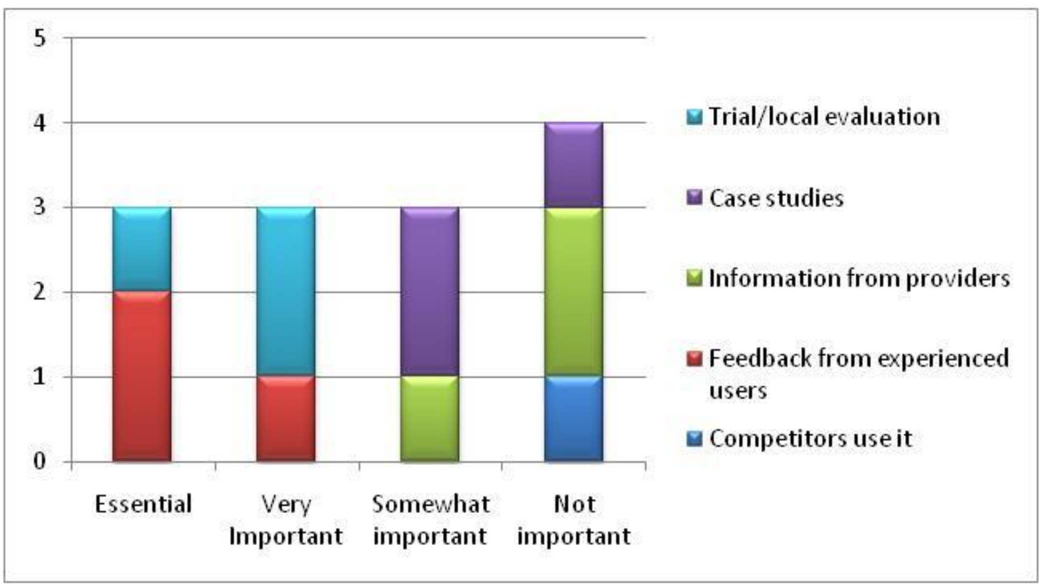


Figure 5. 20 Answer of Q3.5

Q3.5 values the importance given by companies to the different types of supporting information that exist for a given manufacturing process. At the same time it values how important is the role of supporting information when selecting process chains.

Companies prefer to search for supporting information from experienced users and from local trials, rather than trusting information from providers, case studies and preferences from competitors.

6. Concluding Remarks

SBCE offers a great method for controlling costs, reducing time to market and still offer a successful product. Although its principles are not fully applied on the operations of the respondents, many aspects of companies' practices contain SBCE ideas.

The results of the survey show that most of the respondents consider customer values with a high importance. Even that in SBCE different concepts are created in parallel and relatively independent by each functional department, most companies interviewed still generate ideas using brainstorming techniques and communicate it to different departments in different ways. Most respondents agreed that they study a number of concepts and sometimes narrow them down gradually, and sometimes narrow them very fast. Greater success was shown when concepts were gradually eliminated. Capturing knowledge and reusing is an essential tool for SBCE; in the companies that filled out the survey knowledge is captured by reports, checklists and design templates, but the most effective method according to the companies is the assessments of experts in the matter inside the company.

Even though companies are not fully set-based, they are fulfilling the SBCE requirements for manufacturing. Companies concur that the communication between design and manufacturing starts early in the design process, most of them answered that they start during the conceptual design phase and even before, during the requirements definition phase. They also concur that design information is transmitted as something more than a drawing, so they add an extra verbal description to the drawing; failing to comply the SBCE requirement for manufacturing where information should be sent as a set of drawings. All participants apply the process selection methods described on the theory.

In summary, SBCE principles are applied in the respondents only up to a certain extent; therefore it is expected for them to fulfill the SBCE requirements for manufacturing only to some extent.

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