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Master of Science in Management, Economics and Industrial Engineering

# Set-Based Concurrent Engineering Process:

## Contextualization, Industry Analysis and Business Game Development

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## Abstract

New Product Development Models, nowadays play a very important role in manufacturing companies. Each company has been trying to manufacture a product which is efficient and effective in terms of many key performance indicators such as – the most important ones – cost, time, quality, innovation, process flexibility and so on. Most of the companies have been improving their development process in order to increase their efficiency and effectiveness. So many models have been developed and implemented in so many companies; however not all of them were fully efficient and effective model.

Point-Based Engineering, Concurrent Engineering, Stage-Gate Model and Set-Based Concurrent Engineering Model are only some of the models which exist for developing a new product within a company. Some of them are evolved version of the previous ones. For example, the Point-Based Concurrent Engineering is a more complete version of Point-Based Engineering (Sequential Engineering). Companies have been suffering from redesigning and modification which affect negatively on efficiency and effectiveness of the development process. Implementing a model which effectively leads the process to reach to an optimum product is the most challenging issue among the companies.

In this thesis, it is tried to have a broad view of all the models together. Then, focusing on only two models, Point-Based Concurrent Engineering – which is mostly used and applied within the companies – and Set-Based Concurrent Engineering – which is known as a vague and inefficient model – will be explored more in detail. Developing a business game using two explored product development models will be the following aim of this thesis. The business game will be an awareness-educational game which aims at introducing various concepts and enabling factors of two different new product developing models. Through those enabling factors exist in Set-Based Concurrent Engineering; players will be able to develop a predefined product more efficient and effective. As a conclusion of the game, players will be more aware of the Set-Based Concurrent Engineering Model, its concepts and how this model allow the companies to deliver their products faster, cheaper and with higher quality.

# 1 Chapter 1

## 1.1 Scope of the Work

The primary scope of this thesis is to have a broader view and better understanding of the Set-Based Concurrent Engineering Model. This model has been considered as an inefficient model due to spending more time and cost in early stages for exploring different alternatives and gathering information about them; However Toyota Motor Corporation through this model has been leader in the automobile industry. Delivering valuable, high quality within the least development lead time has made Toyota Company to dedicate the huge share of the automobile market.

Most of the companies have been struggling to have a more lean development process. Launching a new product using a lean and sustainable development model can lead a company to be more effective and efficient. Implementing the wrong model or a model which is not efficient enough will add extra development time and cost for companies.

Exploring in details about the existing models of product development process and compare them together, will give us this chance to conclude with the most valuable advantages of them. Set-Based Concurrent Engineering Model as a very successful model for Toyota Company should have been extended among the manufacturing companies. Introducing the Set-Based Concurrent Engineering Model as a very well-organized and a competitive model will be the main scope of this thesis.

## 1.2 Goals of the Work

Developing a business game in order to allow the people understanding how Set-Based Concurrent Engineering Model lead a development process to be efficient and effective will be the main goal of this thesis. The business game should be designed in a manner which shows the people the concepts of the models, how they work within a company, which success factors affect them and what are the advantages and disadvantages of them.

Moreover, teaching and learning concepts of different product development models during universities courses will be difficult and time-consuming for both sides, Professors and Students. Transferring the concepts and definitions of educational material to students through playing an educational game will be the second goal of this work. The business game can be played as an awareness-educational game for related management and industrial courses in universities.

From Marketing and commercial point of view, there will be another goal which is related to the market. This business game can be also played in different companies and manufacturing firms in order to prepare an initial background for implementing the Set-Based Concurrent Engineering Model.

# 2 Chapter 2

## 2.1 Product Development

### 2.1.1 Introduction

From the beginning of emerging products and markets, there was always a competition between the different products in the market. All the companies pursued only one goal. They wanted to gain more share of markets by introducing competitive products which can be fully satisfy customers. They tried always to find a way to deliver their products faster, cheaper and in a high level of quality rather than other competitors. To reach this goal, the development of new product has seen lots of changes which are resulted from customers' requirements and needs. There are also other factors such as corporate growth, technology growth, product variety and so on which affect the path product development. Having purchased a new product which is launched by companies, the customer will look for more and more new and satisfactory version of products. Therefore companies start extracting these needs from the market and transfer them to new products and launch a new version of previous products. As the customers' requirements and needs have been changing (Increasing), the new spaces and opportunities in the market will be discovered by companies. Therefore companies can invest and gain money within these new spaces in the market and produce new products which are more compatible with what customers really expect to receive in the market. In the following, the cycle of emerging new products is shown:

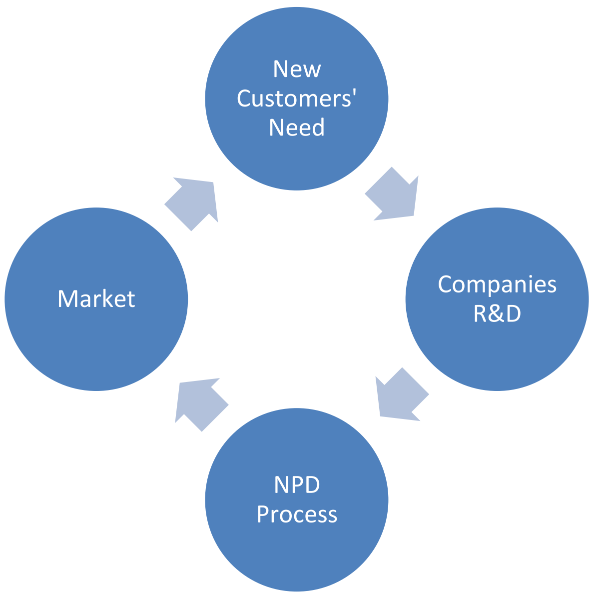



**Figure 2-1 New Product Cycle (Self-Created Figure)**

One of the most important factors dealing with this cycle is New Product Development. NPD plays a critical role in this cycle and most companies based on NPD process try to find out an innovative way to deliver their products which are less expensive, faster in delivery time and more desirable.

### 2.1.2 What does Product Development mean?

"Product Development is the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product" (Ulrich & Eppinger, 1995)

"Agile Product Development Process is one that can rapidly introduce a steady succession of incremental product improvements – which can be called 'NEW' products – that are really planned based on common parts and modular product architecture. This capability results in ultra-fast time-to-market, much faster than possible with independent products that do not benefit from product-family synergies in design and manufacture." (Anderson, 1997)

As it is obvious from these two different definitions which are mentioned above, Product Development –Also called as New Product Development – is at first a process including set of activities. Second of all PD is a broad field of effort in different areas such as design, creation and production of new products.

Many studies have shown different approaches and frameworks of Product Development so far. To have a better idea of these frameworks, they will be briefly explained as follows:

1) Anderson Approach:

   This approach whish also refers as Advance Product Development is based on five phases. These phases include important deliverables. In this approach, the focus on Design phase and Ramp-up Phase are more. Having a product/process design is recommended before prototyping phase which the need for it may be insignificant. Moreover, replacing the term "Ramp-Up" with "Pilot" focuses on having an easier and more flexible new product, if they have been designed with common parts and processes.  The phases of this approach are shown in the following figure.

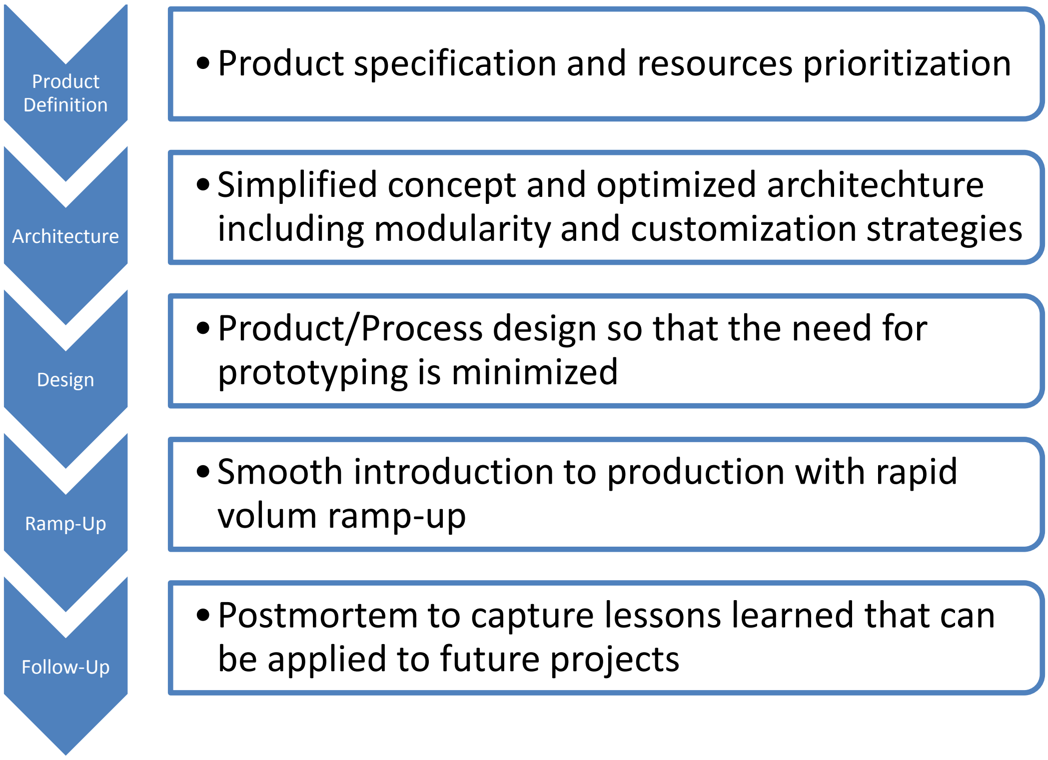



**Figure 2-2 Strategies for Lean Product Development (Walton, 1999)**

2) Wheelwright and Clark

This approach consists of four primary phases. Based on this approach, the cycle time which is considered to fulfill all the phased is thirty-six months from the beginning of the project till the market introduction. The phases of this approach are shown in the following figure.

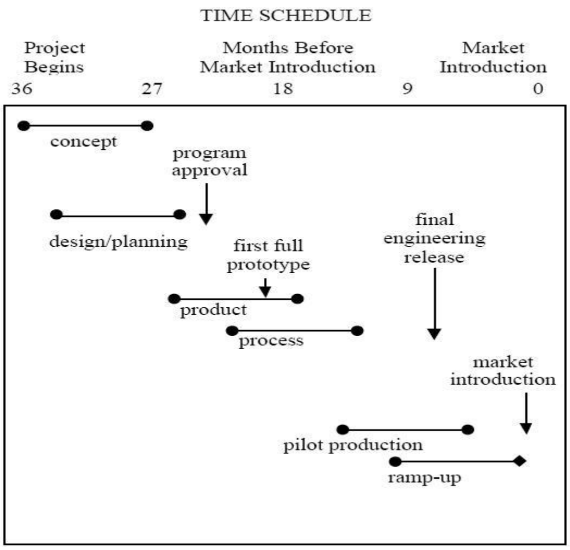



**Figure 2-3 Strategies for Lean Product Development (Walton, 1999)**

3) Ulrich and Eppinger

This approach provides a rich framework and process of the product development with five phases. The activities of each function such as marketing, design, manufacturing and other functions are also provided within a specific phase. For example, manufacturing function in the phase of concept development should estimate manufacturing cost and also assess production feasibility. The following figure will show the Ulrich and Eppinger Product Development Process approach.

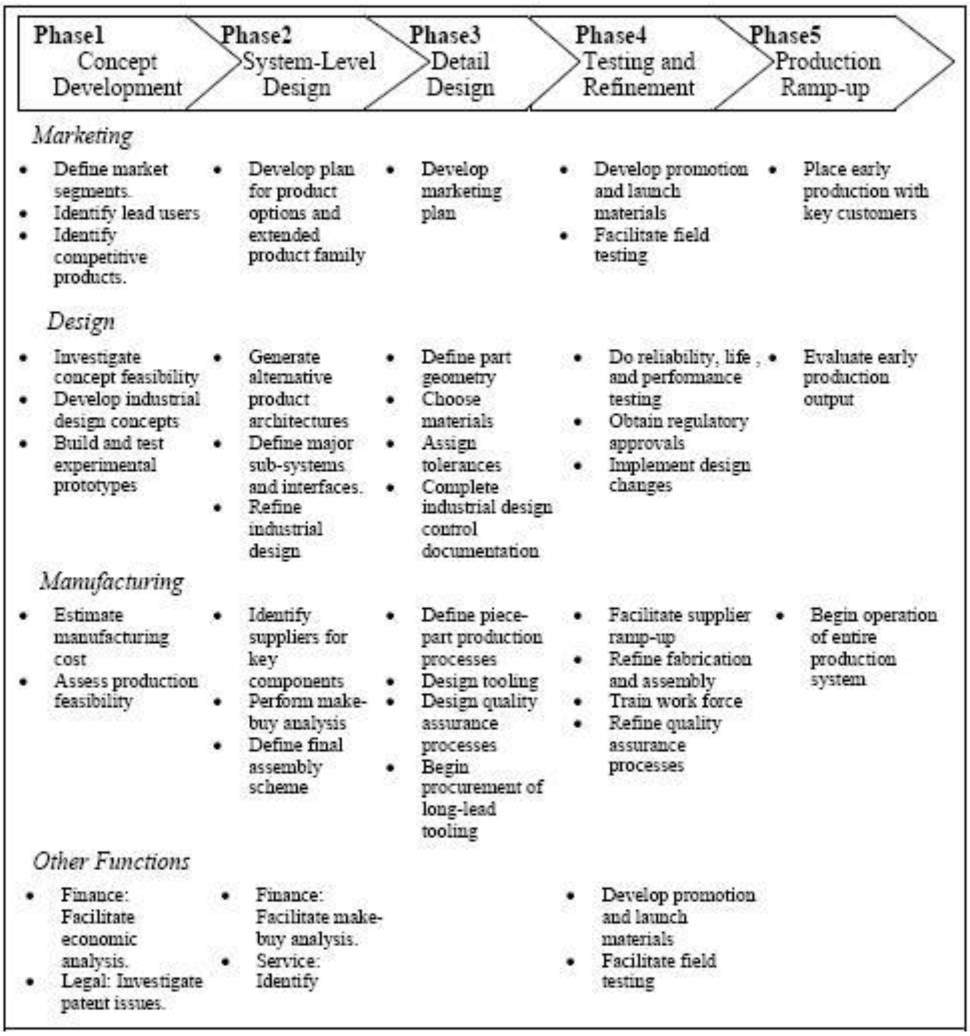



**Figure 2-4 Strategies for Lean Product Development (Walton, 1999)**

### 2.1.3 Strategies and Models

As it is discussed in previous sections, Product Development is simply defined as a process used in business and engineering area in order to create a product – which is different from previous one – and deliver it to the market. Product Development is used because of high competition and innovation existing among different companies in markets. Companies do a huge effort to deliver a new product to markets in a short time and also with high quality. Moreover, companies always take a hard look at best methods and models to become more competitive among other competitors' product development models. Having a successful product development process requires a very strong and stable model in which companies are able to deliver their high quality products within a shorter delivery time and less cost. According to the previous studies, several models have been using so far for product development. To have a better understanding of this paper, it is good to have a short look at these models which are described as follows.

1. Point-Based Serial Engineering
   This model includes a sequence of functions; each of them designs to a single solution or point. Each function comes up with best single solution based on its criteria and it will be ready to be used for the following step. (Sobek, Ward, & Liker, 1999)
   The PBSE usually includes five steps:
   - Problem Definition: Understanding customer's need and establishing product requirements
   - Generating Alternatives: Designers create different alternatives individually or by brainstorming
   - Preliminary Analysis: Engineers carry out an analysis to select a single, feasible and most appropriate, solution for further development
   - Modifying the rest of the concept until all of the product's goals and requirements are met
   - Redoing from Step 1 or 2: In case of any failure, the process should begin from the beginning, either from step 1 or 2

The aim of doing these steps are to reach a best solution from the alternatives, as early as possible, and not to waste the time in developing other alternatives. If the identified solution is not satisfying for customers, it is modified as much as possible or it gives easily its place to a new concept. The following figure will show the Point-Based Serial Engineering approach.

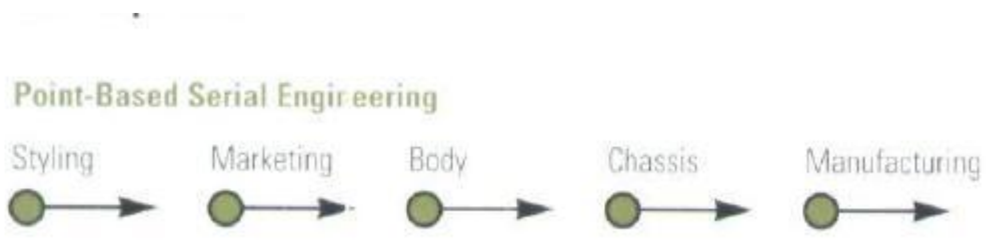



**Figure 2-5 Point-Based Serial Engineering (Sobek, Ward, & Liker, 1999)**

2. Point-Based Concurrent Engineering

According to a journal, Point-Based Concurrent Engineering was defined as "Typical CE is a refinement of point-based design, but still does not break out of the paradigm." (Sobek, Ward, & Liker, 1999) This approach begins with a function, coming up with a solution, which informs other functions with its own solution early, so they can critique and analyze it with their own criteria. The earliness of the feedback results in cheaper and easier modification and design.

The schema of this approach will be shown in the following figure.

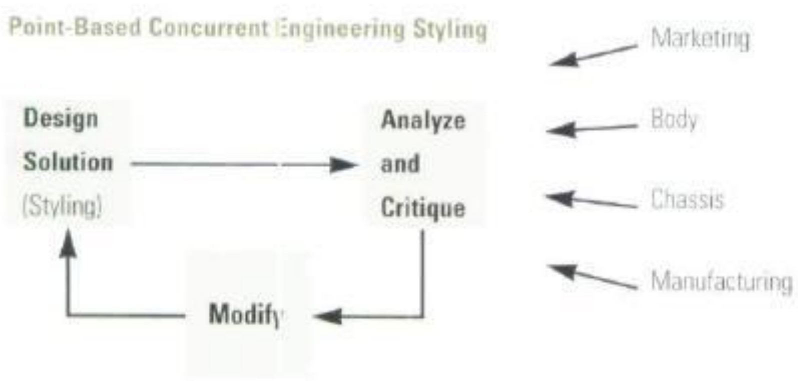



**Figure 2-6 Point-Based Concurrent Engineering (Sobek, Ward, & Liker, 1999)**

According to the competitive advantages of this approach comparing to the previous one, still it has lack of high level of efficiency and effectiveness. Some of its problems are mentioned as follow:

- Facing conflicts and also probability of waste in development process due to not well understanding the limits and needs of other groups in design process
- The Potential of having a change in one group in design process resulting in invalidating the previous decision made by other groups

3. Stage-Gate Model

This model involves a sequence of stages and gates through which the process is carried out. In each stage the work is done and gates are responsible for controlling the sufficiency of quality for the work done in previous stage. The gates make leader and team ensure to meet high standard process execution. Moreover gates make ensure that no critical activity is omitted. This model typically emphasizes a market orientation and inputs, and it devotes far more attention to the frond-end stages that precede the product development phase. The reviews take place after each stage in this model. Usually the reviews are narrow and rigid. (Cooper, 1990)

In the following figure, an overview of Stage-Gate model will be presented.

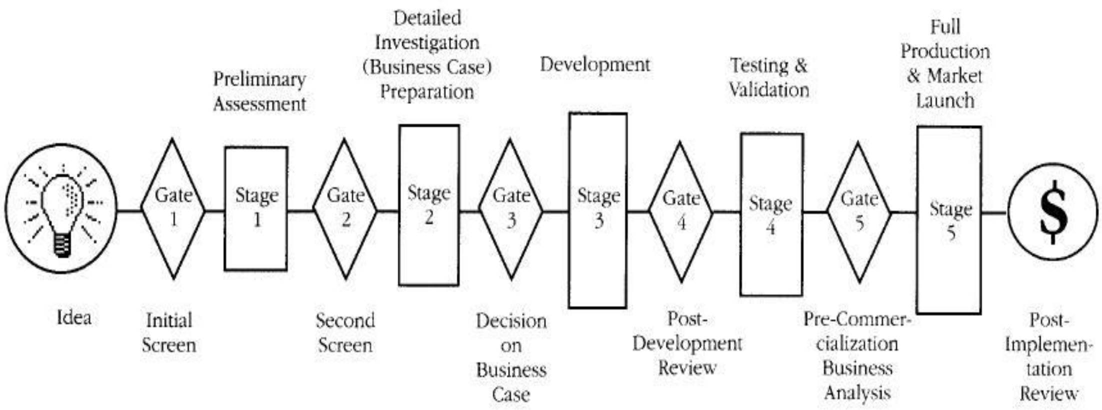



Figure 2-7 Stage-Gate Model (Cooper, 1990)

Considering some advantages such as sharp product definition, reviewing each stage and managerial control, problems will still exist in companies which are using Stage-Gate model. For example, inflexibility can be pointed out as a disadvantage of this model.

4. Spiral Model

   It is model which is different from Stage-Gate model and includes a series of planned iterations expanding several development phases. A key distinguishing feature of the spiral process is the planned, large-scale nature of iterations. Risks, which are assessed in each step of iteration, allow managers to plan an effective approach for next iteration.

   This model is commonly used in development of software products and its proponents claim at reducing in expensive rework in software resulting in lowering the development time and cost.

   The reviews process take place after either each or several stages in this model. The reviews are usually comprehensive and more flexible (Unger & Eppinger, 2009)

   The following figure will show the Spiral Model's overview.

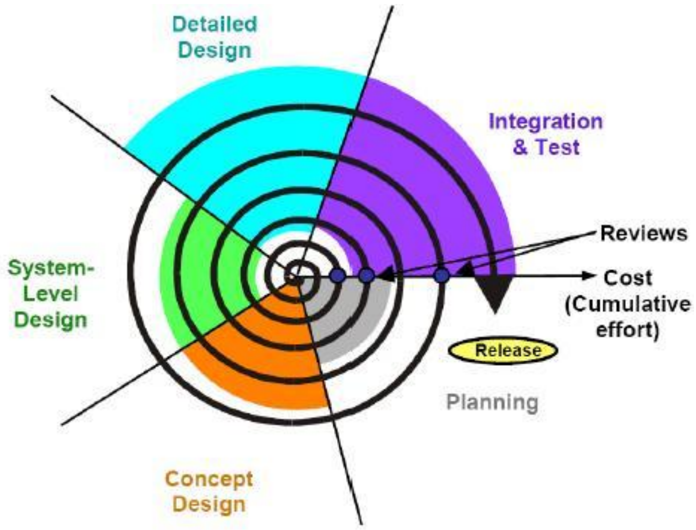



**Figure 2-8 Spiral Molde (Unger & Eppinger, 2009)**

5. Set-Based Concurrent Engineering

   "What we call Set-Based Concurrent Engineering begins by broadly considering sets of possible solutions and gradually narrowing the set of possibilities to converge on a final solution. A wide net from the start and gradual elimination of weaker solutions makes finding the best or better solutions more likely." (Sobek, Ward, & Liker, 1999)

   This approach was first seen in Toyota Motor Corporation. Despite of what this approach was expected as an inefficient model; Toyota Motor Corporation was and is the industry leader in cost, quality and product development lead time. The following figure will show graphically Set-Based Concurrent Engineering.

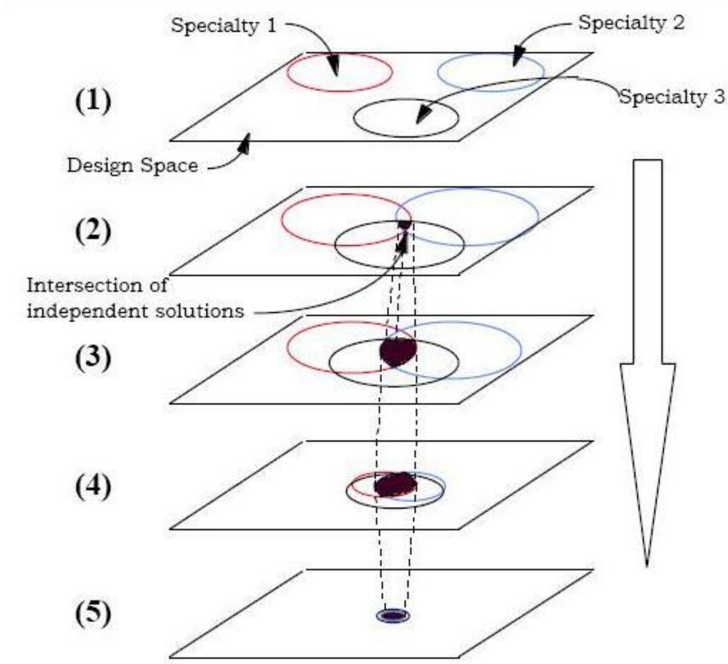



**Figure 2-9 Looking Evidence for SBCE (Bernstein, 1998)**

This approach includes some key features – Enabling Factors – which are very important in product development process. A successful product development process relies strongly on Enabling Factors. They will be gathered and put inside a framework presenting principle of Set-Based Concurrent Engineering. The defined principles will be shown as follows. (Sobek, Ward, & Liker, 1999)

- ✓ Map the Design Space
- ✓ Integrate by Intersection
- ✓ Establish Feasibility before Commitment

Within each principle, there are three different approaches to implementing the principle.

From all the researches and surveyed carried out so far about Product Development Process Models, advantages and disadvantages of these models are gathered in the following table:

| Models | Advantages | Disadvantages |
|---|---|---|
| **Point-Based Serial Engineering** | • Easy to understand and applicability | • Delayed feedbacks<br>• High reworks in process<br>• Low communication among participants |
| **Point-Based Concurrent Engineering** | • Faster early feedbacks from other functions<br>• Simultaneously working | • Probability of iteration and rework<br>• Medium communication |
| **Stage-Gate Model** | • Sharp product definition<br>• Facilitate managerial control<br>• High usage of review points(Gates) | • Inflexibility<br>• Feedback difficulty between phases which are far more than two steps away from each other |
| **Spiral Model** | • Flexibility<br>• Early managing risk | • Requiring more managerial control<br>• High time consuming due to high level of review within the model |
| **Set-Based Concurrent Engineering** | • Efficient communication<br>• Greater parallelism in the process<br>• Promoting institutional learning<br>• Reaching to an optimal design | • Probability of inefficiency and ineffectiveness in case of bad applicability |

**Table 2-1 Product Development Models Advantages and Disadvantages**

## 2.2 Lean Product Development

### 2.2.1 Definition and Concept

As a short phrase of "Lean" definition, it is "increasing value with less work". As a concept "Lean includes several of the popular concepts of management research such as Total Quality Management (TQM), Continuous Improvement, Integrated Product Development (IPD), and Just-In-Time (JIT) inventory philosophy for production products." (Walton, 1999)

Lean production is a process which firstly was used in the Toyota Corporation and originated from Toyota Production System (TPS). (Holweg, 2007)

The main goal of "Lean" philosophy is to reducing inefficiencies while increasing the effectiveness.

### 2.2.2 Lean Thinking

Lean thinking is a very effective method, introduced for the first time in a book called "The Machine That Changed the World: The Story of Lean Production" by Womack, Jones and Ross. In this book, the "Lean Thinking" is referred as a highly evolved managerial method through which an organization will be able to improve the efficiency and the quality level of its product and services. Spending time on wastes in the manufacturing line has been always increasing the human efforts, capitals, spaces, development time and costs. Applying the method of lean thinking enables the companies and manufacturers to eliminate the mentioned wastes and obtain a better product/service, higher productivity company, less costly product/service and more customer satisfaction.

Based on a report, there are some famous principles within Lean Production. (Walton, 1999)

- ✓ Creating economic value – for shareholders – is the objective of each business enterprise
- ✓ Using resources in an efficient way due to their limit
- ✓ Highly effort of business enterprises due to being competitive in having a higher quality, lower cost, and faster delivery time among others
- ✓ Improving on processes by giving people adequate right to make decision in their jobs

### 2.2.3 Wastes of Lean Manufacturing

In the Lean Manufacturing philosophy, the wastes will be the reasons of inefficiencies and ineffectiveness. Omitting the wastes from the manufacturing line enables the company to reach to an optimized development process. Each waste within the company can decrease the customer value and vice versa, a company can increase the customer value by eliminating each certain waste from the entire development process.

Based on researches and articles, there are eight different classes of waste. In the beginning they were classified as seven wastes (Ohno, 1988). Later, with the effort of Liker, the classes of waste were extended to eight wastes which will be mentioned as follows.

1. Defects

   The most popular waste that can be found in production and manufacturing industries is defects or process errors. Defects result in exceeding the value of the product due to increase of production cost.

2. Over-Production

   This waste might also create other wastes such as higher number of defects, more waiting time, higher inventory and scrap finished goods.

3. Waiting

   This waste is considered as the time which workers stop working due to machine breakdown, bottlenecks within a station and lack of equipment.

4. Transportation

   All the unnecessary transportations are considered as waste. Transporting materials from one place to another, having a long-distance transportation for work in progress and inefficient movement of the finished goods are some of the transportation waste.

5. Inventory

   Inventory waste consists of all the surplus items such as raw materials, work in progress and finished goods.

6. Motion

This waste is referred more as human bodies (Sometimes also as IT and Electronics). Unnecessary movement of the workers during their task will result in this waste.

7. Extra Work

   All the unnecessary tasks to which the customers do not pay attention will be considered as the "Extra Work Waste".

8. Non-Utilized Talent

   "Losing time, ideas, skills, improvements and learning opportunities by not engaging or listening to your employees" (Liker J. K., 2004)

### 2.2.4 Tools and Techniques

As the concept and definition of Lean and Lean Production are presented above, developing new products faster, cheaper and with higher quality require applying some technique in Lean Product Development. (Karlsson & Ahlstrom, 1996)

Despite of existence of some techniques before, implementing only all of them together leads to a Lean Production. Based on the researches and papers, there are a huge number of lean tools. Most of the common lean tools will be gathered in the following.

1. 5S Visual Workplace

   It is a tool, composed of five "S"s, by which a well-organized, clean and efficient work environment will be able to be provided for workers. This tool consists of five "S"s which are mentioned below.

   - Seiri (Sort): This step is to organize the work area. The better communication between workers, higher product quality and productivity will be the results of this step.
   - Seiton (Set in Order): Arranging the required items in order is the second step of this tool. The easiness of use and accessibility of the items increase by following this step.
   - Seiso (Shine): The third step of this tool dedicates to keeping the items clean. Having a swept area can enable the workers to work more safely and identify the problems easier.

- Seiketsu (Standardize): Creating a standardized framework and approach for carrying out tasks and activities is the fourth step of this tool.
- Shitsuke (Sustain): The last Step is related to the commitment of the all the previous steps. Discontinuously following the steps will result in turning back from a clean and organized work area to a dirty and chaotic workplace.

2. Value Stream Mapping

   This tool is used to illustrate the relationship among the activities and tasks during the processes. One of the key component of VSM is to separate the value-adding activities from non-value adding activities. Through this tool, it is simpler to eliminate the non-value adding activities, which is a waste and identifying the positions in which there will be a possibility to increase the customer value.

3. Total Productive Maintenance (TPM)

   It is a powerful program for planning the maintenance of the machines in a manufacturing line and to decrease the number of machine's downtime.
4. Kaizen Blitz Events

   This tool is also known as "Continuous Improvement" and it aims at addressing and resolving important business issues or constraints. Kaizen Blitz Events correct constraining factors in a fast, efficient and powerful way.

5. Error and Mistake Proofing

   This tool is also called "Poka Yoke" and is one of the most powerful lean tools in order to realizing that the products and processes are completed correctly for the first time.

6. Single Minute Exchange of Die (S.M.E.D.)

   This tool aims at decreasing greatly the number of machine breakdown, consequently increasing the throughput by creating very fast changeovers and setups.

7. Inventory and Lead-Time Reduction

   As Inventory is considered as one of the wastes in lean thinking, this tool is used in order to avoid excess inventory and as a result decrease the lead-time.

8. KanBan Implementation

   This tool is a labeling mechanism to identify what work is to be done and when. It is a Japanese term which means “Label”.

## 2.3 Point Based Engineering VS Set-Based Concurrent Engineering

This section is dedicated to two models (Point-Based and Set-Based Concurrent Engineering) of the Product Development Process which will be compared to each other more in detail in order to better understanding of how they bring new products to markets. To reach this goal, both models will go through designing a product from the design to launch. Then, a discussion will take place about which one is more efficient and reliable. The successful key factors of models will be compared in the discussion and at the end the strengths and weaknesses of models will be mentioned.

The product which is assumed here will be an Airplane. Although “Airplane” is a very complex product and it has lots of components and sub-components to be designed, engineered and manufactured; a very simple and easy view of an Airplane will be used here.

1. **Designing an Airplane using Point-Based Model:**

As it is discussed in previous sections, Point-Based Model is a traditional model of product development process. The concept of this model is to progress within the process through keeping forward point by point, function by function. A process of developing an Airplane will be carried out using this model as follows.

Assuming an Airplane Manufacturing Company tries to develop a new airplane. In the beginning engineers and designers try to come up with several different alternatives. For example the stylists will try to create three different airplanes design concepts. These three sample designs are shown as follows:

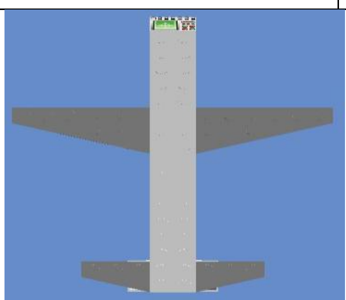
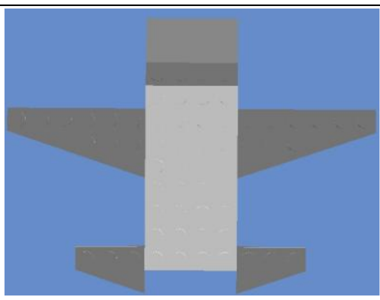
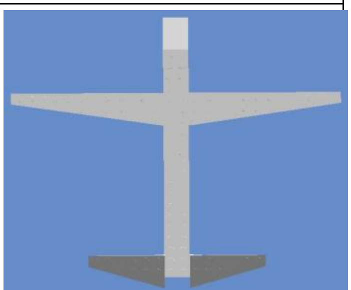
| Alternatives | 1 | 2 | 3 |
|---|---|---|---|
| Designs |  |  |  |

**Table 2-2 Airplane Design Alternatives**

Then engineers try to gather preliminary analysis over the alternatives. This analysis includes the components' specifications, customer requirements and goals and objectives of the product. Then, they will select one of these alternatives as the best one and to conduct it for the further development. Let's imagine that the first alternative is selected due to the fact that the first alternative is more compatible with requirements of the customer and also with company's goals. The other alternatives then will go for more analysis and modification in order to obtain the product's requirements and objectives.

The first alternative will go through the process and engineers try to provide and gather the detail design of this alternative. Then they will introduce its product to supplier. Now supplier should do an assessment of the provided design to see the feasibility of supplying the components of the product to the next upstream point. Here, due to lack of communication and integration, the probability that the supplier gives feedback about infeasibility of the product is high. The designed airplane by engineers is not fully consistent with the requirement of the supplier. In this case the engineers should modify the product and make it compatible also with supplier requirements, or they can use the other alternatives (second or third alternative), if they are met the requirements, and again deliver them to supplier; however the probability of not accepting the design by supplier still exist.

Reaching to a final airplane design which provides the requirements for both engineers and supplier affects the cost and time of the developing process. Having being accepted the product by supplier, the next point is to prototype and test the airplane. In this stage, probable problems will appear in assembling the components or testing the airplane. For example, the manufacturing department will notice a technical problem in joint attachment between body and wings. These problems again lead to iteration and modification of the design which needs to go back to the early points of the process. After some modifications and reworks, the final airplane which is compatible with the whole system will be ready to launch.

In the following the process of developing the airplane will be graphically shown:

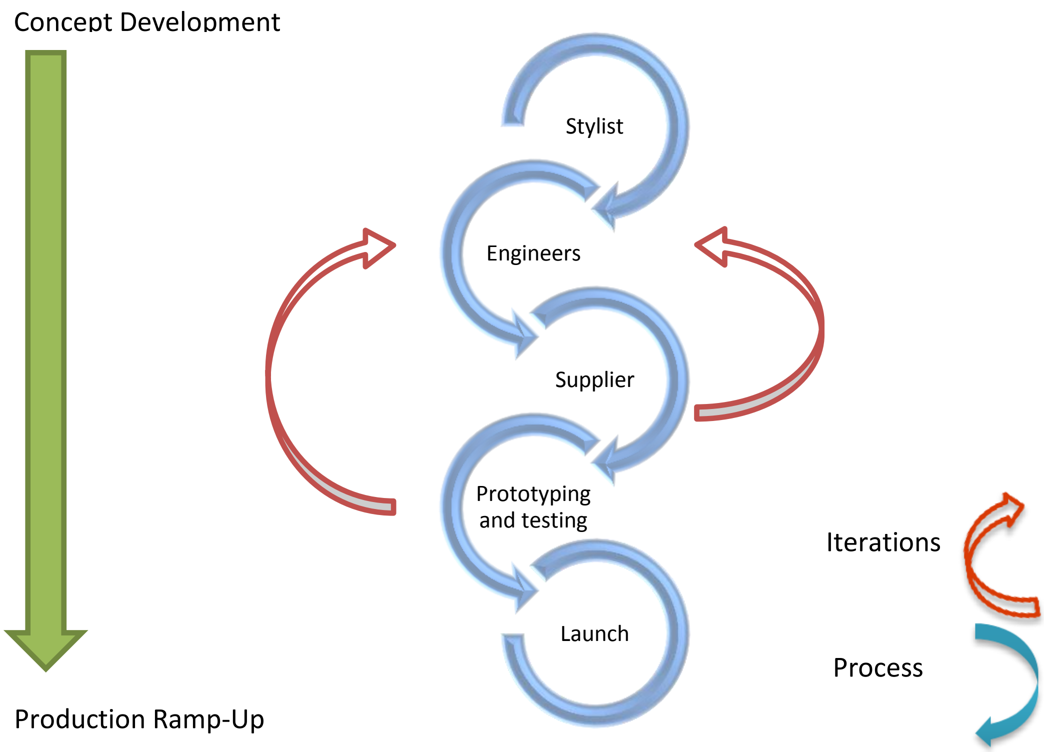



Figure 2-10 Airplane Development Process (Self-Created Figure)

## 2. Designing an Airplane using Set-Based Model:

Developing an Airplane using Set-Based Concurrent Engineering will be based on the principles of Set-Based Concurrent Engineering Model. In this model the company tries to define a set of solutions rather than one and to push them toward the development process pipeline along with narrowing them and eliminating the unfeasible solutions till a satisfactory and optimum solution emerges. As it is discussed before, this model consists of three principles. Each of them encompasses different approaches. Considering principles and their approaches, the procedure of developing an airplane will be mentioned as follows.

In the beginning of the process, concept of an airplane is defined for the project. The functions are divided to four different sections which are Body, Wings, Tails and Cockpit. In this early stage of the process, different functional department defines the feasible regions from their own views. In our example, as we mentioned before, different functional department of Airplane try to define their own acceptable regions based on past experience and experimentation they had before. The criteria to define the regions are based on manufacturability, functionality and design constraints. For example, from manufacturing point of view, a feasible region is that length of the body should not be more than 80 meters.

(Numbers are created). Each function considers all the criteria to clearly define its own feasible regions. Overestimated or underestimated feasible regions will lead in the future high cost and delivery time due to finding unfeasible regions late in the process. The following table will be an example of the feasible regions of Airplane. (Numbers are created and unreal)

| | Manufacturability | Design Constraints |
|---|---|---|
| Body | • Length < 80 meters<br>• Width < 5 meters<br>• Height < 4 meters | • Stability of the Body |
| Wings | • Distance between Head of Airplane and Wings < 35<br>• Length < 14 | • Wing Area<br>• Wing Position on Body |
| Tails | • Length < 7 | • Tail Position on Body |
| Cockpit | • Length < 7 | • Alignment with Body |

**Table 2-3 Airplane Feasible Regions**

The following figure will show the feasible regions defined by each function:

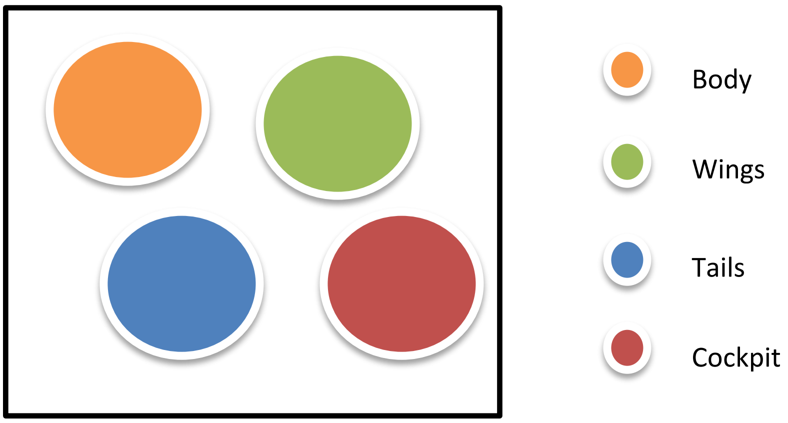



**Figure 2-11 Design Space of Departments (Self-Created Figure)**

Having defined the feasible regions by each function, now they try to design multiple alternatives for each part regarding the constraints within every region. The alternatives must not fall outside of the regions. In our example, the alternatives are designed for each part of the airplane, shown in the following table.

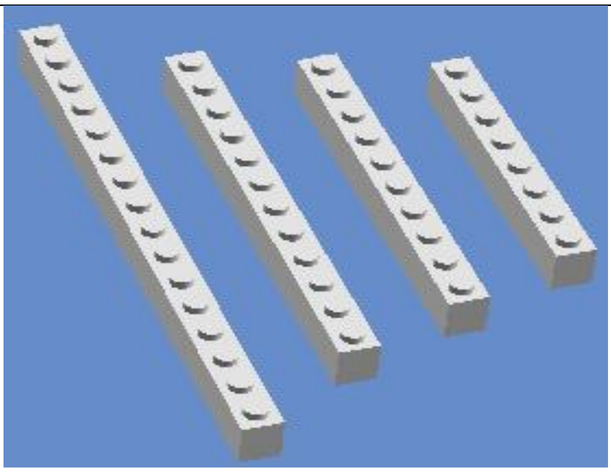
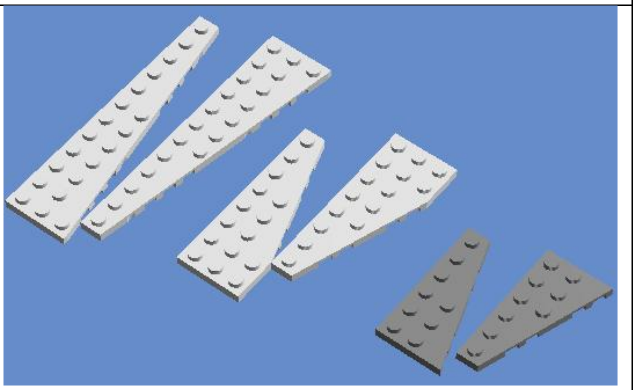
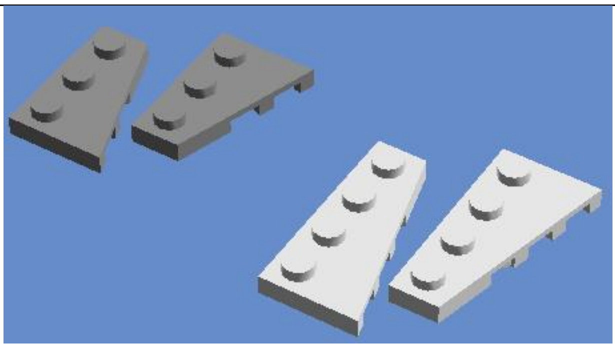
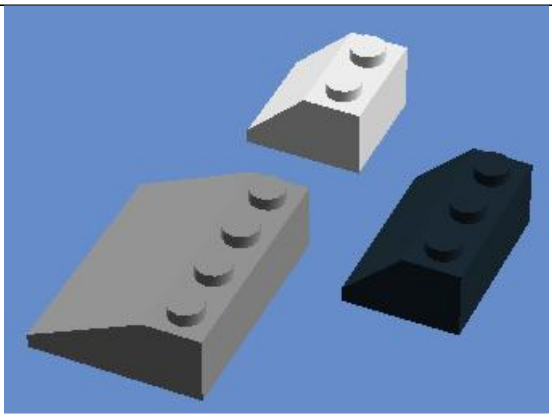
| | Alternatives |
|---|---|
| Body |  |
| Wings |  |
| Tails |  |
| Cockpit |  |

Table 2-4 Component Design Alternatives (Self-Created)

Then all functions communicate together in order to understand the possible regions of the others. Communicating about the alternatives will allow putting all the existing constraints together and have a better view of the possible regions. Moreover understanding the needs and capabilities of other functions will be also another result of communicating together. This step is graphically shown in the following figure.

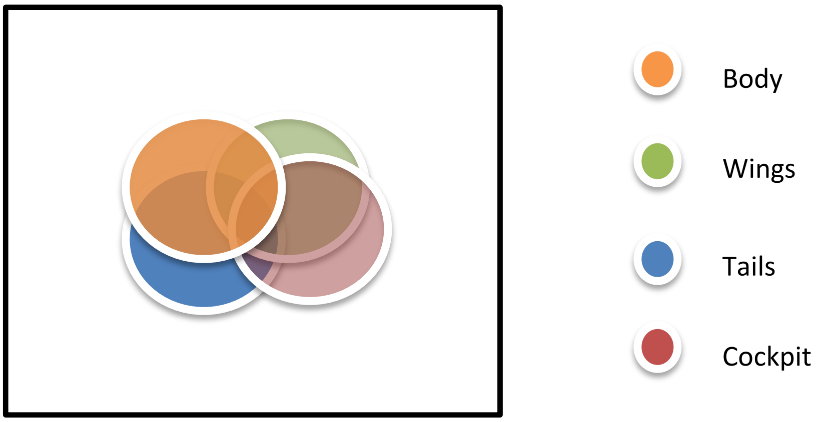



Figure 2-12 Possible Regions by communicating (Self-Created Figure)

The aim of this step is to integrate the possible regions and to focus on the acceptable solutions which are compatible with all the functions.

Having gathered together all the possible sets from all the functions, now they look for feasible sets by integrating the sets. The following figure will show graphically the intersection of all the functions.

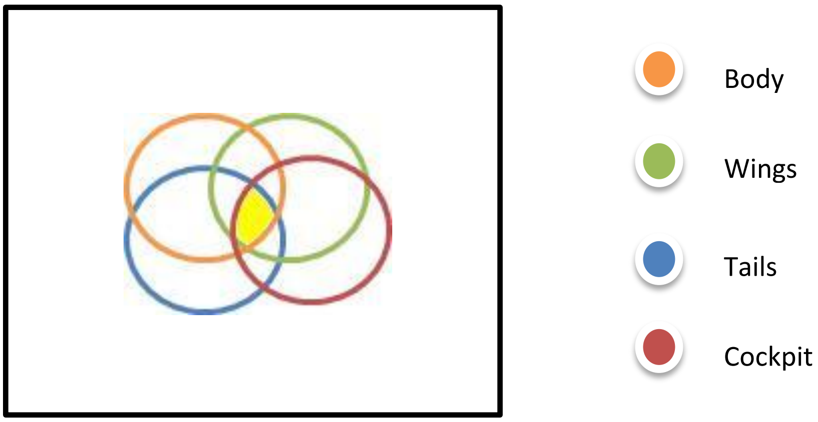



Figure 2-13 Intersection of Departments (Self-Created Figure)

This approach will allow the functions to know more in details about the other alternatives from other sets and by integrating and putting together all of them, they try to find an intersection in order to extract the feasible sets from that. In airplane product development, for example, the shortest possible solution of “Body” cannot be compatible with the longest possible solution of “Wing”. Therefore the shortest alternative of “Body” will not be within the intersection and automatically will be eliminated from the possible solutions. This integration will take place for all the functions based on the data and details they have gathered. Finally there will remain a zone in which you can find all the feasible solutions from all functions.

After finding sets of feasible solutions for the product, now it is time to reach the optimum one. To reach this goal, all the departments will try to eliminate the weak feasible solutions till one satisfactory solution remains. While they are approaching to the optimum solution, they also consider some factors which have a huge impact on the process. In the following they will be mentioned.

- Increasing the Details While Narrowing the Sets Gradually
  Having found the intersection and defined the feasible sets of solutions of airplane, all the departments try to increase the details of each set while the process of narrowing is also carrying out. The compatibility of all the parts (Body, Wings, Tails, and Cockpit) with the whole system is always considered. The communication is also another important factor which is necessary in the whole process to be able to narrow the sets. Component departments will communicate and show the feasible sets to supplier and manufacturer in order to receive feedback from then and to know which one of the solutions are not compatible with supplier’s or manufacturer’s requirements.
- Imposing Minimum Constraints
  Early freezing constraints decreases the level of flexibility and it might have huge costs due to changing and modifying the parts which are not easily assembled. They try not to set the specification from early stages in the process. When the component functions communicate about the feasible sets with manufacturing and only consider nominal dimensions for the components, the manufacturing easily can make a comment on these nominal dimensions which are compatible with manufacturing requirements. Then

send feedback to component functions about the constraints. At the late stage of the process, close to launch the product, they can decide about the exact specifications of components.

- Stay Within the Sets

  From the beginning of finding the intersection till the optimum solution, all the departments must work exactly on the zone of intersection. Ignoring the current feasible set and going to find other possibilities out of the intersection zone will lead to inconsistency with the other departments. Rework, higher cost and delivery time, iteration will be the outcome of not staying within the sets. For example, assume that Body Function will try to look for a new and better Body, in its opinion. They work on designing a new body and increasing the details about it, while the other functions are working on the feasible sets. The time of showing and communicating about the sets, the Body Function will notice that its new part is not compatible with the whole system. Therefore, it needs to go back to the zone and work on the feasible sets within the zone.

Having designed a very simple airplane using both models, it should be more clear the differences and key factors which exist in each model. As it was obvious from the comparison, the main and most important problem of the Point-Based Model is “Iteration”. Because of several reworks and modifications, the process has to go back to previous steps in order to meet the requirements which are compatible with the requirements of the current step. Therefore, cost and delivery time will increase each time that the process is forced to go few steps back. Iteration is resulted from several factors such as:

- ✓ Lack of communication
- ✓ Lack of integration
- ✓ Using one best solution instead of sets of feasible alternatives
- ✓ Ignoring the feasibility of solutions
- ✓ No convergence

In the Set-Based Concurrent Engineering, the “Iteration” will reach to its minimum level due to using Enabling Factors which are used properly in the development process. As it is mentioned in the previous chapter, these enabling factors play their roles within the SBCE

Principles mentioned in previous sections. The Enabling Factors extracted from the research and studies are mentioned as follows:

- ✓ Using more experienced managers and engineers by developing deep technical expertise
- ✓ Using Chief Engineering System
- ✓ High and Frequent Communication: By having more communication about sets of solutions, regions of design space, the richness of communication increases. Therefore it decreases the time and number of meetings.
- ✓ Integration: Determining key constraints on its subsystems based on past experience and info from the CE.
- ✓ Subsystem options: are constraints on interfaces and make the problems easier to be solved
- ✓ Number of Alternatives
- ✓ Number of Teams
- ✓ Late Decision Making
- ✓ Intersection Area
- ✓ Feasible Regions
- ✓ Sets of Solutions
- ✓ Back-Up Solutions
- ✓ Uncertainty Level
- ✓ Level of Increasing Details

At the end of this chapter, the differences within each model will be compared to each other. The following table will show the comparison between Point-Based and Set-Based Concurrent Engineering Model.

| Function | Point-Based Model | Set-Based Model |
|---|---|---|
| Searching the Alternatives | Iterating existing Ideas<br>Brainstorming New Ideas | Defining Feasible Regions |
| Number of Developing Solutions | One – The Best Idea | Several – Sets of Solutions |
| Level of Feasibility of Solutions | Low | High |
| Communication | Communicating ONLY the Best Idea | Communicating Sets of Ideas |
| Alternative Selection Policy | Go for the Best One | Eliminate the Worst One - Narrowing |
| Specification Policy | Freezing the Specification | Imposing Minimum Constraints |
| Decision Risk Control Policy | Establishing Feedback Channels | Using Conservative Options<br>Seek Robustness Concept |
| Rework Policy | Reviewing Often the Progress<br>Establishing Feedback Channels | Stay within the Sets |
| Management Policy | Managing Information at Transition Points | Manage Uncertainty at Process Gate |

**Table 2-5 Comparison between PB and SB Model (Sobek D. K., 1997)**

# 3 Chapter 3

## Set-Based Concurrent Engineering

Applying the Set-Based Concurrent Engineering, instead of other models, will bring a broad range of benefits for companies; however based on the studies, most of the companies consider Set-Based Concurrent Engineering as an inefficient model for their New Product Development Process. The high number of variables and usage of many concepts in this model have brought this thought to companies that applying this model will cost more and increase the delivery time of the product development process. As it was shown in the previous chapter, the only and most important disadvantage of Set-Based Concurrent Engineering could be wrong usage and applicability of the model. Higher cost, Longer Delivery Time and Low Quality could be resulted from ignoring or inappropriate implementation of one the variables in the model.

This chapter aims at providing the whole variables extracted from studies of Set-Based Concurrent Engineering and make a general framework in order to better understanding of implementing the model within a company.

## 3.1 Context of Set-Based Concurrent Engineering

The so called name "Set-Based Concurrent Engineering" is first used in Toyota Motor Corporation. Toyota was the first company which has been taking benefits from this model, despite of all the other companies which consider SBCE model as an odd and inefficient model.

As it is explained before also, Set-Based Concurrent Engineering consists of several enabling factors through which a set of possible solutions will be able to be defined, explored, compared by trade-off curves, integrated, narrowed and converged. The enabling factors lie down behind some principles, each which also has some approaches to be followed during the Product Development Process. These principles have been applied in Toyota Motor Corporation's Product Development for two reasons; first to understand possibilities and define feasible solutions by exploration and communication among designers and engineers and second to use the captured knowledge by documenting findings of each project. The principles of the Set-Based Concurrent Engineering will be explained as follows. (Sobek, Ward, & Liker, 1999)

1. Principle One – Map the Design Space
   i. Define Feasible Regions
   ii. Explore Trade-Offs by Designing Multiple Alternatives
   iii. Communicate Sets of Possibilities

2. Principle Two – Integrate by Intersection
   i. Look for Intersections of Feasible Sets
   ii. Impose Minimum Constraint
   iii. Seek Conceptual Robustness

3. Principle Three – Establish Feasibility before Commitment
   i. Narrow Sets Gradually while Increasing Detail
   ii. Stay within Sets Once Committed
   iii. Control by Managing Uncertainty at Process Gates

Having used these principles and approaches, Toyota Motor Corporation has been known for the least delivery time of product development with the lowest project cost. To better understanding the principles and approaches of the model, the procedure of the Product Development Process of Set-Based Concurrent Engineering, which has been practiced in Toyota, will be explained in this section.

From the early beginning of the project, Chief Engineer with support of the staff tries to come up with vision of the new vehicle considering the basic style of the vehicle (ex. Type of Engine, Type of Suspension, Performance Target …). The Stylists and Manufacturing Engineers will be informed about the basic style of the vehicle. Manufacturing Engineers provide a checklist according to their current and future capabilities. The checklist will then be delivered to both Stylist and Product Engineers in order to communicate about the capabilities and requirements of Manufacturing. In parallel way of Manufacturing Engineers task, the Stylists also try to develop a set of possible design options (usually between five to ten options) regarding their own requirements and the Manufacturing Engineers' capabilities documented in checklist. Having designed the possible options, which are compatible with

Stylists and Manufacturing Engineers, the Product Engineering Groups start studying drawings in order to understand the requirements of the other functions. If Product Engineering Groups encounters an inconsistency during study, they will give feedbacks to previous functions. Feedbacks may include a problem or an improvement in each drawing.

According to the received feedbacks, Stylists and Product Engineering Groups work together to narrow the possible sets and reach a final optimum solution. Product Engineering Groups try to provide a detailed design based on past data, information from other engineering groups and input from Manufacturing Engineers and Chief Engineer. Integrating the activities, communication between functions and exchanging the information frequently among different teams will allow the Stylists to narrow the sets and to reach to a final design which is compatible with the whole system.

While the detailed design of final design is being increased, two prototypes begin. The first one aims at testing the product in different sub-systems and variations in specific design factors. According to the first prototype, in case of modification, some specification should be changed which results to the second prototype aiming at confirming the taken decisions of the first prototype. Having confirmed the prototype, the specifications are fixed at the late stage of the product development and Production Run starts.

## 3.2 Set-Based Concurrent Engineering Requirements

Within the Set-Based Concurrent Engineering, there will be several variables which are the key success factors of the model. Increasing the level of attention to those factors will lead a company to be successful in terms of efficiency and effectiveness of product development process. These factors have been called as "Enabling Factors". This section is dedicated to discuss about the Enabling Factors more precisely in order to provide a broad view of Set-Based Concurrent engineering.

### 3.2.1 Multiple Design Alternatives

Developing a product using more than one design alternative seems to be costly and more time consuming in the first look. Coming up with multiple alternatives instead of one, requires more time to define the designs, gather information about the design, improve the design and make the designs real. Moreover, the cost increases due to developing more than one design alternative. It is obvious that increasing the number of design and developing multiple alternatives in a parallel manner will lead to higher cost and delivery time in early stage of the development process. In the following Figure, it is shown the impact on cost and delivery time in case of increasing the number of alternatives.

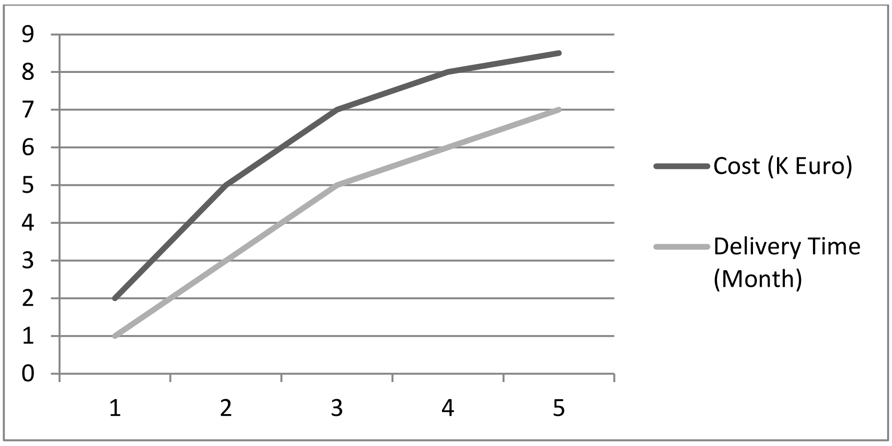



**Figure 3-1 Multiple Alternatives Effect on Time and Cost (Self-Created Figure)**

On the other hand of this apparently inefficient factor, there are some benefits. First, increasing the number of alternatives will increase the probability of taking more benefits of different alternatives. Meaning that developing simultaneously different design alternatives will expand the space of design for each function and therefore the functions will be more able to adapt themselves to other functions' requirements, or mathematical definition is that the probability of finding an area which is compatible with all the system is higher.

Second, using multiple design alternatives will result in less number of iteration late in the development process. Therefore the total time of delivery and cost will decrease during the second half of the development process which is dedicated to prototyping designs. The following Figure will show the iteration rate at the end of the development process.

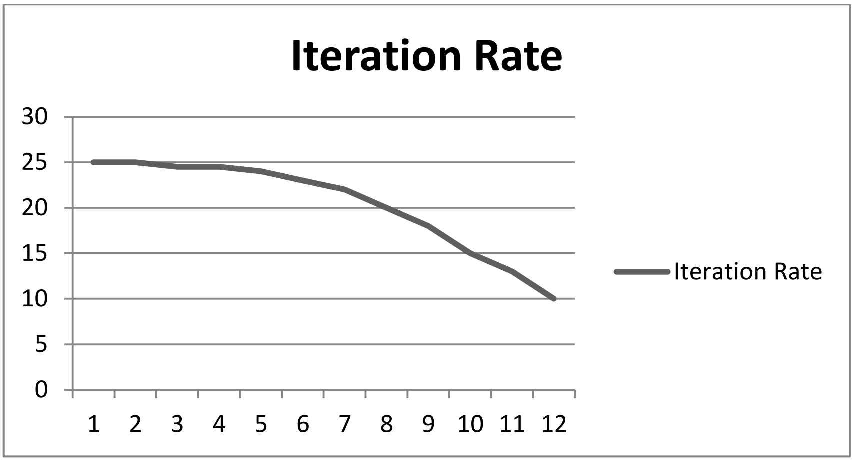



Figure 3-2 Iteration Rate during Product Development Process (Self-Created Figure)

To have a better understanding of using this Enabling Factor, an example of multiple design alternatives will be explained as follows. (Ward A. C., 2007)

Imagine two different airplane companies which are trying to develop a new airplane. The first one is following a traditional product development model and the second one is using Set-Based model. Each bicycle includes four sub-systems: Body, Wings, Tails, and Cockpit. Let's assume a 15% chance of major problem caused by each subsystem and 30% chance of incompatibility of all the subsystems.

Some rules also should be considered. The following table will show the probability rules:

| Rules | Equation | Comment |
|---|---|---|
| 1 | Pf = 1 - Ps | Pf: Probability of Failure<br>Ps: Probability of Success |
| 2 | Pn = n*Pi | Pn: Probability of a number of independent events<br>Pi: Probability of individual event |

Table 3-1 Probability Rules

In the first company only one design is in progress for each subsystem. Therefore, based on the rule one, the probability of success of each subsystem can be calculated. Then based on rule two, the total probability of development process success can be calculated by multiplying all the subsystems probability, including the success probability of all subsystems. The following table will show numerical calculation of the traditional company.

| Subsystems | Probability of Success |
|---|---|
| Body | 0.75 |
| Wheels | 0.75 |
| Tails | 0.75 |
| Cockpit | 0.75 |
| System Integration | 0.7 |
| Total | 0.22 |

**Table 3-2 Probability of Success using Point-Based**

As it is obvious in the table, the total probability of success for the company to develop a new bicycle will be only 22% which is very low. The traditional company will notice this low probability of success late in the process and to reach a better result and higher success probability percentage, it will have to increase the effort in development process (Re-designing the product, higher communication, new technology and so on). Therefore it will encounter to more iterative process and consequently the cost and delivery time of the development process will increase.

In the second company – using Set-Based model – each subsystem take benefit of three design alternatives with a 20% probability of failure for each design alternative. The following table will show the numerical calculation of the second company.

| Number of Design Alternatives | Probability of Failure of all Design Alternatives for each Subsystem |
|---|---|
| 1 | 0.2 |
| 2 | 0.2 |
| 3 | 0.2 |
| Total | 0.008 |

**Table 3-3 Probability of Failure using Set-Based Concurrent Engineering**

Using rule one, the success probability of each subsystem will be 0.992.

| Subsystems | Probability of Success |
|---|---|
| Body | 0.992 |
| Wheels | 0.992 |
| Tails | 0.992 |
| Cockpit | 0.992 |
| System Integration | 0.7 |
| Total | 0.68 |

**Table 3-4 Probability of Success using Set-Based Concurrent Engineering**

As it is shown in the table, the probability that at least one successful alternative creates is 68%, comparing to the previous one is much higher.

As conclusion, using multiple design alternatives will increase the cost and time required to search and gather information for each of the alternatives; but later in the process, when you will face with inconsistencies and incompatibility of the design with the whole system, having more than one alternative will help you to take benefit of different alternatives not to iterate the process to much and to prevent huge costs and time. The following figure will show the cost of the whole product development process considering multiple design alternatives in traditional and Set-Based model.

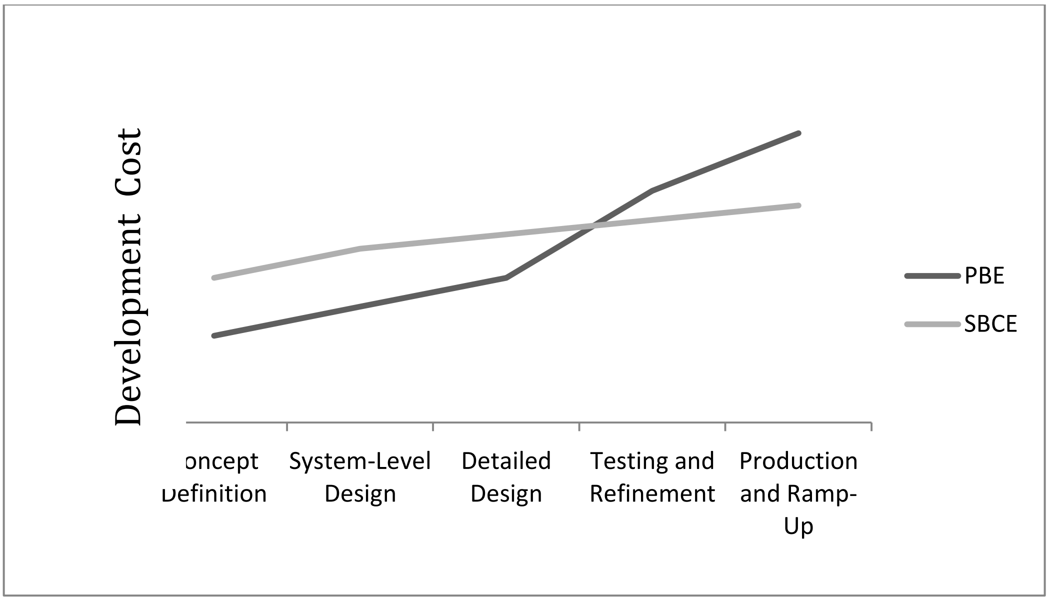



**Figure 3-3 Development Cost during Product Development Process (Self-Created Figure)**

### 3.2.2 Communication between Functions

Set-Based Concurrent Engineering Model benefits from high level of communication among the functions within the development process. Including such factor to the process will result in shortening the delivery time of product development. According to a journal, Set-Based design communication is more prevalent among Japanese than among U.S parts suppliers. (Liker, Sobek, Ward, & Cristiano, 1996 ). This is related to some specific features of product development. Years of experience with early involvement of suppliers in design, the degree of product-process design overlap, the degree to which subsystems are interdependent and the use of quality function deployment (QFD) are features which make Set-Based Concurrent Engineering different from other models.

One of the main and effective communications in Set-Based Concurrent Engineering is Design-Manufacturing Relationship. Providing a design which is not compatible with manufacturing function could result in rework and modification of the design. The less exchanging the information between Design and Manufacturing function, the more probability of design modification in the manufacture department. In the following Figures, the relationship between design and manufacturing department is shown.

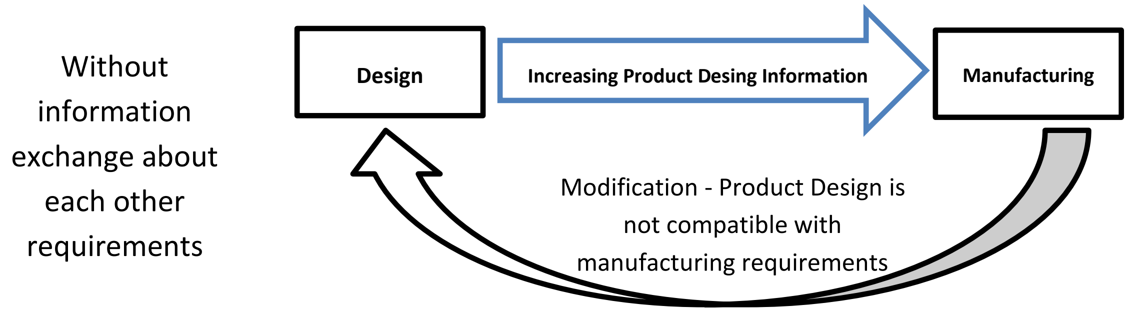



**Figure 3-4 Relationship between Design and Manufacturing Department (Self-Created Figure)**

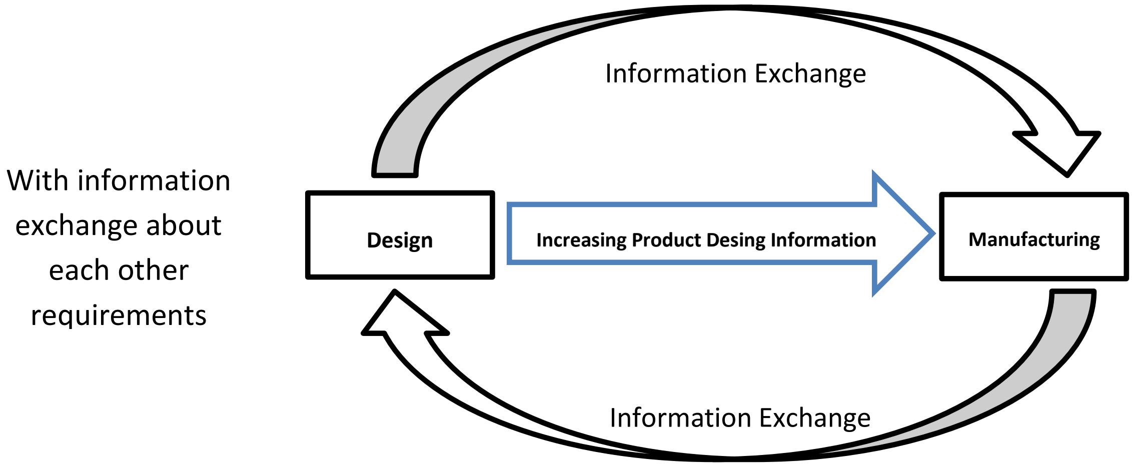



**Figure 3-5  Relationship between Design and Manufacturing Department (Self-Created Figure)**

The Design-Manufacturing Relationship is divided to three classes as follow. (Adler, 1995)

1. Mutual Relationship – also called as Reciprocal Model in which an optimization of product and process is carried out through performing an in-depth design reviews to assess manufacturability of designs and also putting manufacturing engineers to product design teams in a full-time basis.
2. Before Project Relationship – Define a set of limitations by both Design and Manufacturing before the project starts. Following this model, when the project starts, the product designers already know about the requirements and constraints and they can design the product which is compatible with manufacturing's limitations.
3. Continuous Relationship – The concept of this approach is that Design and Manufacturing work together for several months after the product design releases to the Manufacturing in order to increasing the quality of the product.

Another effective feature of product development is to involve supplier from early stage in the development process. Toyota meets with its supplier less often for shorter periods of time than any other major auto company in the US or Japan even though Toyota suppliers appear to have greater design responsibility, and report fewer communication problems (SOBEK & Ward, 1996). Involving supplier early in the product development will result in understanding the capabilities of each other and based on each other's requirements they can easily decide about the optimum solution. The specifications are not fixed in this approach and manufacturer allows suppliers' hands open to make decisions about set of product specifications delivered by manufacture.

On the other hand, communication with supplier and giving more responsibility to supplier from the early beginning in the development process requires a very strong reliability between the supplier and parent company. Communicating ambiguously about the product specifications must not lead to a low quality product due to an easy and cheap product specification decision made by supplier. Moreover, supplier's experience is also another factor which is required in communicating with manufacturer about taking decisions of vague situation. This type of communication should be carried out by prototyping different designs, testing them, gathering information about them and providing trade-off curves, which will be discussed later.

The following Figure will show the communication between the Toyota Company and one of its suppliers. It is obvious from the picture that supplier and Toyota try to define their own space of capabilities and then based on supplier's proposals; they will come up with certain product specification which is compatible with the whole system.

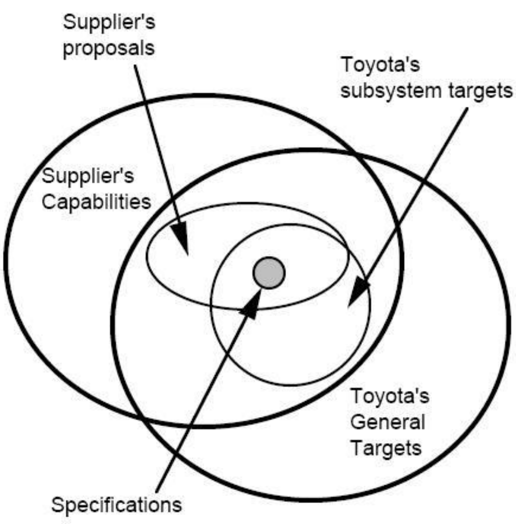



**Figure 3-6 Principles from Toyota's SBCE Process (SOBEK & Ward, 1996)**

Quality Function Deployment (QFD) is another effective method of communication in which customers and company will exchange information together. In QFD, the customers' requirements will be transferred to operational level. Moreover the quality of product will be also improved in the design stage using QFD methodology. Generally, QFD provides a useful framework for the development of decision support systems for the application of concurrent engineering (Cristiano, White, & Liker, 2001). Some necessary factors should be considered for having a successful application of QFD:

- ✓ The powerful involvement of the cross-functional team
- ✓ Taking benefits of expertise in different functions area in order to foster the decisions about downstream issues earlier in the process

In conclusion applying an effective Set-Based Concurrent Engineering Process will require a very strong communication between different functions. Early communication will lead to understanding requirements of each functions, high richness of information about different designs and consequently less necessity of rework/modification of designs late in the process.

Gathering as much as information as possible in early stages when they are cheap, exchanging space limitation and performance requirements between supplier and company with giving the supplier autonomy to design the parts to meet the constraints; and minimizing the barriers among different functions in product development process will result to a strong and successful level of communication required for application of Set-Based Concurrent Engineering Process.

### 3.2.3 Delaying Decision in the Process (Higher Flexibility)

Another apparent inefficiency in the Set-Based Concurrent Engineering is called "Delaying Decision". As it is discussed earlier, companies are trying to deliver their product as early as possible to the market in order to be leader and gain more share of the market among the other competitors. According to studies about uncertainties in the development process, it is difficult to take decisions in early stages because of not availability of data and information till the project goes to detailed design phase. However In conventional model of development process, the companies take decisions as early and fast as possible in order to decrease the delivery time. They use a single idea, follow an iterative process and carry out enough number of design modifications until finally they reach the closest solution which is compatible with customers' requirements. However the time of iterative process is uncertain and they may encounter a huge increase in time due to difficulty of changing the things which are already fixed.

Early decisions in development process will result in engineering changes and lack of product quality late in the process. Moreover, the more changes in downstream, the more increase of time and cost in development process. It is more costly and time consuming when a taken decision in downstream needs to be changed due to not compatibility of specifications with downstream functions.

In the companies using Set-Based Concurrent Engineering, on the other hand, the companies try to decrease the delivery time of the product development process by taking decisions late in the process. Moreover, delaying decisions result in decreasing the iterative process and also increasing compatibility with customer requirements which consequently lead to higher level of product quality. A famous example of delaying decision is about Toyota's fixing body hard points. In Toyota Motor Corporation, the key dimensions of body shape is not fixed early, therefore they decrease the time for the stamping die designers after the body shape is fully determined. (Ward, Liker, Cristiano, & Sobek, 1995)

Delaying decisions approach has also more advantages rather than shortening the time of the product development process. Impacting on the cost of the project, richness of the knowledge and high influence of being consistent with customers' requirements will be discussed in the following as the other benefits of delaying decisions.

Early decisions in a product development process leads to an increase in committed costs. However not all of these costs are considered in total cost of a project. Therefore, later, at the last phases of the project, the costs will increase due to early decisions taken in the project. Set-Based Concurrent Engineering model follows delaying decision approach in order to decrease the committed costs in early phases such as concept definition and system-level design. Therefore, incurred costs will be easier to be closely pursued. The following figure will show the committed and incurred cost during the different phases of product development process.

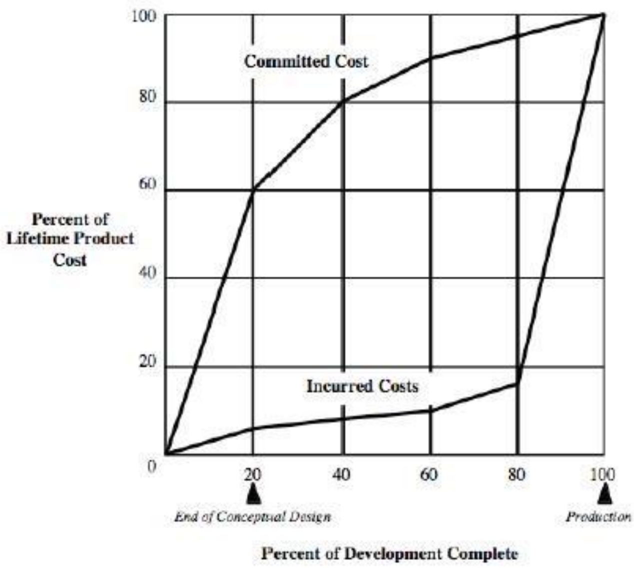



**Figure 3-7 Committed and Incurred Cost of Product Development Process's Phases (Bernstein, 1998)**

The next advantage of the Delaying Decisions Approach, which will be discussed in the following, is about the level of knowledge within the product development process. As a project goes from upstream to downstream phases, the level of captured knowledge will increase. As it is also mentioned before, taking decisions are difficult in early stages of the development process rather than last phases. The reason is obvious and it is due to lack of information and knowledge in the primary stages of projects. On the one hand, in conventional model, companies tend to take decisions early about the concept and designs of the product in order to reduce the time of upstream phases, consequently decrease delivery time of product development. However, based on most studies, it is proved that most of the decisions taken early will encounter to rework and modification of designs in downstream due to incomplete data. On the other hand, in the Set-Based Concurrent Engineering Model, the managers and engineers postpone some decisions which their rate of uncertainty is high. Therefore, they allow the project to go on, gathering more data, carrying out more analysis and get more experience about the designs. With this approach, when they understand better the requirements and product specifications, they take decisions and will reach to an optimum solution.

In the following figures, the difference of two models will be graphically shown, considering the delaying decisions.

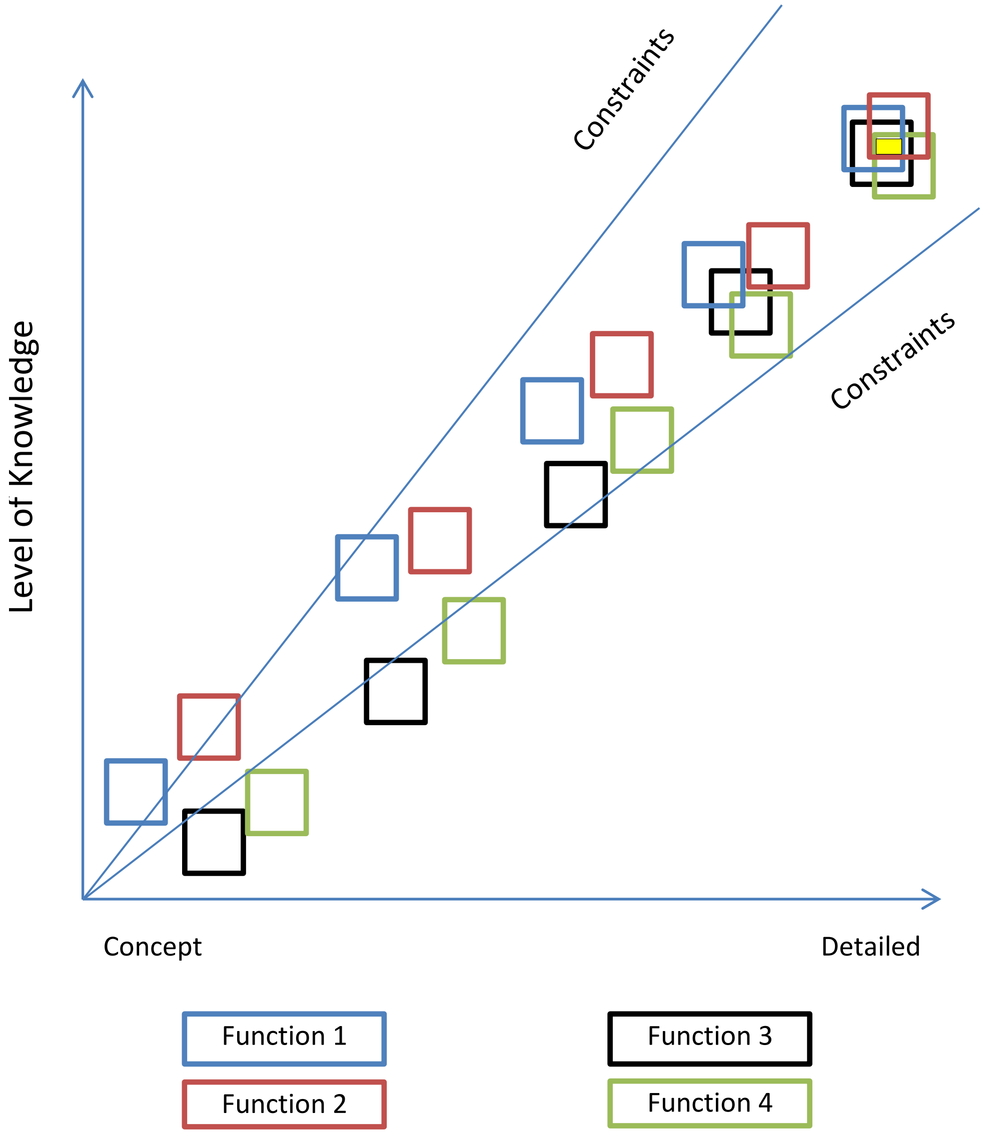



Figure 3-8 Level of Knowledge in Product Development Process (Self-Created Figure)

As it is shown in the Figure, the more a project moves toward Detailed Design, the more the level of knowledge of different functions increases, the better understanding of requirements among different functions and consequently the easier decisions about the constraints can be taken.

The last advantage of the delaying decision is dedicated to the customer requirements and product quality. By taking decision about critical issues late in the process, the probability of having a higher level of product quality increases. Moreover, by delaying decisions, it is easier to meet the customer requirements, considering also having access to more knowledge.

### 3.2.4 Integration

In the Set-Based Concurrent Engineering, different functions have a common goal which is trying to find an optimum solution which is able to work in whole system. This goal will generate from integration system which exists inside the Set-Based concurrent Engineering Model. The integration system will fulfill during the development system through different approaches. Intersection between different functions, imposing minimum constraints and taking benefits of robustness system will allow Set-Based Concurrent Engineering to reach an optimized system.

To compare integration system in Set-Based Concurrent Engineering with other models, an example will be explained in the following. This example is about selecting time for a meeting. (Ward, Liker, Cristiano, & Sobek, 1995)

In this example, time and date of a meeting for a group of persons are going to be defined. In the first approach, imagine that the organizer of meeting will decide about the date and time and inform the first person about it, however the first person might not able to attend and they together decide about another date and time which is then not compatible with the third person. They need to change it again. It may iterate many times due to having no related knowledge about each individual. The following Figure will show this example graphically. (The blue arrow shows the information exchange between two different person(s) and the red one shows the inconsistency of the information with the next person)

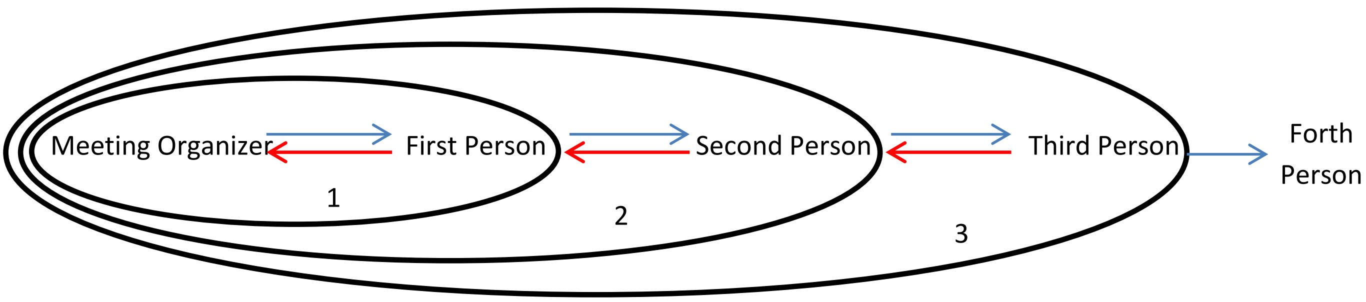



Figure 3-9 Meeting Example (Self-Created Figure)

In the second approach, more communication among the functions takes place. All personnel will decide to have a meeting in order to set the date and time of the important meeting. This approach – like the previous one – is also time-consuming due to finding a date and time for the first meeting, however the communication between the functions has increased.

The third approach is about fixing a date and time by the most powerful member of the group and forcing the other people to attend. This approach is like fixing and freezing the specifications – discussed in the previous part – early in the development process which eventually results in increasing the time and cost of the development process.

The last and forth approach is about understating about each individuals free date and time by exchanging them between themselves. Then, an intersection among them will be easily emerged in order to set the date and time for the meeting. Applying this approach will bring the benefits of defining the date and time of the meeting more quickly, with less iteration. Moreover, the knowledge level of different functions about each function's requirement will also increase.

One of the factors that will lead to facilitating the integration process is "Conceptual Robustness". Conceptual Design is achieved when engineering decisions concerning one aspect of a design remain valid in the face of design decisions made in other aspects of the design. (SINGER, DOERRY, & BUCKLEY, 2009). Conceptual Robustness helps decreasing the time of development process through somehow standardization. According to design robustness, a function can breakdown a design to smaller sub-designs. Then if one of these sub-designs is able to be compatible with all requirements of other functions, the progress of that sub-design will continue regardless of the decisions taken by other functions in downstream stages. Using this concept not also brings standardization into the development process and reduces the time of the project but also it results in reusability of parts in future projects.

All Toyota sedans are using essentially the same methods for creating torsional stiffness; all door outer panels are manufactured using four hits of the stamping dies. (Ward A. C., 2007)

### 3.2.5 Trade-Off Curves

A trade-off curve is a relatively simple tool that is consistently used by Toyota engineers to understand the relationship of various design characteristics to each other. In a trade-off curve two subsystem's performance are mapped in different axes and then will be used to illustrate subsystem performance relative to the two characteristics. (Morgan & Liker, 2006)

As it is discussed earlier in this section, multiple alternatives is one of the way to decrease the time and cost of the product development process. Another benefit of selecting multiple alternatives is that it allows generating and creating trade-off curves. Trade-off Curves are one of the useful tools in development process. By using trade-off Curves, it is possible to demonstrate the feasibility limitations of sets. These curves will be also able to be used for those sets and designs which have not been tested yet. They make the process of selecting easier, faster and more efficient through focusing only on those alternatives with which other functions are compatible. Therefore all system can ensure that those alternatives will be able to pass the test. For example, Toyota typically does not run durability tests on prototype because the trade-off curves system ensures that all vehicles will pass. Instead, Toyota tests cheap production vehicles for durability in order to refine the trade-off curves. This is the only way to meet modern standards of quality. (Ward A. C., 2007)

In the following figure, a trade-off curve showing the back pressure versus noise reduction on an exhaust system will be shown.

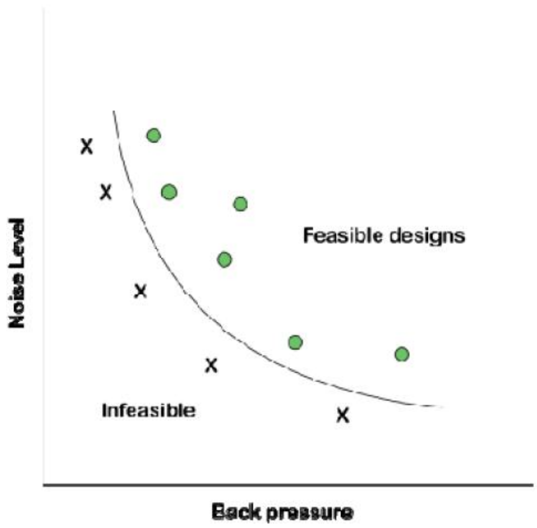



Figure 3-10 Example of Trade-Off Curve (Kennedy, Harmon, & Minnock, 2008)

As it is seen in the above figure, according to the trade-off curves, feasible and infeasible designs will be recognizable easily, regarding both subsystem's performances; Noise Level and Back Pressure. One of the exhaust system suppliers of Toyota provides around 40 different prototypes for one vehicle project. This high range of prototypes results in developing trade-off curves which allow Chief Engineer to have a clear view of the relationship between the back pressure and engine noise.

### 3.2.6 Chief Engineer

A very important role in entire development process is considered as Chief Engineer in the Set-Based Concurrent Engineering. Toyota Chief Engineers have little formal authority; none of the functional engineers, who do the actual design work, work for the Chief Engineers. (Kennedy, Harmon, & Minnock, 2008). Chief Engineers are in a higher level than functional engineers from technical point of view. Moreover, they are responsible for production concept, set value and performance targets and try to transfer the customer voice into the product development process. Functional managers are responsible to decide how the project should be developed and by whom, however chief engineers make decisions about what should be developed and when.

# 4 Chapter 4

## Surveys and Analysis

Having studied the concept and context of the Set-Based Concurrent Engineering Model and its Enabling Factors in details from different articles and papers, it is somehow obvious that applying Set-Based Concurrent Engineering – rather than using other models – within a company can bring lots of benefits in terms of flexibility, better communication and integration among different departments, innovative product, efficiency and effectiveness. As it is also mentioned in the previous chapters, most companies – Except Toyota Motor Corporation which is the leader of Set-Based Concurrent Engineering – think that model is a very time/cost- consuming model which makes the product development process more inefficient and ineffective. To have a more clear understanding of how different companies are using which type of product development process models and which one they think are more effective, this chapter focuses on the product development process models which are being used in different companies. For that purpose, there are some goals which are mentioned in the following:

- How many companies are following a certain product development model
- How many companies are successful in terms of efficiency and effectiveness using their own models
- How many companies are taking benefits of applying Set-Based Concurrent Engineering model within the company
- A real comparison in terms of efficiency and effectiveness between different product development process models

In order to reach those goals, a survey is carried out through a multiple-choice questionnaire in which the current state of product development process in different companies is evaluated. This survey consists of 14 different companies. The questionnaire are mostly focusing on Set-Based Concurrent Engineering model and its Enabling Factors in order to gather data from different companies, understand how many of them follow this model also in reality and how many of them can increase the efficiency and effectiveness of their product development process.

The questionnaire includes several questions in different areas such as Product Development, Product Design and Knowledge-Based Engineering. There are also some questions considered as additional questions. The results of the questionnaire from different companies will be evaluated in this chapter and as conclusion; the Set-Based Concurrent Engineering will be assessed in terms of the goals mentioned earlier.

## 4.1 Questionnaire

1. Do you have a formal product development (PD) mode (Visual representation of the PD process, including the various stages, activities, mechanisms and supporting tools) and is it effective in guiding the PD operations? (Select one option)

| Options | | Effectiveness | | |
|---|---|---|---|---|
| | | Not Effective | Somewhat Effective | Very Effective |
| | There is currently no PD model | | | |
| | The current PD model is developed by a central organization that administer its implementation, but it is not followed | | | |
| | The current PD model is developed by a central organization that administers its implementation, and it is followed | | | |
| | The current PD model is developed, and maintained by decentralized groups that administer its implementation in their respective areas | | | |

Table 4-1 Current Product Development Model within Companies

2. Is there a technical leader who is responsible for the entire development of a product from concept to launch? (Select one option)

| Options | | Effectiveness | | |
|---|---|---|---|---|
| | | Not Effective | Somewhat Effective | Very Effective |
| | No technical supervisor has responsibility for the entire development of a product | | | |
| | A project manager (non-technical) has responsibility for the entire development of a product while an engineer or a group of engineers share some responsibility | | | |
| | A chief engineer with a team of engineers have responsibility for the entire development of a product | | | |

Table 4-2 Product Development Responsibility

3. Every specification is a compromise between what customers want and what can be provided. How is a product specification stabilized in your product development process? (Select one option)

| | Options |
|---|---|
| | Specification provided early on by customer or central organization and must be adhered to |
| | Specification provided early on, but subject to engineering alternations |
| | Specification grows through continuous interactions along the stages of PD as the product understanding matures |

Table 4-3 Stabilization of the Product Specification

4. How do you select the design solution that will be developed? (Select one option)

| | Options |
|---|---|
| | We only produce one design solution for each product |
| | We identify multiple solutions, and select the one that most closely matches the design specification |
| | We identify multiple solutions, and select the solution that has the lowest development costs |
| | We design multiple solutions for each product/component, and rule them out as more information becomes available (due to prototyping, testing, integration etc.) |

**Table 4-4 Selecting Process of Design Solution**

5. Do manufacturing/production engineers play an active role in each stage of product development? (Select one option)

| | Options |
|---|---|
| | Once the design is complete, it is communicated to the manufacturing engineers |
| | Once the detailed design is prepared, the manufacturing engineers are involved |
| | Once the final concept is selected, the manufacturing engineers are involved |
| | Manufacturing engineers are involved in concept selection |
| | Manufacturing engineers provide design constraints to design engineers before design solutions are prepared and they are also involved and referred to throughout the development process |

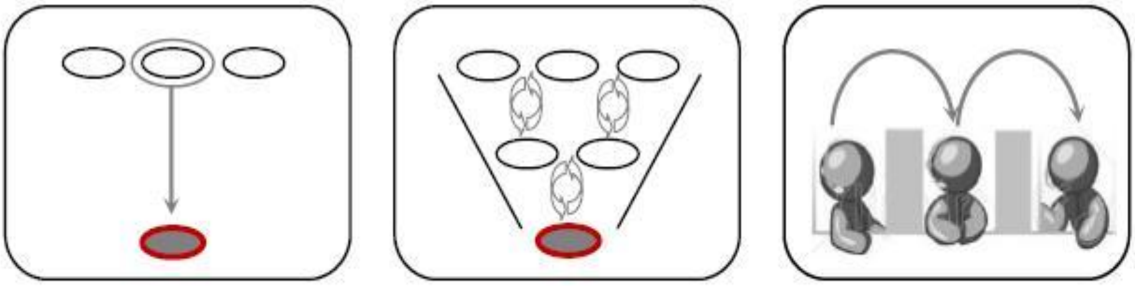
**Table 4-5 Manufacturing/Production Engineers Roles in Product Development Process**

6. Do your suppliers provide you with multiple alternatives for a single part (component)? (Select one option)

| | Options |
|---|---|
| | Suppliers provide one part (solution) based on a detailed design specification that we provide |
| | Suppliers have flexibility to provide one (solution) based on a rough design specification that we provide |
| | Suppliers provide multiple solutions for most parts and we work with them to develop the solution |
| | Suppliers inform us on developments in what they can provide and we together develop multiple solutions and progressively eliminate weak solutions as the product design solution matures |

Table 4-6 Supplier's Strategy of Alternatives

7. From the diagrams below can you indicate what method(s) of product 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 Engineering | | | | | | | |
| | Sequential Manner | | | | | | | |

Table 4-7 Current Product Development Model

8. Currently what are the implemented mechanisms to capture knowledge in your organization and how efficient do you assess them? (Select one each)

| Mechanisms | | Frequency of Use | | | | Effectiveness | | |
|---|---|---|---|---|---|---|---|---|
| | | Never | Sometimes | Always | | Not Effective | Somewhat Effective | Very Effective |
| | Verbal communication | | | | | | | |
| | Questionnaires | | | | | | | |
| | Document Templates | | | | | | | |
| | Web-Blogs/Notice Boards | | | | | | | |
| | Other | | | | | | | |
| | We have no implemented mechanisms to capture knowledge in our organization | | | | | | | |

**Table 4-8 Knowledge Capturing Mechanisms**

9. What technologies or functions are used in your company to realize that captured knowledge is reused and shared during the product development process and how frequent it is used? In addition, do you think the knowledge content of the provided technologies is adequate in supporting decision taking in an efficient way? (Select one for usage and one for efficiency if applicable)

| Technologies and Functions | | Frequency of Use | | | | Efficiency | | |
|---|---|---|---|---|---|---|---|---|
| | | Never | Sometimes | Always | | Not Supportive | Some Content is Adequate and Supportive | All Content is Adequate and Essential for Decision Taking |
| | Knowledge | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Based Engineering System | | | | | | | |
| | Check Lists | | | | | | | |
| | Design Templates | | | | | | | |
| | Design & Development Handbook or Manual | | | | | | | |
| | Quality Gates | | | | | | | |
| | Assessment and Judgment from Experts in your Organization | | | | | | | |
| | Wikis | | | | | | | |
| | Web Serves/Intranet | | | | | | | |
| | E-Books | | | | | | | |
| | Reports | | | | | | | |
| | Other | | | | | | | |

**Table 4-9 Technologies for Reusing and Sharing Captured Knowledge**

10. What are the main problems with your current PD model? (You may select more than one option)

| | Options |
|---|---|
| | Too many sign-offs required (bureaucracy) |
| | Needs to be updated to meet changing demands |
| | Causes work to be delayed due to unnecessary tasks/activities |
| | Engineers are forced to spend time on lengthy documentation (reports) |
| | The model has not been well communicated to employees |

**Table 4-10 Problems of Current Product Development Model**

11. What are the main challenges that you face in product development? (You may select more than one option)

| | Options |
|---|---|
| | Products are not innovative enough |
| | We normally face cost overruns |
| | We are always overburdened with the quantity of work |
| | Downstream engineers passed optimized designs that require significant modification or redesign |
| | Others |

Table 4-11 Product Development Main Challenges

12. Is your company working with any Lean consulting companies address the issue of product development? If so then what is the scope of their work?

| | Options |
|---|---|
| | Applying Lean 6 Sigma to product development |
| | Applying Lean manufacturing techniques to product development (e.g. 5 principles, 5s etc.) |
| | Applying Value Stream Mapping to product development |
| | Applying Set-Based Concurrent Engineering (or SB design) to product development |
| | Others |

Table 4-12 Lean Consulting Companies Relationship

## 4.2 Survey Results and Assessment

This section dedicated to analyze the survey results. The results of different companies are gathered together for each question. In the following the companies which attended to the survey will be mentioned, with a bit explanation about them:

The gathered results of all companies are mentioned in the following for each question.

1. Do you have a formal product development (PD) model (Visual representation of the PD process, including the various stages, activities, mechanisms and supporting tools) and is it effective in guiding the PD operations?

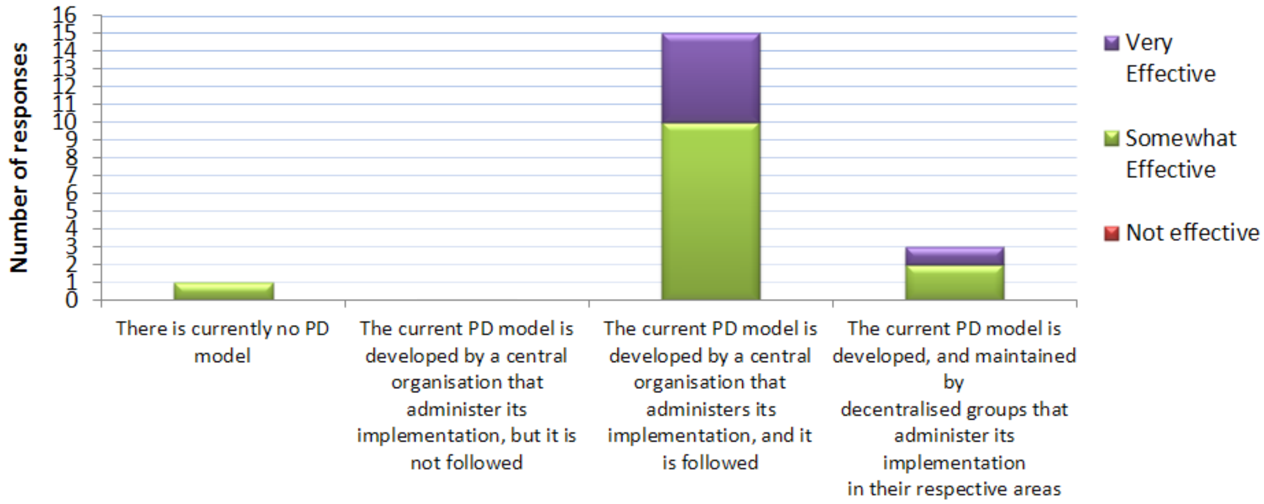



Figure 4-1 Current Product Development Model within Companies

The result of the first question shows that most of the companies follow a Product Development Model. Except one company which does not have a model in its company, the rest have their implemented model developed either by a central organization or decentralized groups. Moreover the results show that the majority of the companies have realized their model as "Somewhat Effective" which means that even with implementing a defined Product Development Model; most of the companies do not experience a very high level of effectiveness.

2. Is there a technical leader who is responsible for the entire development of a product from concept to launch?

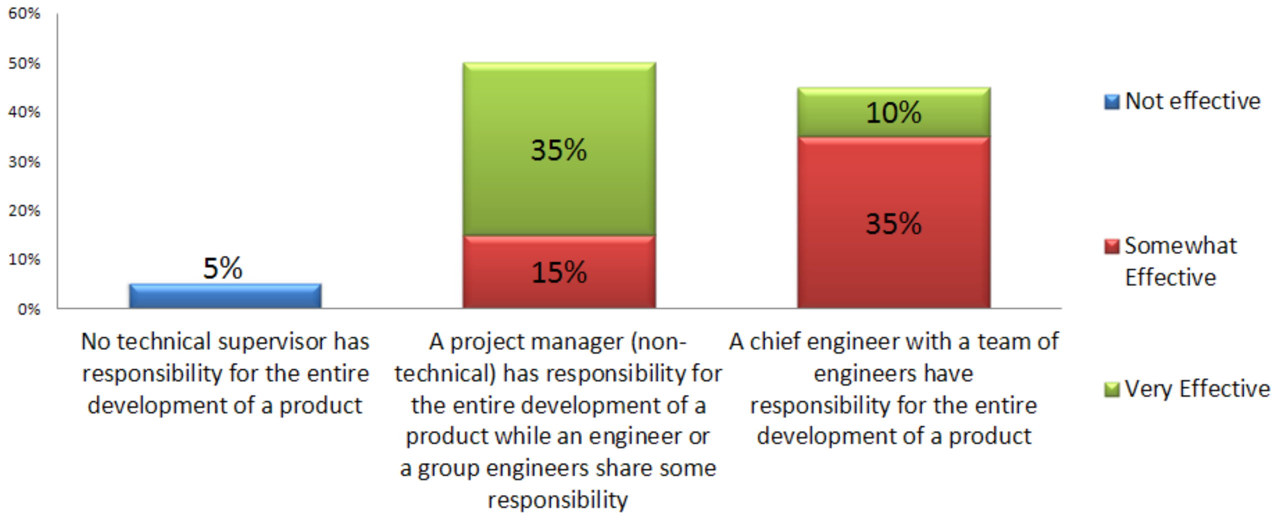



**Figure 4-2 Product Development Responsibility**

The need for a responsible person for entire product development process is a necessity as it can be realized from the result of the second question. Most interviewed companies are using either a project manager or a chief engineer who are responsible for entire development process.

3. Every specification is a compromise between what customers want and what can be provided. How is a product specification stabilized in your product development process?

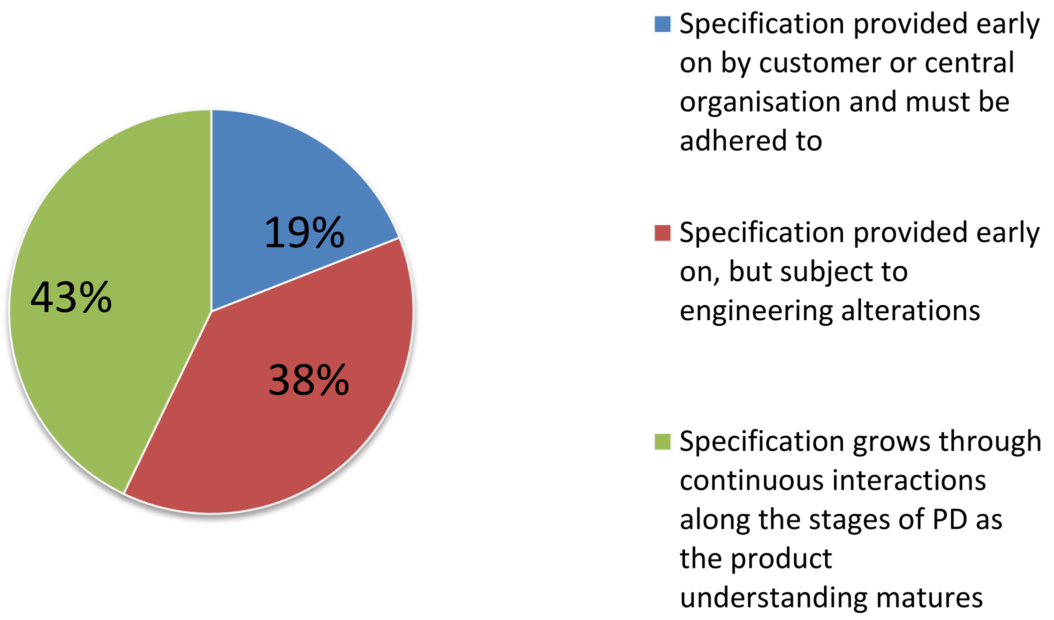



Figure 4-3 Stabilization of the Product Specification

Delaying decisions is one of the important enabling factors used in Set-Based Concurrent Engineering. As it is gathered from the result of this question, the highest percentage of the interviewed companies take a decision about specification in downstream stages of development process, while the level of information about the product has been increasing.

4. How do you select the design solution that will be developed?

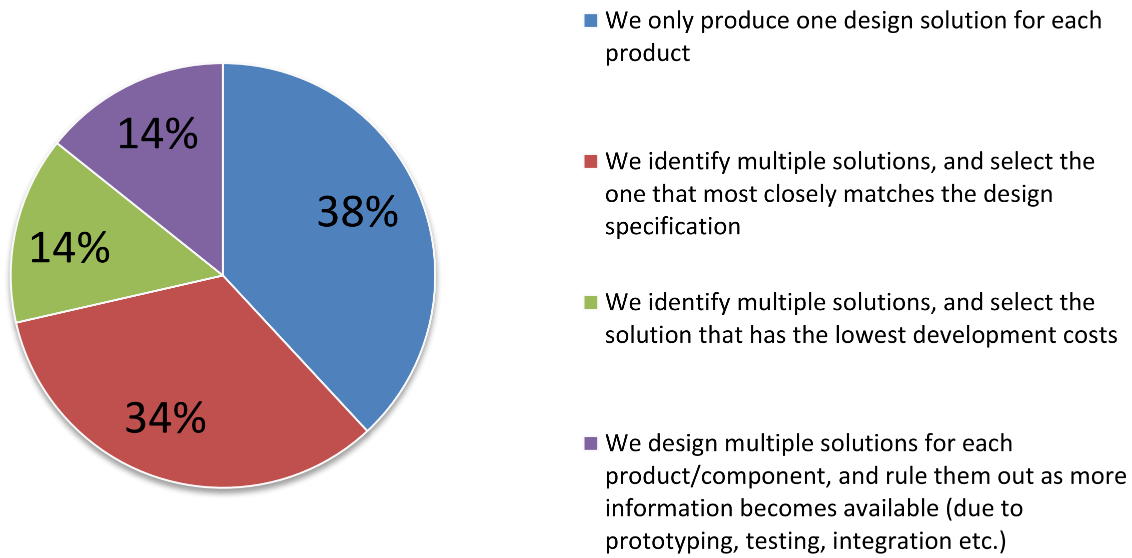



Figure 4-4 Selecting Process of Design Solution

This question is closely related to the using multiple alternatives instead of using one apparently best alternative. From the result, the highest percentages belong to those companies who produce either only one design solution or multiple solutions and select the one that matches the design specification. Only 14% of companies follow the SBCE's enabling factor which is to use different alternatives and narrow them while the information increases.

5. Do manufacturing/production engineers play an active role in each stage of product development?

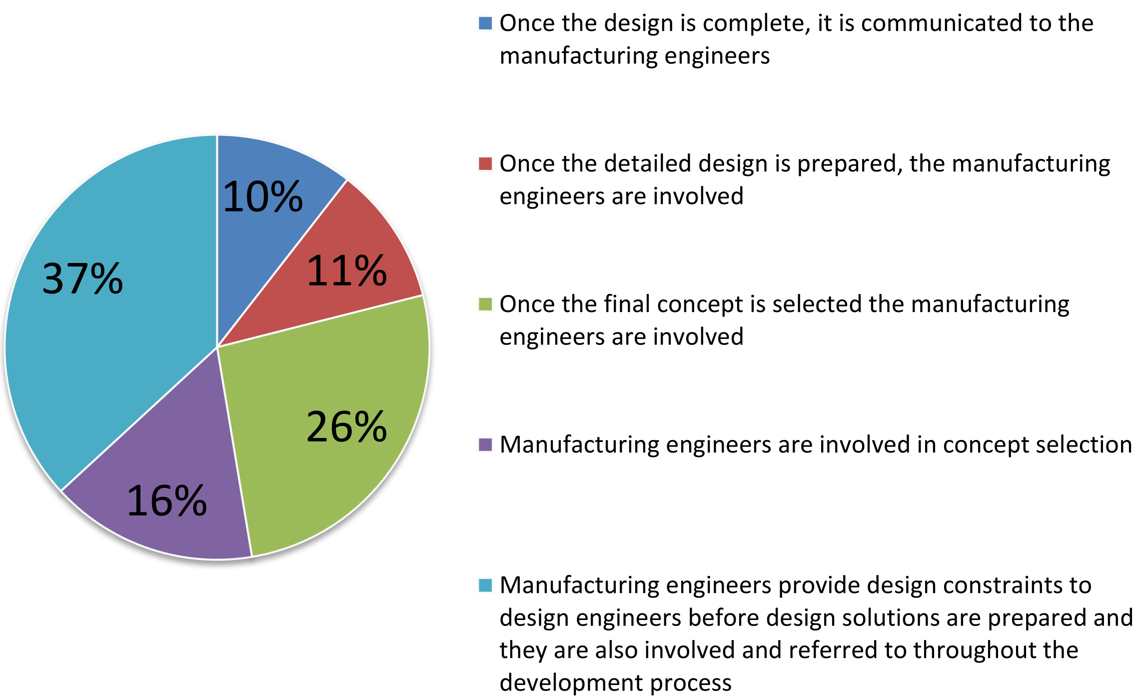



**Figure 4-5 Manufacturing/Production Engineers Roles in Product Development Process**

This question shows the communication between the manufacturing engineers and early stages of product development (Before concept definition, concept definition, etc.). From the results, in the most companies, the manufacturing engineers are involved in early upstream stages and communicate about the product with upstream functions; however, they are still some companies in which manufacturing engineers are involved in the product development process when the final concept is selected.

6. Do your suppliers provide you with multiple alternatives for a single part (component)?

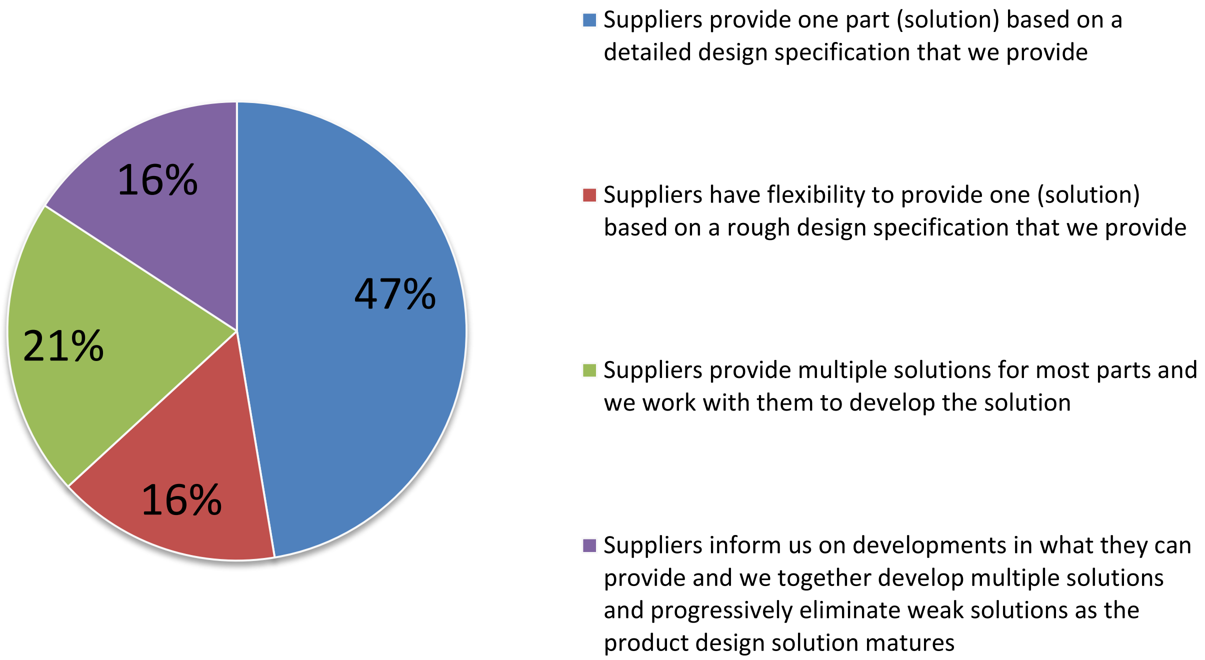



**Figure 4-6 Supplier's Strategy of Alternatives**

In this question, the relationship between supplier and company is considered. As it is obvious from the result, the highest percentage belongs to companies for which suppliers provide only one part. Only few companies ask their suppliers to be involved in the product development process, to inform them about their capabilities, develop multiple alternatives together and eliminate the inferior solutions in order to reach the optimum one.

7. From the diagrams below can you indicate what method(s) of product development do you currently follow and rate its effectiveness?

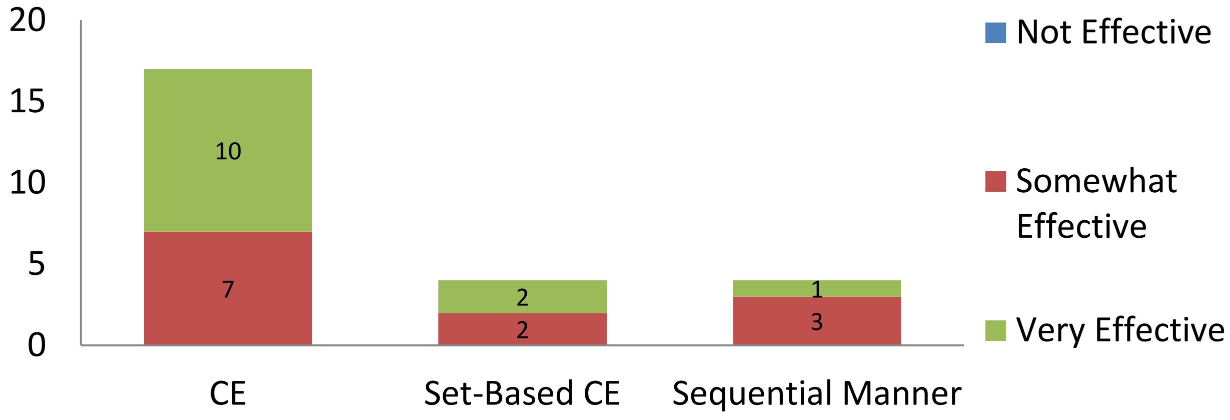



Figure 4-7 Current Product Development Model

This question shows that which company follows which type of product development model. From the captured results, Concurrent Engineering model is the most popular model among the companies and they also report that this model is effective. Few companies which follow the Set-Based Concurrent Engineering report that this model is also effective; however it is not completely implemented.

8. Currently what are the implemented mechanisms to capture knowledge in your organization and how efficient do you assess them?

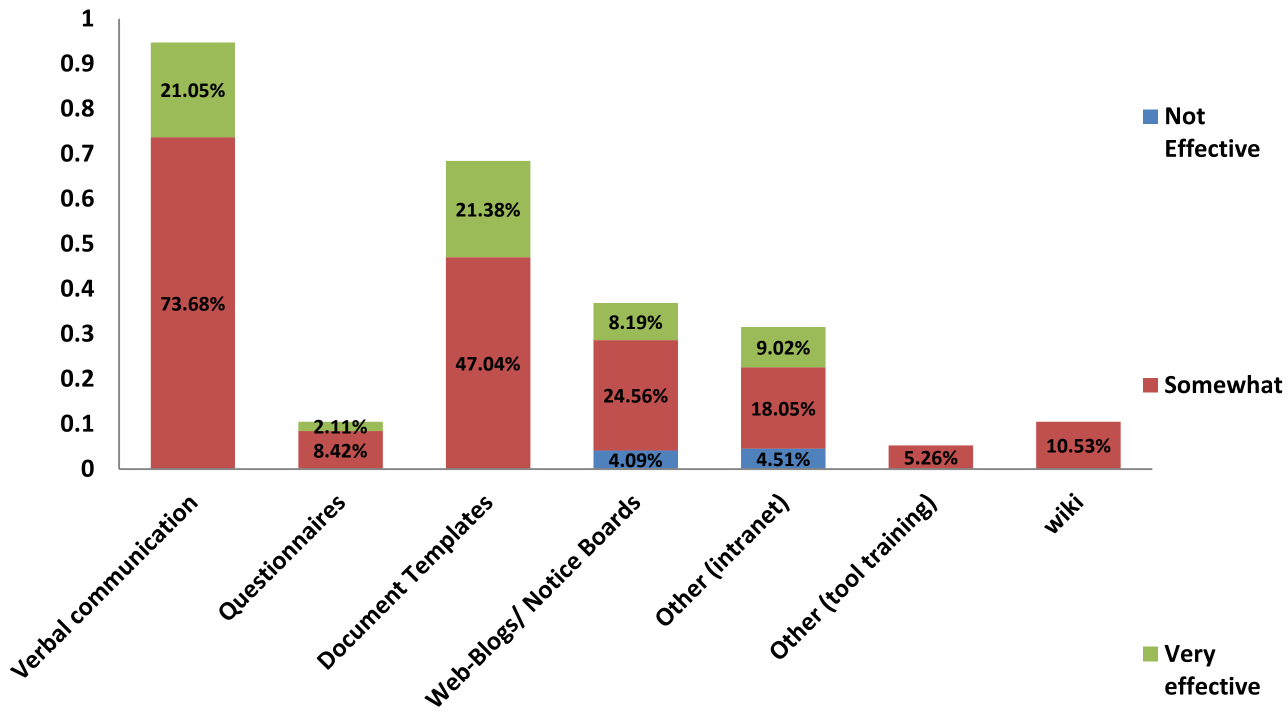



**Figure 4-8 Knowledge Capturing Mechanisms**

Applying a communication method in a very effective method is a really challenging issue. Most companies report that verbal communication is the most famous method that they are using within their company. Moreover, form the results, it can be also mentioned that document templates method has a bit more effectiveness than the former method.

9. What technologies or functions are used in your company to realize that captured knowledge is reused and shared during the product development process and how frequent it is used? In addition, do you think the knowledge content of the provided technologies is adequate in supporting decision taking in an efficient way?

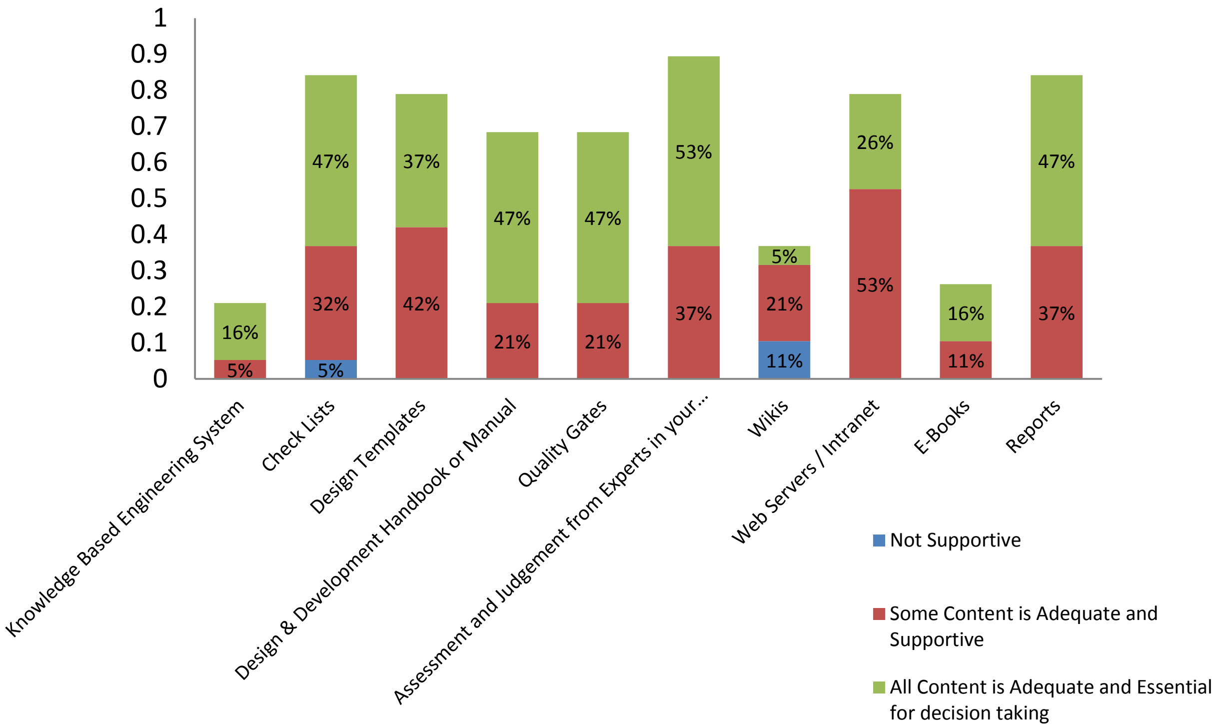



Figure 4-9 Technologies for Reusing and Sharing Captured Knowledge

Among the companies, they are different methods and tools for sharing the knowledge between different functions and departments. The most popular one from the results is getting advantage of experts within the company. Checklists are also known as an effective tool for some companies, according to the results.

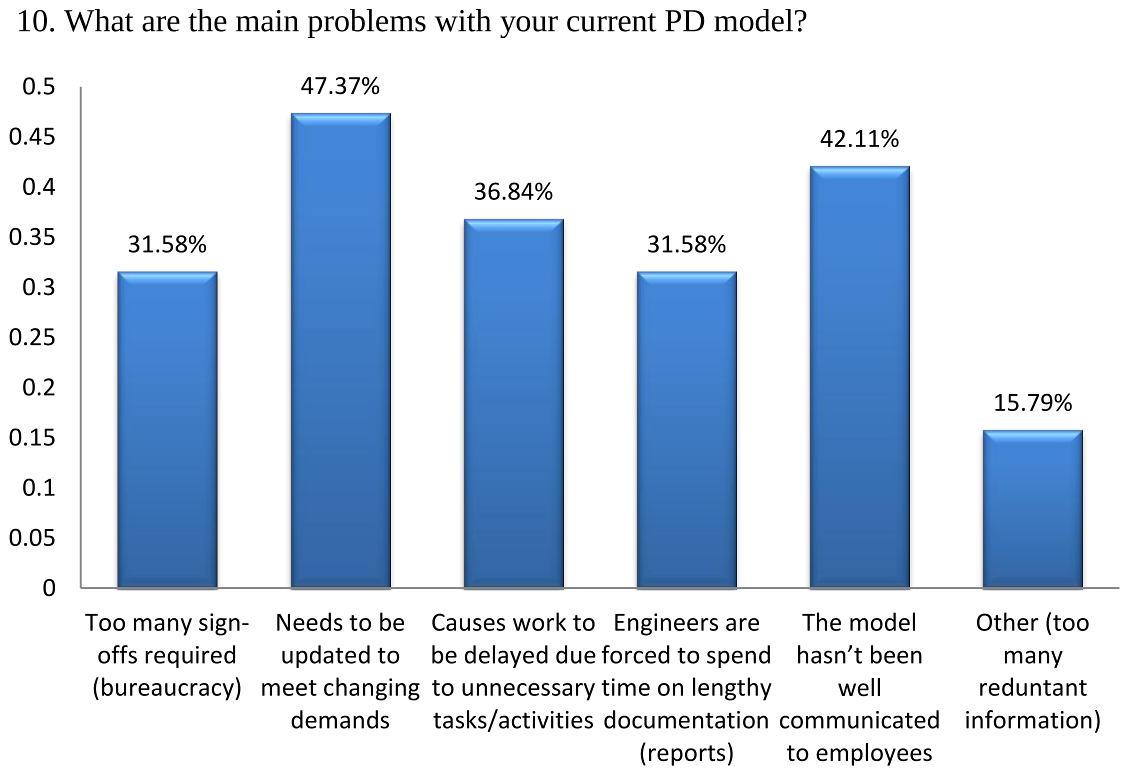



**Figure 4-10 Problems of Current Product Development Model**

The above result chart shows that the most important issue for most companies is related to updating and modifying the product in order to meet the changed demands. In addition, the other important problems are related to either bad implementation of the model among the employees or delaying in works due to unnecessary tasks/activities.

11. What are the main challenges that you face in product development?

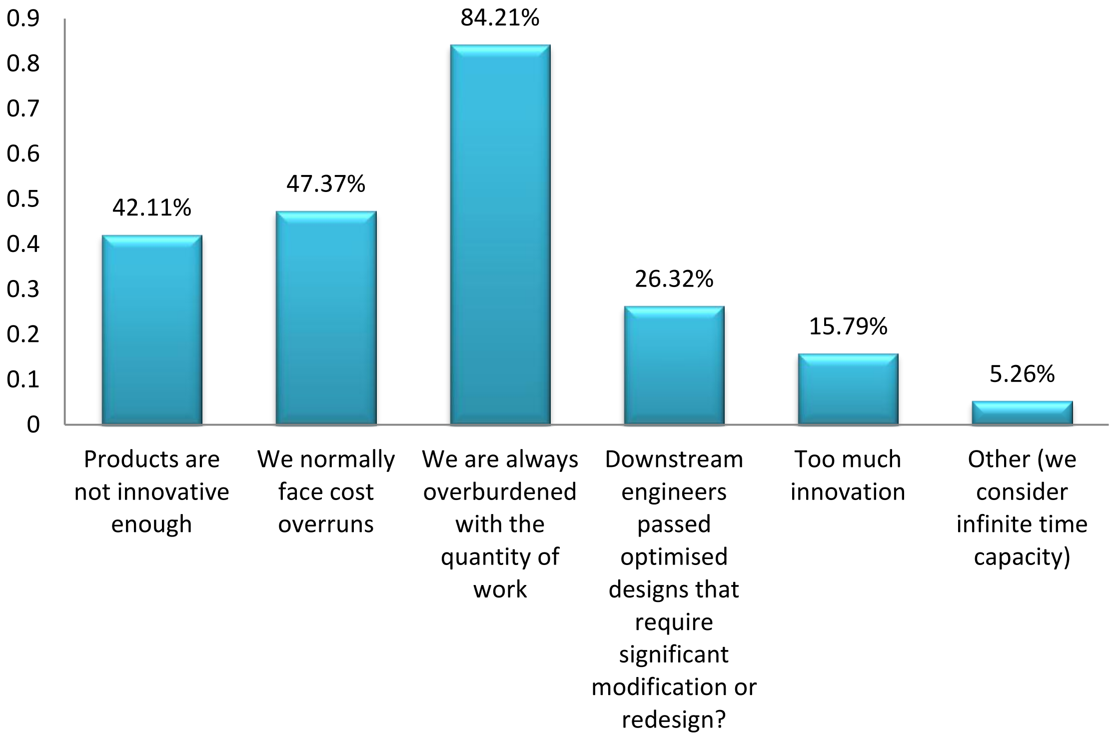



**Figure 4-11 Product Development Main Challenges**

The results from this question show that the highest percentage of the companies is suffering from the too many work within the company. The incremental cost during the product development process is also another main challenge for the interviewed companies.

12. Is your company working with any Lean consulting companies address the issue of product development? If so then what is the scope of their work?

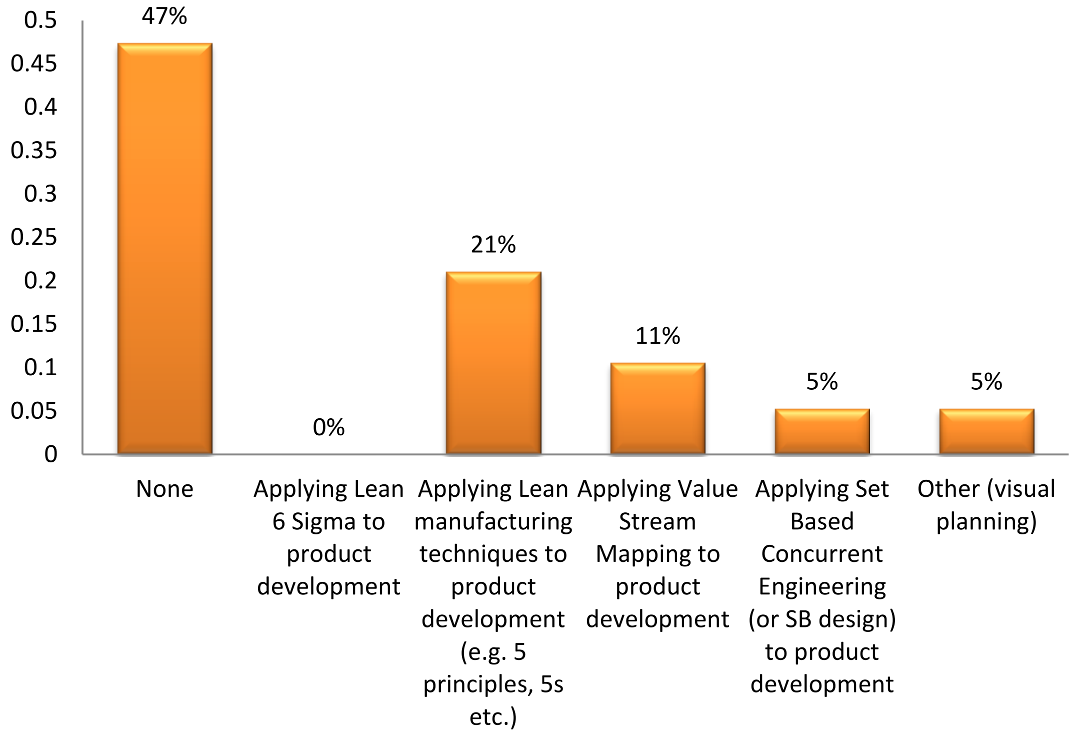



**Figure 4-12 Lean Consulting Companies Relationship**

It is seen from the results that most of the companies are not working with any lean consulting companies which may decrease the efficiency and effectiveness of their product development process. Only few companies are trying to take advantage of working with product development consultants such as lean manufacturing techniques, value stream mapping, Set-Based Concurrent Engineering.

## 4.3 Conclusion

Set-Based Concurrent Engineering Model is known somehow in the real world; however it is not well-known applied or captured. According to the analyzed data above from companies, it is obvious that most of the companies trying to use a lean model in order to be a leader in their market. Applying Concurrent Engineering Model by most of the companies and using some of the approaches and concepts of Set-Based Concurrent Engineering Model within their product development process brings us to this belief that the companies are going to be addressed to Set-Based Model.

Some companies despite of implementing Set-Based Concurrent Engineering Model within their company are not applying all the enabling factors of the model; however they reported the model as a "somehow effective" or "very effective" product development model. As an example, ABB Company which has been using Set-Based Model and considered it as a "very effective" model is does allow the manufacturing engineers to be involved within the product development process after concept approval. In addition, its suppliers provide them only one solution based on the detailed design.

The last, but not least point is that most of the companies have been had this eager to move toward a more efficient and effective product development process. The combination of the enabling factors that are applied within their product development process shows that they have a low level of set-baseness which through a comprehensive introduction about set-based concurrent engineering they can increase their level of set-baseness and improve their product development process significantly.

# 5 Chapter 5

## Set-Based Concurrent Engineering into Business Game

## 5.1 Business Game Introduction

This chapter is dedicated to creating a business game in which the definitions and concepts of Product Development Models will be implemented within the game. The aim of the Business Game is to provide an educational game for players in order to better understanding of the new product development models, concepts, how they work, advantages, disadvantages and their impact on the development process.

To reach that goal, the business game takes benefits of the previous chapters in which all the models and strategies are completely covered. According to the models, only two models will be applied in the business game, Point-Based and Set-Based Concurrent Engineering Models. Due to complexity of the models with a huge range of criteria and relationships between the existing departments and functions, business game is tried to be as simple as possible in order to be clear enough, understandable and easily playable.

## 5.2 Set-Based Concurrent Engineering Process Business Game

The game is designed for developing a new airplane, according to the given and pre-defined customer requirements. To have a better understanding of the two models, the game will be played in two different rounds. In the first round the players should follow a Point-Based Concurrent Engineering Model and in the second round they will use the same customer requirements for designing their airplane using Set-Based Concurrent Engineering Model. Using the later model will allow players to progress their development process smoother and more flexible through several enabling factors.

The enabling factors consist of some tools and approaches which together they make an integrated system supporting players to reach to the optimum airplane. The schematic view of development process affected by enabling factors will be shown as follows.

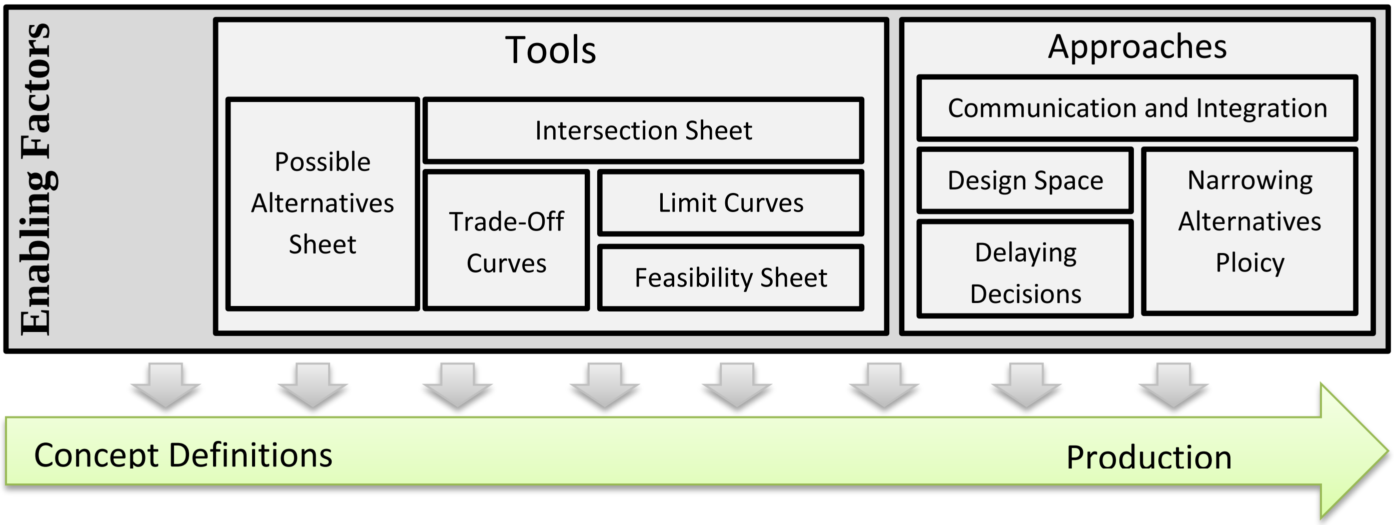



Figure 5-1 Enabling Factors (Self-Created Figure)

The above schematic view shows that while the product development process proceeds, players can reach to an optimal solution through implementing the enabling factors in the whole system. Applying the approaches and tools related to Set-Based Concurrent Engineering make this model more concurrent and effective in the second round, compared to the first round.

It is also tried to show the different levels of the product development process within the game. The related levels considered in the game are system level and sub-system level. A combination of tools and approaches will be taken into consideration to progress the development process for different levels. In order to have a clear view of different levels, the schema of the whole system will be defined as follows, considering different levels.

| Level | Approaches | Tools |
|---|---|---|
| Sub-System Level | Design Space (Multiple Alternatives) | Trade-Off Curves |
| | Delaying Decisions ( Setting Specifications Postponement) | Possible Alternatives Sheet |
| | Narrowing Alternatives Policy | Intersection Sheet |
| System Level | Design Space (Multiple Solutions) | Intersection Sheet |
| | Narrowing Alternatives Policy | Limit Curves |
| | Delaying Decisions | Feasibility Sheets |

Communication and Integration

Table 5-1 Different Levels of Set-Based Concurrent Engineering Business Game (Self-Created Table)

The above table shows that players will be involved of applying different approaches through different tools during the second round game in order to improve their product development process and consequently reach to an airplane which has the least development time and cost.

The table shown above can be extended by a very brief example of development process which will be taken place in the game. For the sub-system level, the players first need to define multiple design alternatives for each component of the airplane. Using trade-off curves they are able to find the possible design alternatives for each component. Not freezing the specifications of the component using some provided sheets can help players to avoid any probable iteration time and cost in the late stages of the development process. Then, they can narrow their design alternatives for each component by finding the intersection between different departments (Body and Cockpit Department).

In the system level, the players will use the intersection of the components designs alternatives in order to create the possible solutions for the whole airplane (System Level Design Space). Then the players will try to narrow their system level design space through limit curves to find the feasible designs of airplane. The optimum airplane can be reached by having a feasible sheet and comparing development time and cost of them.

## 5.3 Business Game

### 5.3.1 Game Overview

This game is an awareness simulation game aiming at introducing some concepts and key features of Set-Based Concurrent Engineering to players. The game can be used as an academic business game with the aim of improving the knowledge of the players. The game can be played as:

- ✓ A practical assignment or exercise for students in the university
- ✓ A training course in a manufacturing company in order to introduce the new model to workers in different functions
- ✓ A presentation for managers of industrial corporations in order to introduce the model

#### *5.3.1.1 Game Introduction:*

The game is about an airplane manufacturing company. The new strategy of the company is to produce a new product in order to get higher market share and increase shareholders' value. To do this, the company needs to use some successful factors within its product development process. This part will be the game and the players are responsible for product development processes' departments.

#### *5.3.1.2 Game Participants:*

The product development process game will consists of the both players and non-players. Players are those who involve in the game and impact on the decisions that should be taken during the game and non-players are those who provide some information or material for players while the game is in progress. Game can be played by two or more groups; each consists of different players who will be responsible for each department. The players of the game are mentioned in the following table.

| Departments | Players | Non Players |
|---|---|---|
| Body Department | * | |
| Wing Department | * | |
| Tail Department | * | |
| Cockpit Department | * | |
| Tester | | * |

**Table 5-2 Game Players**

#### 5.3.1.3 Game Evaluation:

To evaluate the game, there will be a comparison method of two different rounds for each group. Different factors and performances will be evaluated for each group. Playing time, development time and cost will be calculated for each round, and at the end they will be compared to each other in order to understand how much efficient the new development process is.

#### 5.3.1.4 Business Game Rules:

Several concept and definitions lie behind this game. To better understanding these concepts, some assumptions and rules must be taken into considerations. These assumptions and rules are added to the game in order to make the game more simple and understandable. These assumptions and rules will be mentioned in the following:

- ✓ The game should be played within a certain amount of time which will be announced in the beginning of the game.
- ✓ All the players must exactly do the assigned works which are pre-defined for each function and will be given to each function before the game.

#### 5.3.1.5 Components Details:

This game will be played with LEGO bricks. The product will be Airplane which will be created by players using LEGO bricks. Each brick (airplane component) has a certain number of points on it. The cost, delivery time, capacity and weight of every LEGO will be calculated based on the points on each of them. The cost, delivery time, capacity and weight of every point are shown in the following table:

| | Cost | Ordering Time | Capacity | Weight | Length | Width |
|---|---|---|---|---|---|---|
| 1 single point | 10 | 0.5 | 3 | 100 | 1 | 1 |

Table 5-3 Characteristics of Single Point

Example:

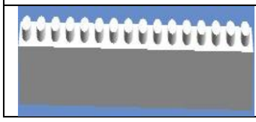
| Component | Name | # of Points | Cost | Ordering Time | Capacity | Weight | Length | Width |
|---|---|---|---|---|---|---|---|---|
|  | Body | 16 | 160 | 8 | 48 | 1600 | 16 | 1 |

Table 5-4 Example of One LEGO Item

Assumptions:

- ✓ The "Wing" and "Tail" components will have unsymmetrical shape. Therefore to make the calculation easy, the points on these two components will be considered only by the points of the longest row.
- ✓ The Capacity which is "Number of Passengers in Airplane" will be only calculated through the body components.

Example:

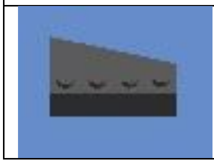
| Component | Comp. Name | # of Points | Cost | Ordering Time | Capacity | Weight | Length | Width |
|---|---|---|---|---|---|---|---|---|
|  | Wing | 4 | 40 | 2 | - | 400 | 4 | 2 |

Table 5-5 Example - Wing Component

There are also another consideration which is about a wing component and cockpits. The length and width of those parts are calculated as below:

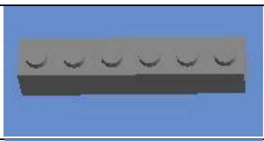
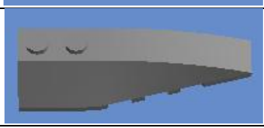
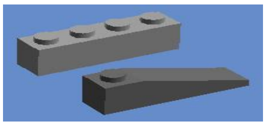
| | | Length | Width |
|---|---|---|---|
| Equal number of points on both shapes in length dimension |  | 6 | 1 |
| |  | 6 | 2 |
| Equal number of points on both shapes in both dimensions |  | 4 | 1 |

Table 5-6 Component Point Similarities

#### *5.3.1.6 Game Successful Factors:*

In the game, some successful factors – called also Enabling Factors, extracted from SBCE – will be used to show how these factors can impact on the whole process and lead to having a more lean process. These Enabling Factors are only part of the whole factors which exist in the SBCE model. Due to simplicity of the game, all of the factors are not able to be implemented in the game. Enabling Factors which are used in the game are presented as follows:

- ✓ Communication and Integration
- ✓ Use of Multiple Alternatives (Design Space)
- ✓ Imposing the Minimum Constraints
- ✓ Narrowing and convergence process instead of picking the best idea
- ✓ Using Trade-Off Curves

#### *5.3.1.7 Expected Results from the Game:*

Doing this game by players will be expected to have some benefits for players. As it is mentioned before, the goal of this game is to introduce the concept of the SBCE and how this model affects the process of product development in the real world. We expect from the players to figure out the following objectives:

- ✓ What the SBCE is.
- ✓ Key Factors (Enabling Factors) which lead to a successful product development process exist in SBCE model.
- ✓ How these Key Factors affect the process.
- ✓ Comparing the results together and understand the leanness of the process after implementing SBCE model.

### 5.3.2 Game Instruction:

The game will take place in two rounds. Each round will use a specific model for developing the new product. Having completed the first round, a brief presentation will be carried out to make the players understand the problems of the first round and also to have a more clear idea about second model which will be used in the second round and what key factors the players should take into consideration in the second round. The steps of the game will be ordered as follows and then each step will be explained in details.

1. Round One – Playing the game using traditional model (Point-Based Concurrent Engineering)
2. First Round Results Analysis
3. Learning Session (Problems – SBCE Brief Introduction)
4. Round Two – Playing the game using Set-Based Concurrent Engineering Model
5. Second Round Results Analysis
6. Conclusion

In each round there will be a game instruction which will be given and explained to the players before each round begins. Game instruction consists of roles and tasks of players and non-players, and how the game should be played. Moreover, the related materials will be also given and provided to players of each group.

The game follows a product development process framework. This framework should be used in the game and is graphically shown in the following figure:

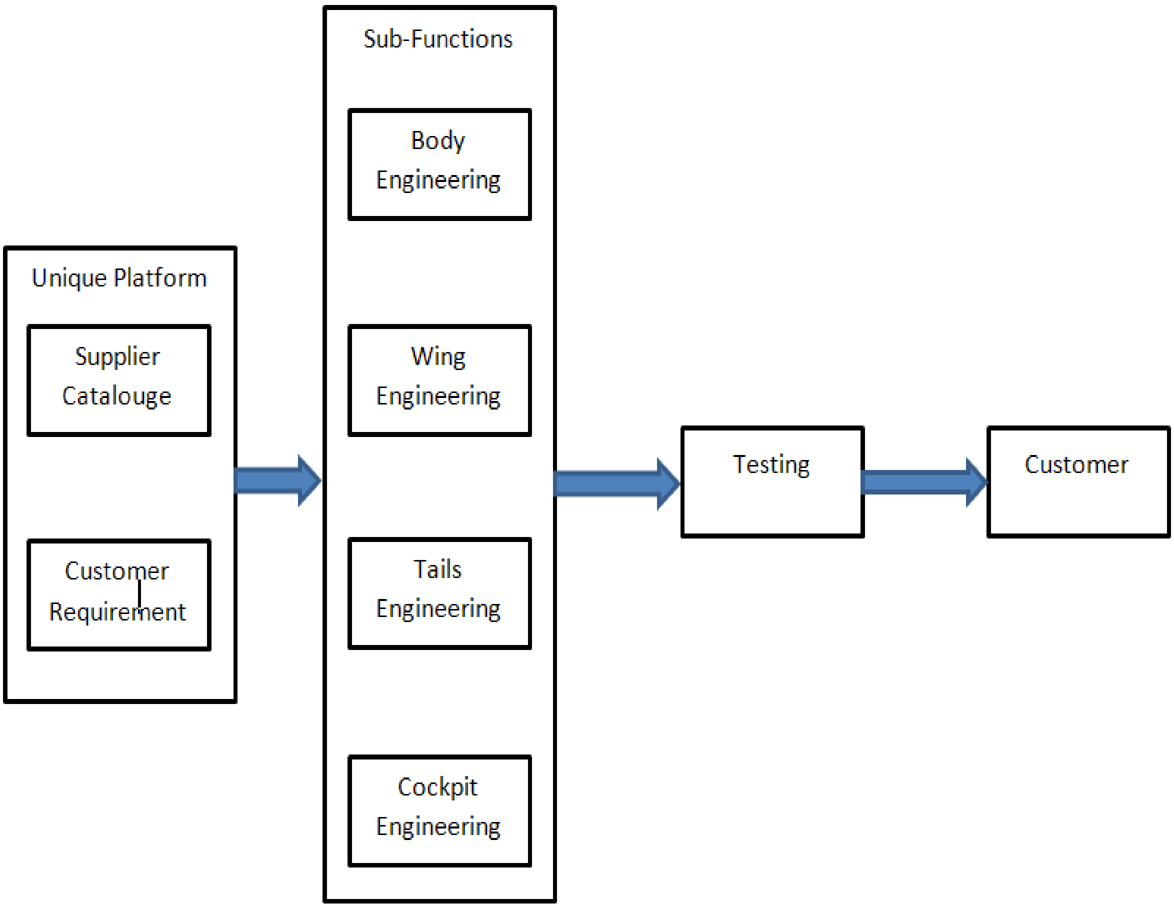



**Figure 5-2 Business Game Procedure (Self-Created Figure)**

In the beginning of the development process, there will be a unique platform consisting of "Supplier Catalogue" and "Customer Requirements" which are given to Product Engineers. "Supplier Catalogue" is a sheet of paper in which the supplier will inform the company about its components for each part of the airplane. In the following table, "Supplier Catalogue" is shown:

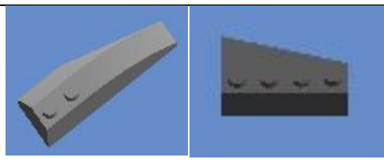
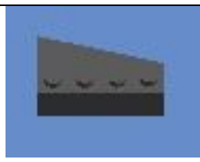
| Components | Figures |
|---|---|
| Body |  |
| Wings |  |
| Tails |  |
| Cockpit |  |

**Table 5-7 Supplier catalogue of Airplane Components**

"Customer Requirements" is defined as what exactly customer ask the airplane manufacturing company. It will be given to the product engineering in order to understand how they should develop the airplane based on the requirements of the customers. In the following the requirements which are necessary from customer point of view are mentioned:

- ✓ Number of Passengers (NP)
- ✓ Weight (W)
- ✓ Length (L)
- ✓ Wing Span ($W_S$)
- ✓ Tail Span ($T_S$)

In the second box, which is related to the product engineering function, there are different sub-functions including "Body Engineering Function", "Wings Engineering Function", "Tails Engineering Function" and "Cockpit Engineering Function".

Moving toward the downstream stages, there will be "Testing Section" and "Supplier". "Testing Section" is a process in which some certain constraints are going to be evaluated. If an airplane design is able to pass those constraints, it will be ready to be ordered to supplier. The constraints are shown in the following:

- ✓ Length vs. Wing Span

  This constraint represents the compatibility between Wing Span and Length. In order to design an airplane which can fly, the Wing Span variable should be between two third of the length of the airplane and length of the airplane. The following equation shows this constraint in mathematic language.

  $$\frac{2}{3}L =< ws < L$$

  **Equation 5-1 Wing Span Constraint**

- ✓ Weight vs. Weight of Passenger (Ratio of Weight)

  Since total weight of the airplane consists of two parameters (weight of the components of the airplane plus the weight of the passengers), this constraint relates to the balance of the airplane. This constraint says that the weight of the passengers should not be more than the weight of the components of the airplane; otherwise the airplane will be over weighted and cannot fly. The following mathematical equation shows this constraint.

  $$Rw < 1.25$$

  **Equation 5-2 Ratio of Weight Constraint**

  The parameter "Rw" is a rate which represents the ratio between the weights of the airplane with the weight of the passengers. The weight ratio is calculated as follows:

  $$wp < wa$$

  **Equation 5-3 Ratio of Weight Related Equation**

  In the following section, the weight of the passengers and the weight of the components of airplane will be explained.

- ✓ Airplane Stability (Tail vs. Wing)

  This constraint is about the airplane stability which represents the relationship between length of the tail and wing. In order to have a stable airplane, the length of the tail should be less or equal than the length of the wing; otherwise the airplane cannot fly. The following equation shows this constraint.

$$lt < lw$$

**Equation 5-4 Airplane Stability Constraint**

- ✓ Cockpit and Body Alignment

  The last constraint is about the compatibility of the body and cockpit of the airplane. The airplane can only fly when the length of the cockpit is equal to the width of the body. The alignment of these two dimensions of the airplane should be equal. The following mathematical equation shows this constraint.

$$lc = wb$$

**Equation 5-5 Cocnpit and Body Alignment Constraint**

In the last sections of development process, there are "Assembly Function" and "Customer". Having finished the assembly of an airplane, it will be delivered to customer.

#### *5.3.2.1 Airplane Dimensions and Constraints*

Playing the game requires a little information about the airplane and the constraints related to the airplane. In order to reach to a successful and effective development process, players should consider those constraints during the game. In the following, the airplane dimensions and its constraints will be explained:

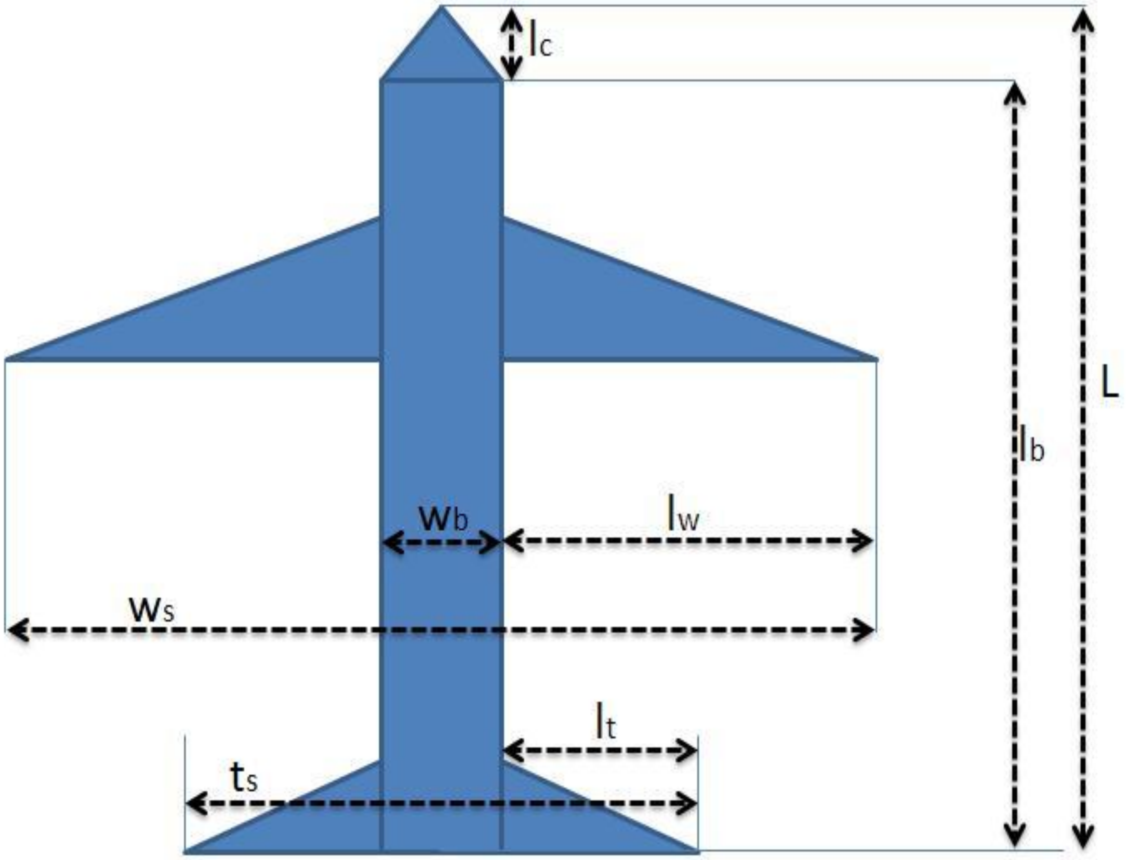



Figure 5-3 Airplane Dimensions (Self-Created Figure)

| | |
|---|---|
| $L$: Length of Airplane | $lw$: Length of Wing |
| $lb$: Length of Body | $wb$: Width of Body |
| $lc$: Length of Cockpit | $Ws$: Wing Spane |
| $lt$: Length of Tail | $Ts$: Tail Span |

In the following the dimensions of airplane are explained:

$$L = lb + lc$$

**Equation 5-6 Length of Airplane**

$$Ws = (2 * lw) + wb$$

**Equation 5-7 Wing Span**

$$Ts = (2 * lt) + wb$$

Equation 5-8 Tail Span

### *5.3.2.2 Explanation of Customer Requirements Variables*

In the following the variables which are related to the customer requirements are explained:

- ✓ Number of Passengers (NP): The number of people whom an airplane can carry during a flight.

NP = Number of Points on Body * Defined Number of Seats for each Single Point (equals to 3)

Equation 5-9 Number of Passengers

- ✓ Weight (W): Total weight of airplane

$$W = wa + wp$$

Equation 5-10 Total Weight of Airplane

$$wa = Weight\ of\ Body(wb) + Weight\ of\ Wings(ww) + Weight\ of\ Tails(wt) + Weight\ of\ Cockpit(wc)$$

Equation 5-11 Weight of Airplane

$$wp = NP * Average\ Weight\ of\ every\ Person\ (Considered\ as\ 60\ Kg)$$

Equation 5-12 Wight of Passengers

- ✓ Cost (C): Total Development Cost

$$C = Cost\ of\ Components\ (cc) + Cost\ of\ Iteration\ (ci) + Cost\ of\ Penalty\ (cp)$$

Equation 5-13 Total Development Cost

$cp$: The imposed cost in case of not being in ranges of customer requirements

| Cust. Req. | NP | L | Ws | Ts | W |
|---|---|---|---|---|---|
| Cost of Penalty | 30% | 40% | 10% | 5% | 20% |

Table 5-8 Penalty Cost Table

- Percentage of components cost

$ci$: The imposed cost in case of rework or modification (Redesigning)

| Variables | Value |
|---|---|
| Cost of Iteration | 30% of cost of components |

Table 5-9 Iteration Cost Table

- ✓ Development Time (DT): Total Development Time

$$DT = Ordering\ Time\ (ot) + Assembly\ Delivery\ Time\ (ADT) + Iteration\ Time\ (it)$$

Equation 5-14 Total Development Time

$it$: The time that is added to total development time in case of rework or modification (Redesigning)

| Variables | Value |
|---|---|
| Iteration Time | 30% of components ordering time |

Table 5-10 Iteration Time Table

ADT: The required time that supplier delivers the components to assembly function. This time is based on Length of Wing due to the complexity of the wings. The Assembly Delivery Time is calculated as follows:

$$ADT = ADTR * Total\ Number\ of\ Single\ Point$$

Equation 5-15 Assembly Delivery Time

| Length of Wing | 3 | 4 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|
| ADTR | 80% | 70% | 60% | 50% | 40% | 30% | 20% |

Table 5-11 Assembly Delivery Time Rate Table

After introducing the necessary pre-requisites for the game, each steps of the game will be completely explained in the following.

### 5.3.3 Round One

This round will be played using traditional model of product development process. The Product Engineering Functions will be divided to four sub-functions as mentioned earlier and players will be assigned to each sub-function. The instruction of playing first round will be explained as follows:

1. The supplier Catalogue and Customer Requirements as a Uniform Platform will be given to each sub-functions.

| Customer Requirements | Ranges | |
|---|---|---|
| | Min | Max |
| Number of Passengers | | |
| Weight | | |
| Length | | |
| Wing Span | | |
| Tail Span | | |

**Table 5-12 Customer Requirements Table**

Considering the Customer Requirements and Supplier Catalogues, each Sub-Function should come up with design of each part of the airplane. The players in each Sub-Function should guess and estimate the most likely best design of each component.

2. Having designed the components, they should document their design in a sheet of paper, which is called "Airplane Specifications". Each department should write down their designed component specifications.

<table>
<tr><td colspan="8">Group NO:</td></tr>
<tr><td rowspan="3">Number of Trying</td><td colspan="6">Airplane Specifications</td><td rowspan="3">Status</td></tr>
<tr><td colspan="2">Body Dep.</td><td>Wing Dep.</td><td>Tail Dep.</td><td colspan="2">Cockpit Dep.</td></tr>
<tr><td>lb</td><td>wb</td><td>lw</td><td>lt</td><td>lc</td><td>wc</td></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

**Table 5-13 Airplane Specification Sheet**

3. After writing the specifications for all components, they should give the paper to “Tester” in order to test their airplane and see whether their airplane is able to fly or not. In case of any inconsistency among the components, they should again try to redesign those components which are not able to meet the corresponding constraints and again write down their new design in the next row of “Number of Trying”. One sheet in which all the constraints are written will be given to groups for their second try. The process of redesigning and modifying the components design will affect the development process in terms of iteration time and cost. Moreover it also influences the “Playing Time” which the players should spend more time in order to design an airplane which is able to fly.

4. In case of passing the “Testing Section” the players will assemble the airplane with the LEGO bricks and it is ready to be delivered to customer. If one group cannot design the airplane after five times trying based on the given customer requirements, the development process of that group will be considered as “Fail”. In this case, the time and cost of the development process are not considered.

### 5.3.4 Results Analysis

In this step the results of the different groups in the first round will be analyzed. Based on each group's Airplane Specification Sheet, those groups who are able to meet the constraints will be shown their performances graphically at the end of the first round. Their development process performance consists of development cost and time. These performances are shown to the groups graphically and in each graph; the time and cost will be broken down in order to allow the players to understand how much iteration their development process faces during the business game.

### 5.3.5 Learning Session

This step aims at increasing the players' awareness about the key successful factors within the product development process, how to use these factors and what kind of positive effects can these factors inject to the process in order to have a leaner Product Development Process. The learning session includes:

- ✓ A short presentation aiming at introducing Set-Based Concurrent Engineering
- ✓ The Enabling Factors within the SBCE model and their effects on the process

The short presentation of SBCE model will cover the topics as shown in the following:

- ✓ What is Set-Based Concurrent Engineering?
  A short and brief definition of Set-Based Concurrent Engineering will be presented.
- ✓ Which are the enabling factors within the model?
  Enabling Factors will be briefly described. The Enabling Factors within the game are:
  - Communication and Integration
  - Multiple Alternatives (Design Space)
  - Imposing Minimum Constraint
  - Narrowing instead of picking (convergence)
  - Trade-Off Curves

- ✓ How can enabling factors affect the process?

  The effects of each Enabling Factors will be addressed to existing KPIs within the game.

### 5.3.6 Round Two

Based on the presentation after the first round, the second round will start. Players have more information about how to improve the development process and how to use the enabling factors in order to reach to a more effective process. In the beginning of the second round, the players will be informed how to play the game. The procedure of the second round will be in order as follows.

1. As all the groups have already had the customer requirements and supplier catalogue from the previous round, they start playing the game. The customer requirements for each group are the same in the second round.
2. Along with previous given data, different trade-off curves will be also given to players. There will be four different trade-off curves; each of them is dedicated to a certain department. Every trade-off curve has three criteria, vertical axes, horizontal axes and three different lines which represent different status for "width of Body". The vertical axes of trade-off curves represent one of the related customer requirements. The horizontal axes of trade-off curves represent different possibilities of one airplane's dimension. The players should figure out the possible alternatives for that dimension of the airplane regarding the given customer requirements. An example of one trade-off curve which is related to Body Department is shown below.

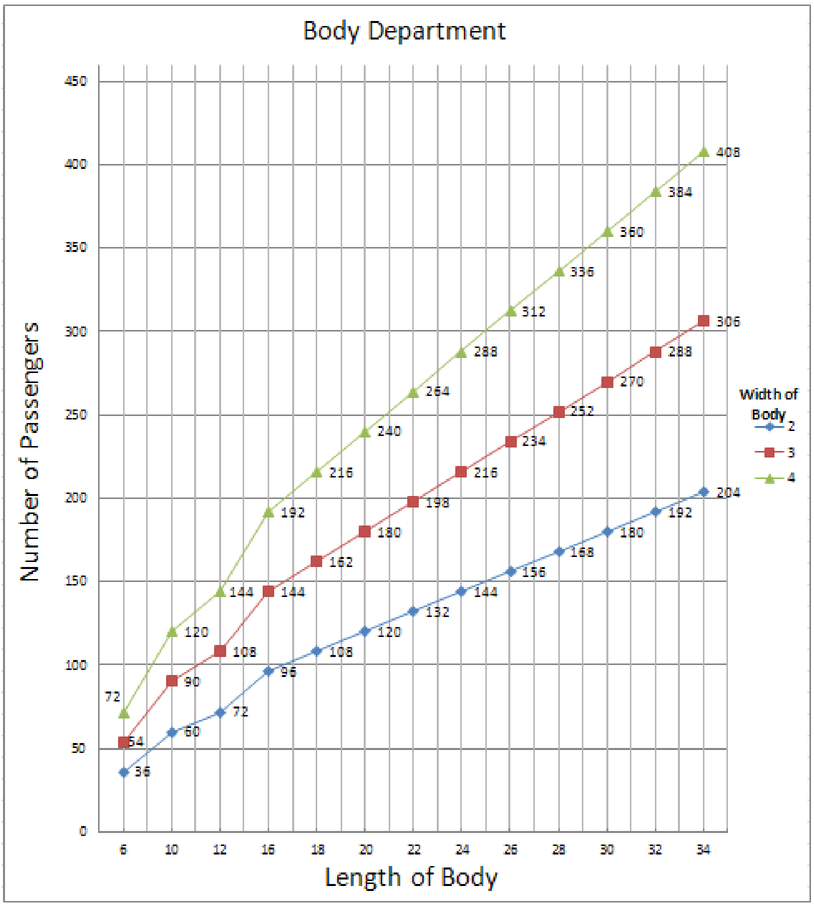



**Figure 5-4 Body Department Trade-Off Curve (Self-Created Figure)**

Together with trade-off curves, four different design space sheets will be also given to players, each of them related to one certain department. These design space sheets give players to have a wide range of design alternatives for each component instead of one. According to the trade-off curves, the players should fill the design space sheets. A design space sheet for Body Department will be shown as an example as follows.

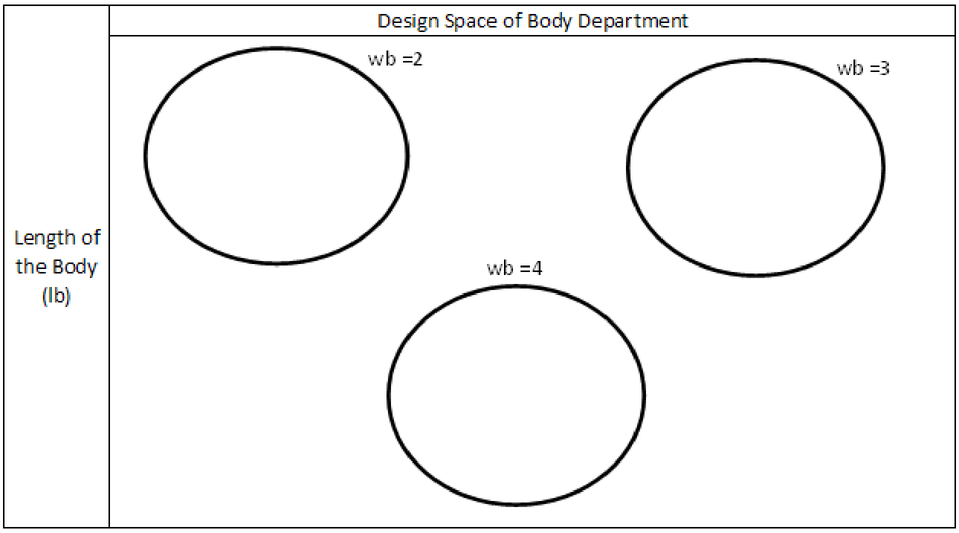



**Figure 5-5 Body Department Design Space (Self-Created Figure)**

3. Having finished the previous task, all players of a group should fill out another sheet, called "Possible Design Alternatives". In this sheet, all the possible design alternatives which have already been captured from the trade-off curves will be transferred there according to the different "Width of Body". The view of the Possible Design Alternatives will be shown below.

| Possible Design Alternatives | | | |
|---|---|---|---|
| Dimensions | wb | | |
| | 2 | 3 | 4 |
| lb | | | |
| lw | | | |
| lt | | | |

**Figure 5-6 Possible Design Alternatives (Self-Created Figure)**

4. The next step will be creating sets of possibilities with those possible design alternatives from the previous task. Since it is possible that players face to more than twenty possible solutions, an excel sheet was already provided for them in order to put the data easier and create their possible solutions in a

more standardized manner. The players should create sets of possibilities based on a combination of “Length of Body”, “Length of Wing” and “Length of Tail” considering different “Width of Body”. A very short example is provided in the following for better understanding.

Imagine that through trade-off curves, the below possible design alternative is generated.

| Possible Design Alternatives | | | |
|---|---|---|---|
| Dimensions | wb | | |
| | 2 | 3 | 4 |
| lb | 12 | 14 | |
| lw | 3<br>4 | 3<br>4 | 3 |
| lt | 3<br>4 | 3 | 3 |

Figure 5-7 Example of Possible Design Alternatives (Self-Created Figure)

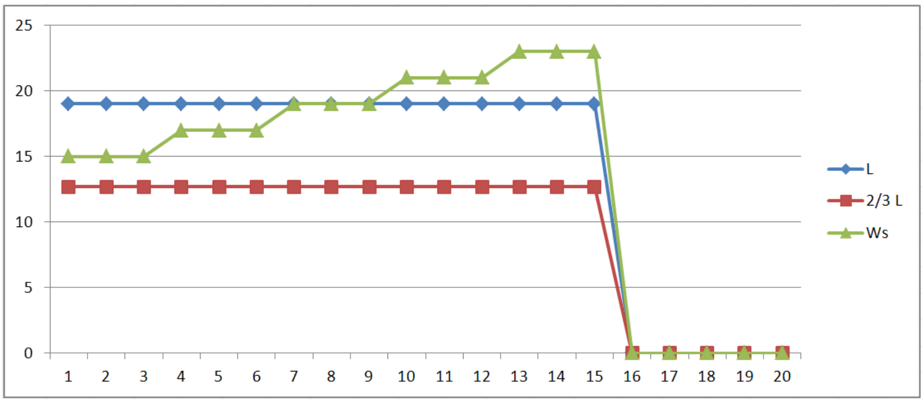
From the above sheet, it is obvious that for the “width of Body” equal to four, there is no possible alternative. Therefore, the last column will be eliminated. For the first two columns, the possible solutions should be created for each column. In the following table the generated combination of possible solutions will be shown. (The last column will be filled based on the Cockpit and Width of Body Alignment, lc =wb).

| No | Set 1 | | | | | | Set 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | lb | wb | lw | lt | lc | | lb | wb | lw | lt | lc |
| 1 | 12 | 2 | 3 | 3 | 2 | | 14 | 3 | 3 | 3 | 3 |
| 2 | 12 | 2 | 4 | 3 | 2 | | 14 | 3 | 4 | 3 | 3 |
| 3 | 12 | 2 | 3 | 4 | 2 | | | | | | |
| 4 | 12 | 2 | 4 | 4 | 2 | | | | | | |

**Table 5-14 Example - Creation of Sets of Possibilities**

As it is shown in the above table, there will be two sets, first one has four possible solutions and second one has two. In total, six possible solutions are generated.

5. Having generated the possible solutions, the players should narrow them based on some limited curves which allow the players to understand which one of the possible solutions is able to turn into a feasible one. There will be two different limited curves which can be found in the given excel sheet. These limited curves are based on the airplane constraints. Through this narrowing process, the players can reach to those feasible solutions which are both in the range of the customer requirements and also able to pass the testing section. An example of a limited curve will be shown in the following.



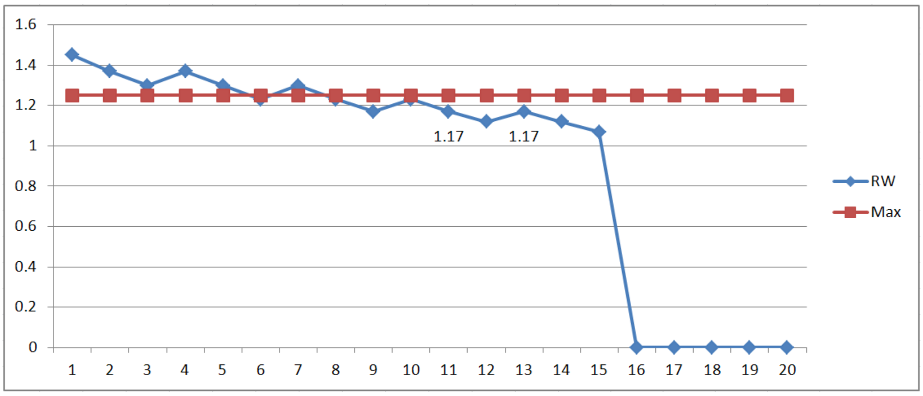



**Figure 5-8 Limit Curves (Self-Created Figures)**

The above charts show the limited curves which are related to the different constraints. The first one is related to the "Length vs. Wing Span" and the second one is related to the "Ratio of Weight" Constraint. The horizontal axis represents the possible solutions. Here it is seen fifteen possible solutions; however not all of them are feasible solutions. Based on the first chart, only those possible solutions (Green Line) can be accepted which are in the range of the red and blue lines. From first chart, the first six possible solutions are acceptable.

In the second chart, the possible solutions (Blue Line) should be under the red line. Blue Line represents the "Ratio of Weight" constraint. From the all fifteen possible solutions, the last ten possible solutions are under the red line and can be acceptable.

Considering both constraints and both charts, there is only one feasible solution (Number six) which meets the requirements of both charts.

6. Having narrowed the possible solutions and found the feasible solutions, the players should transfer those feasible solutions to a new sheet of excel, defined as "Feasible Solutions". The Development Time and Cost of these feasible solutions will be shown in another sheet to players. They can compare different feasible solutions together in terms of time and cost and decide the optimum one which has the least development time and cost.

### 5.3.7 Results Analysis

Having completed the second round and found one optimum feasible solution, the players will be aware of the development time and cost of both rounds and they can simply compare them in order to understand how much efficient they were in the second round, using the Set-Based Concurrent Engineering Model.

Despite of comparing the development time and cost of the two rounds, all the groups are able to reach at least one feasible solution which is in range of all customer requirements, without any iteration.

### 5.3.8 Conclusion

Having played the game, some points should be captured by groups through playing the game in two different rounds:

- ✓ Understanding Point-Based and Set-Based Concurrent Engineering Models of product development process
- ✓ Understanding the weak and strength points of each model
- ✓ Having a better understanding of the enabling factors of the Set-Based Concurrent Engineering
- ✓ Realizing the fact that how these enabling factors affect the performance of the process

The last but no least point is that through Set-Based Concurrent Engineering, the development process is more likely to be improved. Applying and implementing the enabling factors within the Set-Based Concurrent Engineering into the development process lead to having less iteration which consequently results to decreasing the development time and cost. Moreover, the probability of reaching to a more optimum design is higher than the time when Point-Based Concurrent Engineering is being applied within a company.

# 6 Chapter 6

## Validating the Business Game

## Chapter Introduction

Developing only a business game without validating it cannot bring effective results. In order to validating the business game, it scheduled as a workshop in which some players are able to play the business game. The business game was scheduled to be played in a management class of Politecnico di Milano, Milan, Italy and also in a conference taken place in Spain. More information about how game was carried out will be mentioned in the following. Moreover, the following sections are divided into two parts; each dedicates the procedure of the game for different places.

## 6.1 Playing Business Game in A Management Class of Politecnico di Milano

The game was performed in a lab-computer class, since in the game there is an excel sheet with which the players should play the second round of the game. The duration time of the game was about three and half hours, regarding the presentation time of the two rounds. The class consisted of 35 students, divided into 7 groups, each of them 5 students.

The requirements for each group were different. Based on the number of students which were predicted before the class, seven different customer requirements was provided; however the requirements for each group is considered the same for both rounds in order to have a cost and time comparison between them.

In the beginning of the class, the game was presented to the students. A game presentation was provided, both in computer and printed paper, for the students. In this game presentation, the main points such as, aim of the game, airplane dimensions, LEGO components, rules and assumptions, round one, short presentation of Set-Based Concurrent Engineering and round two with its way of playing were completely explained.

### 6.1.1 First Round Results

Having presented the game presentation, the players started playing the game, for a given time of one hour. The students spent approximately ten minutes to fully understand what the game wants from them and then using the LEGO bricks, they tried to design their own airplane. When each group came up with a design, they gave their design to tester in order to see whether their airplane can fly or not. Within the pre-defined certain time, from seven groups, only five of them could design an airplane which can pass the testing section. The others couldn't design or modify their design after one hour, so they considered as failed groups. The playing time of the test (the time that each group spent from the beginning to reach to a design which can fly) and number of try vary among the teams. The following table shows the gathered data from all groups for the first round.

| Group Number | Number of Try | Passing Time | Status |
|---|---|---|---|
| 1 | 3 | - | Fail |
| 2 | 1 | 47’ | Pass |
| 3 | 2 | 49’ | Pass |
| 4 | 2 | - | Fail |
| 5 | 3 | 57’ | Pass |
| 6 | 2 | 53’ | Pass |
| 7 | 2 | 55’ | Pass |

**Table 6-1 Pass and Failure Table – First Round - Italy**

According to the different customer requirements for different groups, the results (cost and time of development) of each group should not be compared to others. The following table shows the development time and cost of each group.

| First Round Development Time and Cost | | |
|---|---|---|
| Group Number | Time | Cost |
| 1 | - | - |
| 2 | 45,6 | 380 |
| 3 | 52,5 | 518 |
| 4 | - | - |
| 5 | 102 | 1445 |
| 6 | 77,2 | 1192 |
| 7 | 108,3 | 1675,7 |

**Table 6-2 Development Time and Cost – First Round - Italy**

The first important point that can be captured from two tables is the time and cost of their design increased, according to the number of try that each group had (As it was mentioned in the previous chapters, redesigning and modifying the design lead to increase the time and cost of the development process and based on the game rules and assumptions, each group encountered extra time and cost from second try). The increased time and cost of each group was provided and shown to each group during the game in order to understand how much waste of time and cost they had during their development process. For instance, the following two charts will show the time and cost breakdown of the fifth group.

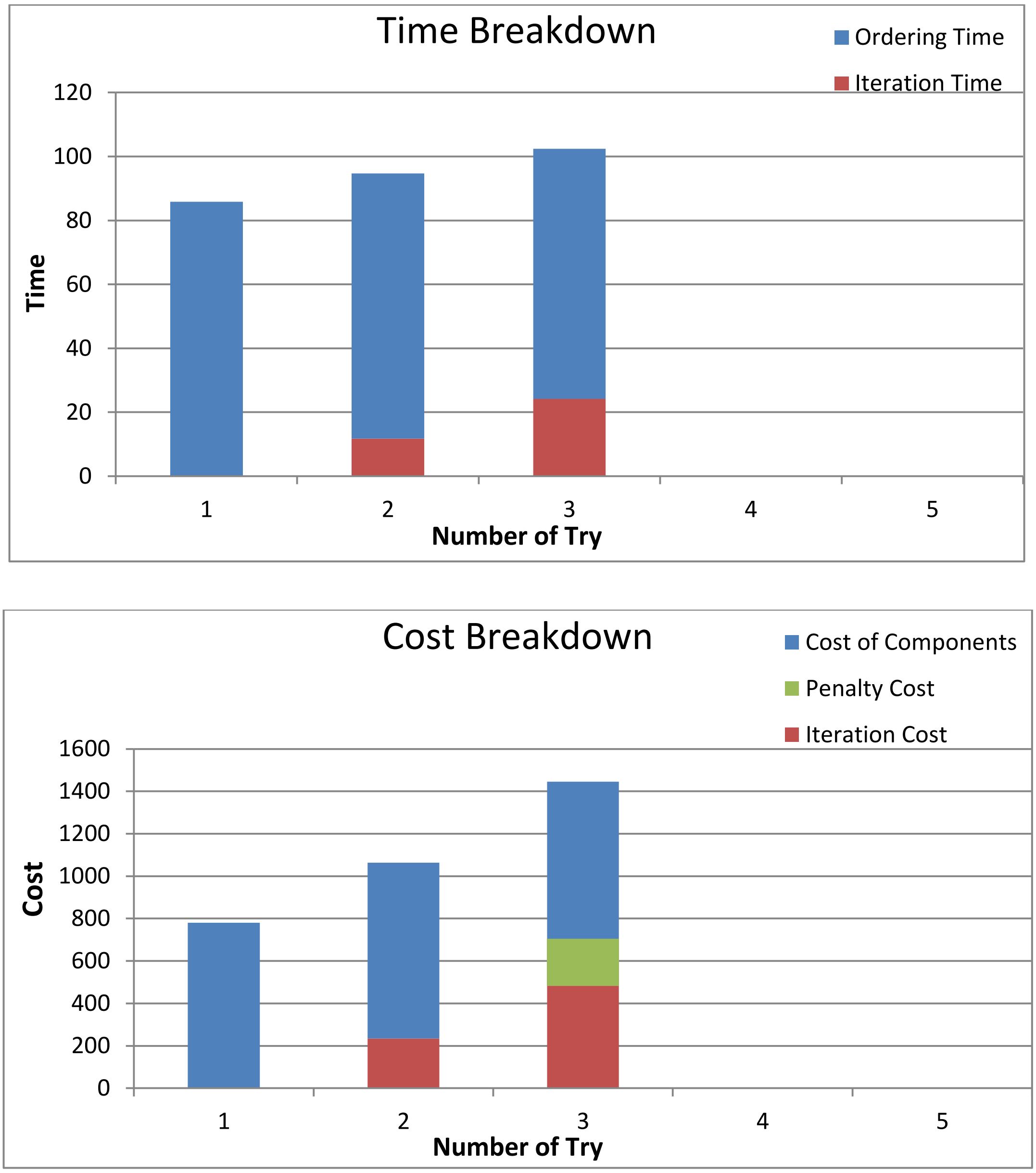



**Figure 6-1 Time & Cost Breakdown - Group NO.5 – Italy**

In the above charts, the time and cost breaks down into different time and cost in order to understand how much time and cost increased based on new design in each redesigning try.

As it is shown in the above graphs, group number five tried to design and redesign the airplane for three times. The blue columns for both graphs represent the real time and cost of the design; but since the number of tried is increasing, the time and cost also will be affected by iteration time and cost. In the first graph, the iteration time (represented by red color) leads the development time to be rising in each try. Cost is also affected by iteration cost and penalty cost (which is due to not being in the range of the customer requirements, represented as green color) in the second graph.

The group number five tried to design their best combination of airplane and after testing it, the airplane could not meet the constraints. Their design could not meet the constraints (Explained in the business game chapter) number two which is related to the weight and number four which is related to the cockpit and body alignment. Therefore they had to redesign their components in order to meet the defined constraints. In their second try, they redesign a new airplane, with different dimensions for cockpit and length of the wing, however again their design could not pass the test due to having problem with weight constraints. For the third time, they had to change their length of airplane's body using also different numbers for different dimension of the airplane. Finally their airplane could fly; however they could not find a design which is exactly in the given customer requirements. Therefore a penalty cost also added to their cost and caused their development cost to be increased again, regarding other iteration cost which was already added to the cost and time because of previous iterations.

In conclusion, the fifth group was attempting to reach to the best design through iterating the process and reaching to the components designs which are able to meet the constraints. There are some main points in this example which are explained in the following:

a) Iteration was the most important factor which caused their development process not to be effective and efficient. The development cost and time increased through few numbers of iterations that they experienced.
b) They had to redesign and modify their designs when the components were not compatible to each other. The problem of redesigning and modifying the components can be solved by using multiple alternatives (Design Space) rather than only one design for each component.
c) Since they were using only one design, they had to fixed the specifications of their components early and in the testing section when they figured out that their design

could not be met the constraints, they had to change the specifications, eventually change their design which lead to having more iteration. This problem can be solved by using "Delaying Decisions" which means not to freeze the specifications early.

d) Meeting the constraints requires a comprehensive understanding of all the departments. Since different departments tried to discuss with others in order to design the best airplane, they did not have a complete and clear view of other departments. Therefore at the end of the process (Testing Section) they experienced incompatibility of components, caused to not reaching the defined constraints. This problem can be omitted by using and understanding about requirements of other department through trade-off curves which gives this possibility to players to understand better the requirements of other departments and design a component which is compatible with the whole system.

### 6.1.2 Second Round Results

After presenting a short introduction about the Set-Based Concurrent Engineering and its enablers and explaining the way how the players should play, the players tried to design their airplane using Set-Based Concurrent Engineering Model. Again the time considered for the second round was one hour. Within the exact time of one hour, all of the teams could reach to at least one single optimum solution with the first try. The following table shows the status and playing time of all seven groups.

| Group Number | Number of Try | Passing Time | Status |
|---|---|---|---|
| 1 | 1 | 38' | Pass |
| 2 | 1 | 30' | Pass |
| 3 | 1 | 40' | Pass |
| 4 | 1 | 32' | Pass |
| 5 | 1 | 25' | Pass |
| 6 | 1 | 39' | Pass |
| 7 | 1 | 35' | Pass |

**Table 6-3 Pass and Failure Table – Second Round - Italy**

From the above table, it is obvious that all the teams could design an airplane within the first try. Therefore using the Set-Based Concurrent Engineering Model, all the teams could eliminate the redesigning and modifying process (No iteration), consequently reducing their development time and cost.

In addition, the performance of all the teams is gathered in the following table.

| Second Round Development Time and Cost | | |
|---|---|---|
| Group Number | Time | Cost |
| 1 | 58 | 580 |
| 2 | 45,6 | 380 |
| 3 | 45,6 | 380 |
| 4 | 52,8 | 440 |
| 5 | 56 | 800 |
| 6 | 61,6 | 880 |
| 7 | 71,4 | 1020 |

**Table 6-4 Development Time and Cost – Second Round - Italy**

As it is seen from the above tables, all the teams improved their development process by using Set-Based Concurrent Engineering. Like the previous round, as an example, the summary of second round of the group number five will be explained as follows.

Having found the possible designs (using design spaces) for each component, they generated sets of possibilities, based on airplane's dimensions. They could reach to three sets of possibilities and, in total, create forty seven possible solutions for airplane. The table of their possible solutions will be shown in the following.

Politecnico di Milano

Set of Possibilities

| 1 | lb | wb | lw | lt | lc | 2 | lb | wb | lw | lt | lc | 3 | lb | wb | lw | lt | lc |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 22 | 2 | 6 | 6 | 2 | 1 | 16 | 3 | 6 | 6 | 3 | 1 | 12 | 4 | 6 | 6 | 4 |
| 2 | 22 | 2 | 6 | 7 | 2 | 2 | 16 | 3 | 6 | 7 | 3 | 2 | 12 | 4 | 6 | 7 | 4 |
| 3 | 22 | 2 | 6 | 8 | 2 | 3 | 16 | 3 | 6 | 8 | 3 | 3 | 12 | 4 | 6 | 8 | 4 |
| 4 | 22 | 2 | 6 | 9 | 2 | 4 | 16 | 3 | 7 | 6 | 3 | 4 | 12 | 4 | 7 | 6 | 4 |
| 5 | 22 | 2 | 7 | 6 | 2 | 5 | 16 | 3 | 7 | 7 | 3 | 5 | 12 | 4 | 7 | 7 | 4 |
| 6 | 22 | 2 | 7 | 7 | 2 | 6 | 16 | 3 | 7 | 8 | 3 | 6 | 12 | 4 | 7 | 8 | 4 |
| 7 | 22 | 2 | 7 | 8 | 2 | 7 | 16 | 3 | 8 | 6 | 3 | 7 | 12 | 4 | 8 | 6 | 4 |
| 8 | 22 | 2 | 7 | 9 | 2 | 8 | 16 | 3 | 8 | 7 | 3 | 8 | 12 | 4 | 8 | 7 | 4 |
| 9 | 22 | 2 | 8 | 6 | 2 | 9 | 16 | 3 | 8 | 8 | 3 | 9 | 12 | 4 | 8 | 8 | 4 |
| 10 | 22 | 2 | 8 | 7 | 2 | 10 | 16 | 3 | 9 | 6 | 3 | 10 | 12 | 4 | 9 | 6 | 4 |
| 11 | 22 | 2 | 8 | 8 | 2 | 11 | 16 | 3 | 9 | 7 | 3 | 11 | 12 | 4 | 9 | 7 | 4 |
| 12 | 22 | 2 | 8 | 9 | 2 | 12 | 16 | 3 | 9 | 8 | 3 | 12 | 12 | 4 | 9 | 8 | 4 |
| 13 | 22 | 2 | 9 | 6 | 2 | 13 | 16 | 3 | 10 | 6 | 3 | 13 | | | | | |
| 14 | 22 | 2 | 9 | 7 | 2 | 14 | 16 | 3 | 10 | 7 | 3 | 14 | | | | | |
| 15 | 22 | 2 | 9 | 8 | 2 | 15 | 16 | 3 | 10 | 8 | 3 | 15 | | | | | |
| 16 | 22 | 2 | 9 | 9 | 2 | 16 | | | | | | 16 | | | | | |
| 17 | 22 | 2 | 10 | 6 | 2 | 17 | | | | | | 17 | | | | | |
| 18 | 22 | 2 | 10 | 7 | 2 | 18 | | | | | | 18 | | | | | |
| 19 | 22 | 2 | 10 | 8 | 2 | 19 | | | | | | 19 | | | | | |
| 20 | 22 | 2 | 10 | 9 | 2 | 20 | | | | | | 20 | | | | | |

| 4 | lb | wb | lw | lt | lc | 5 | lb | wb | lw | lt | lc |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | 1 | | | | | |
| 2 | | | | | | 2 | | | | | |
| 3 | | | | | | 3 | | | | | |
| 4 | | | | | | 4 | | | | | |
| 5 | | | | | | 5 | | | | | |
| 6 | | | | | | 6 | | | | | |
| 7 | | | | | | 7 | | | | | |
| 8 | | | | | | 8 | | | | | |
| 9 | | | | | | 9 | | | | | |
| 10 | | | | | | 10 | | | | | |
| 11 | | | | | | 11 | | | | | |
| 12 | | | | | | 12 | | | | | |
| 13 | | | | | | 13 | | | | | |
| 14 | | | | | | 14 | | | | | |
| 15 | | | | | | 15 | | | | | |
| 16 | | | | | | 16 | | | | | |
| 17 | | | | | | 17 | | | | | |
| 18 | | | | | | 18 | | | | | |
| 19 | | | | | | 19 | | | | | |
| 20 | | | | | | 20 | | | | | |

**Figure 6-2 Sets of Possibilities - Group No.5 - Italy**

Through limited curves they narrow these possible solutions to reach to feasible solutions (those that can be met the constraints and accepted by testing section). Having done this task, only eight feasible solutions remained. The Limited Curves of group NO.5 are shown in the following as well (Only for first set).

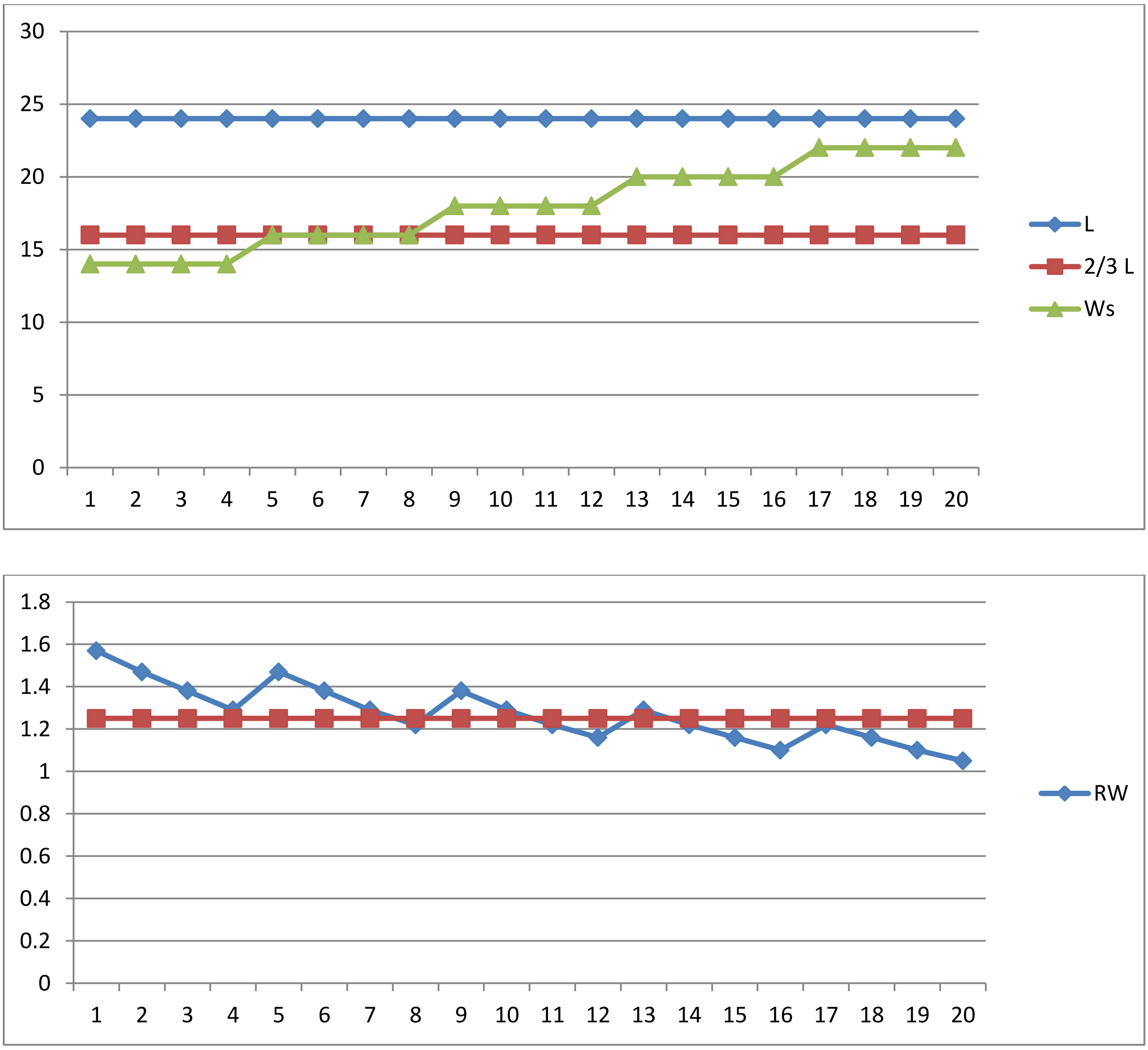



**Figure 6-3 Limit Curves - Group No.5 - Italy**

Based on these eight remaining feasible solutions, they selected the optimum one (Feasible Solution No. 5) which had the minimum development time and cost among the others. The development time and cost of all eight feasible solutions are shown in the following graphs.

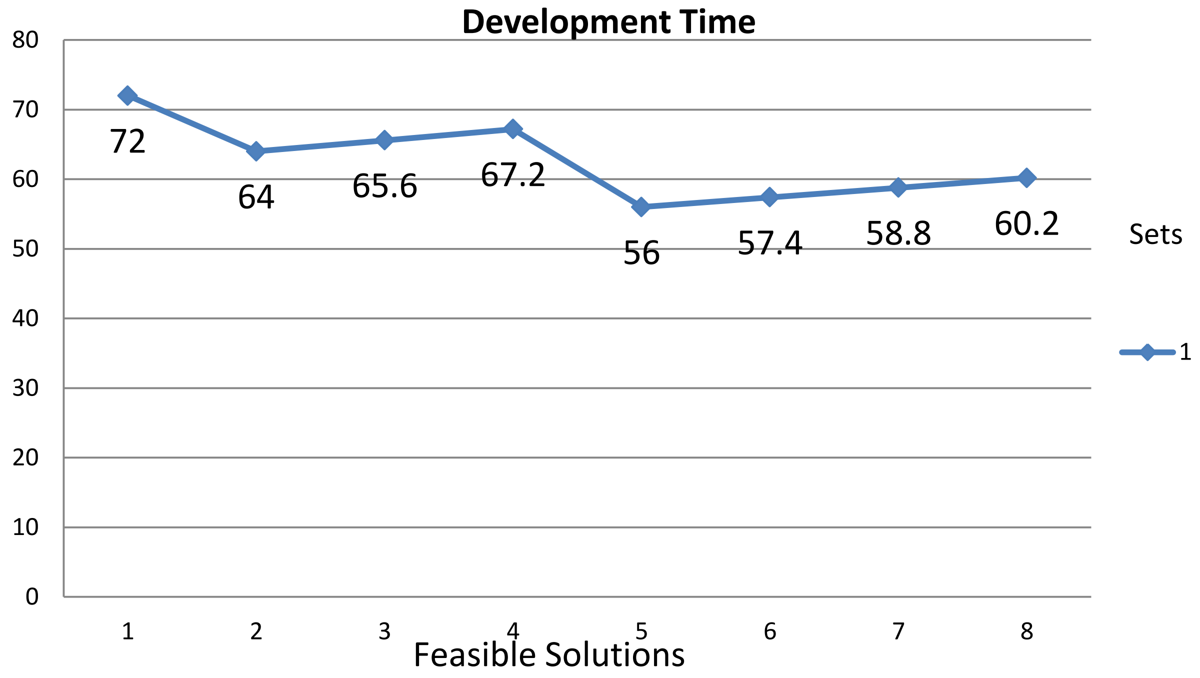



Figure 6-4 Development Time - Group No.5 - Italy

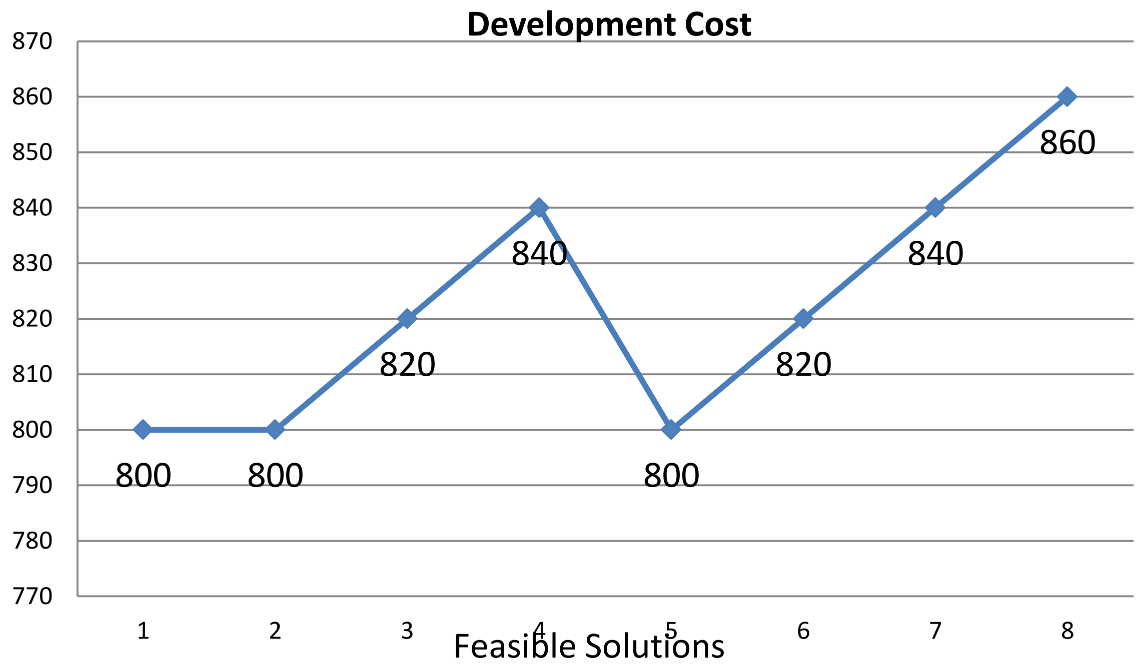



Figure 6-5 Development Cost - Group No.5 - Italy

### 6.1.3 Conclusion

Having finished playing the two rounds, players can compare their performances of both rounds in order to figure out how much improvement they could get during the second round, using Set-Based Concurrent Engineering Model. Based on the enabling factors implemented in the second round of the game, all the groups could decrease the development time and cost, according to the results of both rounds. Moreover based on the recorded playing time of each group, it is also seen that within a shorter time of playing the player could reach to the optimum solution in the second round, using Set-Based Concurrent Engineering.

The following tables will show the comparison of both rounds performances for all the groups.

| Group Number | Passing Time | | Improvement (Minutes) |
|---|---|---|---|
| | Round One | Round Two | |
| 1 | - | 38’ | - |
| 2 | 47’ | 30’ | 17’ |
| 3 | 49’ | 40’ | 9’ |
| 4 | - | 32’ | - |
| 5 | 57’ | 25’ | 32’ |
| 6 | 53’ | 39’ | 14’ |
| 7 | 55’ | 35’ | 20’ |

**Table 6-5 First and Second Rounds Passing Time Results – Italy**

| Both Rounds Development Time | | | |
|---|---|---|---|
| Group Number | Round One | Round Two | Improvement (Percentage) |
| 1 | - | 58 | >50% |
| 2 | 45,6 | 45,6 | 0% |
| 3 | 52,5 | 45,6 | 14% |
| 4 | - | 52,8 | >50% |
| 5 | 102 | 56 | 45% |
| 6 | 77,2 | 61,6 | 20% |
| 7 | 108,3 | 71,4 | 34% |

**Table 6-6 First and Second Rounds Development Time - Italy**

| Both Rounds Development Cost | | | |
|---|---|---|---|
| Group Number | Round One | Round Two | Improvement (Percentage) |
| 1 | - | 580 | >50% |
| 2 | 380 | 380 | 0% |
| 3 | 518 | 380 | 27% |
| 4 | - | 440 | >50% |
| 5 | 1445 | 800 | 45% |
| 6 | 1192 | 880 | 27% |
| 7 | 1675,7 | 1020 | 40% |

**Table 6-7 First and Second Rounds Development Cost - Italy**

From the above tables, it is seen that all the groups have an improvement for their second round development process of the game, regarding Playing Time, Development Time and Development cost. Since the group number one and four could not pass the game in the first round, so their improvement considered as a percentage “more than fifty percent”. Moreover, the group number two, which could pass the first round of the game by designing the right airplane at the first try, and since there was only one feasible solution for them, there was no more improvement that they could apply for their development process. Other groups had a significant improvement in their development process.

To complete this section, there will be a comparison, as an example, between the both rounds of the game for group number five. Extracting the results from the above table, the results of that group will be summarized in the following table.

| Group No. 5 Results | | | |
|---|---|---|---|
| | Playing Time | Development Time | Development Cost |
| First Round | 57’ | 102 | 1445 |
| Second Round | 25’ | 56 | 800 |
| Improvement (Percentage) | 56% | 45% | 45% |

**Table 6-8 Product Development Improvement Table - Group No.5 – Italy**

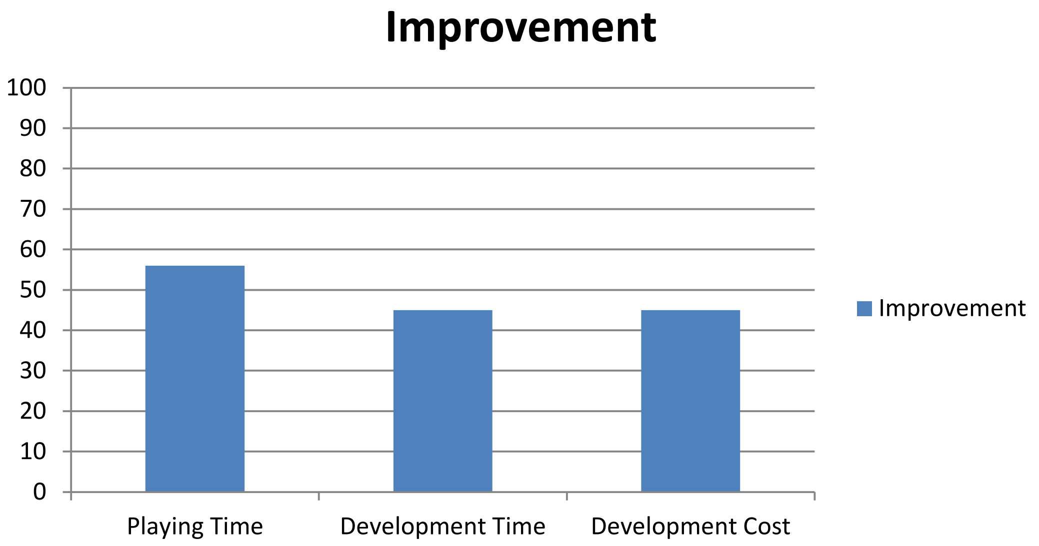



**Figure 6-6Product Development Improvement - Group No.5 - Italy**

The shown table above represents the results captured from the fifth group. In the first round they spent almost the whole given one-hour time in order to design their airplane. But using the Set-Based Concurrent Engineering they could design the optimum airplane and decrease the playing time by 32 minutes, which is an improvement of 56%.

Moreover they also had an improvement of 45% in both development time and cost in the second round through applying enabling factors which helped them to design and reach to an airplane faster and more efficient.

## 6.2 Playing Business Game in a Conference in Spain

This section is dedicated to the results of the business game in Spain where there was a workshop in November 2011, consisting of some experts.

The game was played in three different groups, each includes four players. In the following the results of the business game will be explained in details.

### 6.2.1 First Round Results

Having played the business game by three different groups, the results of them are gathered in the following tables.

| Group Number | Number of Try | Passing Time | Status |
|---|---|---|---|
| 1 | 3 | 60’ | Pass |
| 5 | 3 | 27’ | Pass |
| 7 | 2 | 33’ | Pass |

**Table 6-9 Pass and Failure Table - First Round - Spain**

| First Round Development Time and Cost | | |
|---|---|---|
| Group Number | Time | Cost |
| 1 | 83,8 | 1068 |
| 5 | 58,8 | 840 |
| 7 | 125,2 | 2430 |

**Table 6-10 Development Time and Cost – First Round - Spain**

All the groups were able to come up with an airplane design within the certain given time. The passing time which is the time that players spent to reach to a feasible design and also the development time and cost of each group are gathered in the above table. Like the previous section, as an example the breakdown time and cost of one of the group, Group No. 1, will be shown in the following figure.

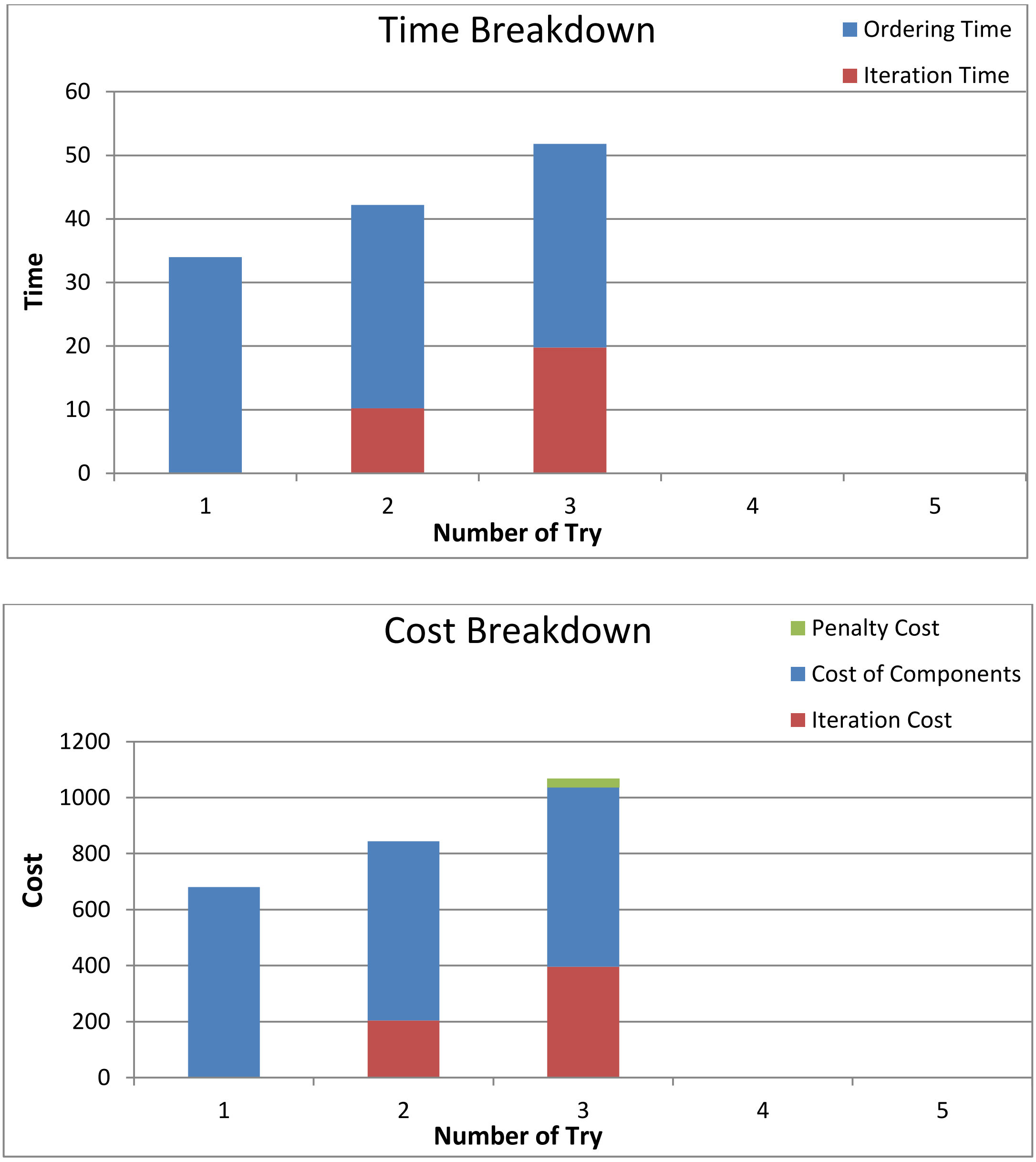



**Figure 6-7 Time and Cost Breakdown – Group No.1 - Spain**

As it is seen it the above figure, the Group No. 3 had to redesign its airplane for three times. The red bars for both graphs represent the iteration time and cost which accumulated each try. There is also a penalty cost for the third try due to the fact that their design was not in the range of customer requirements.

### 6.2.2 Second Round Results

Using Set-Based Concurrent Engineering Model in the second round, the results of the game for three groups will be shown in the following tables as well.

| Group Number | Number of Try | Passing Time | Status |
|---|---|---|---|
| 1 | 3 | 60’ | Pass |
| 5 | 3 | 27’ | Pass |
| 7 | 2 | 33’ | Pass |

Table 6-11 Pass and Failure Table - Second Round - Spain

| First Round Development Time and Cost | | |
|---|---|---|
| Group Number | Time | Cost |
| 1 | 62 | 620 |
| 5 | 58,8 | 840 |
| 7 | 74,8 | 1120 |

Table 6-12 Development Time and Cost - Second Round – Spain

Moreover, the performance of the Group No1 as an example will be shown below.

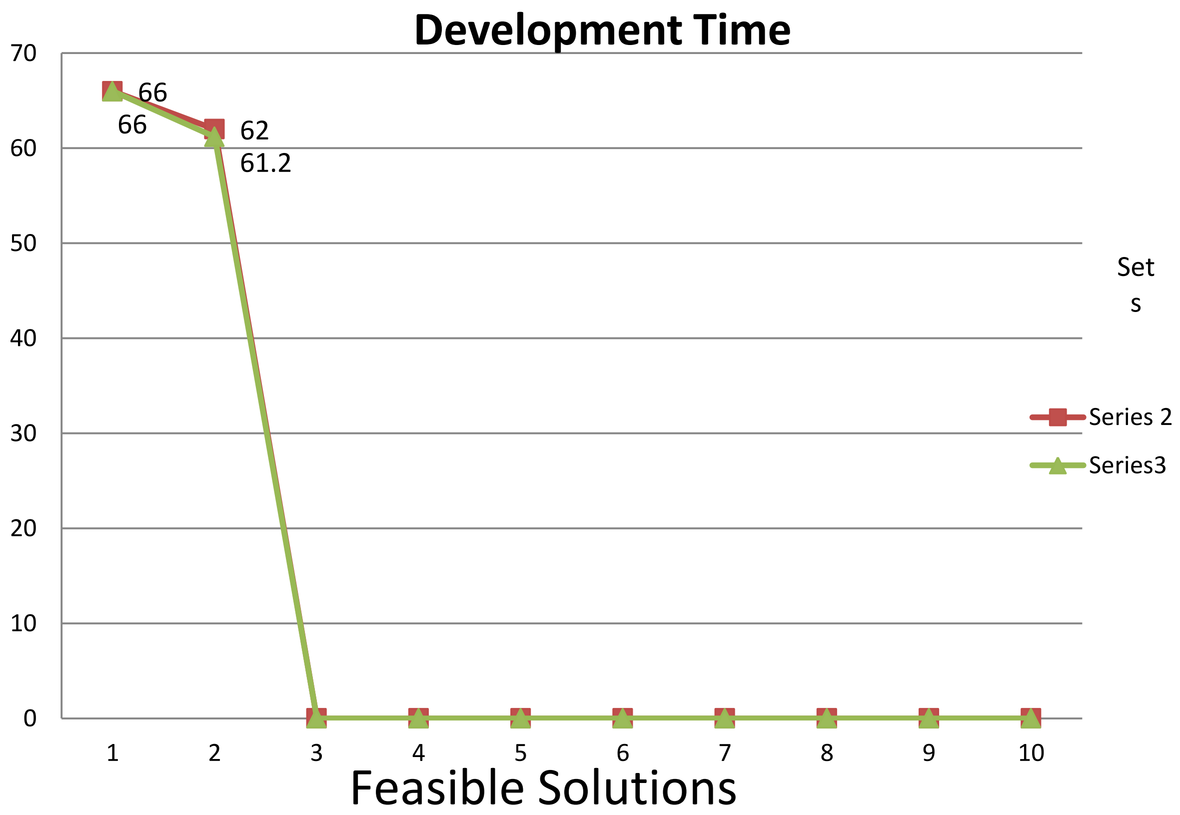



Figure 6-8 Development Time - Group No1 – Spain

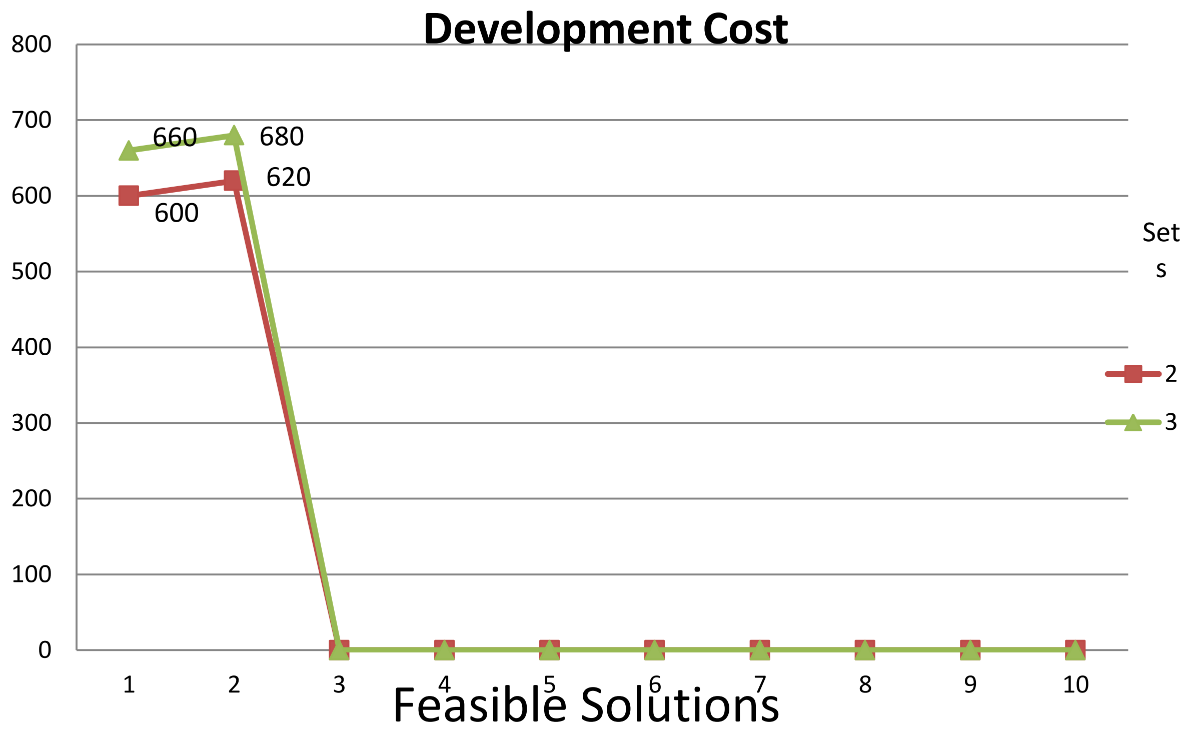



Figure 6-9 Development Cost - Group No1 – Spain

As it is obvious from the above figures, there are four feasible solutions found by Group No1. Two feasible solutions in Set No2 (Red Line), and the other two in Set No3 (Green Line) are the most optimum solutions. It was up to the players to choose the most optimum one based on time and cost, which they selected the second feasible solutions from Set No2, having the time and cost of 62 and 620.

### 6.2.3 Conclusion

Comparing the results of both rounds will be the general conclusion of this game which was played in Spain. Considering the passing time, development time and development cost of each group for both rounds show the rate of improvement of each group. In the following tables, the both rounds results of all groups will be shown.

| Group Number | Playing Time | | Improvement (Minutes) |
|---|---|---|---|
| | Round One | Round Two | |
| 1 | 60' | 38' | 22' |
| 5 | 27' | 25' | 2' |
| 7 | 33' | 25' | 8' |

Table 6-13 Both Rounds Passing Time – Spain

| Both Rounds Development Time | | | |
| --- | --- | --- | --- |
| Group Number | Round One | Round Two | Improvement (Percentage) |
| 1 | 83,8 | 62 | 26% |
| 5 | 58,8 | 58,8 | 0% |
| 7 | 125,2 | 74,8 | 40% |

**Table 6-14 Both Rounds Development Time - Spain**

| Both Rounds Development Cost | | | |
| --- | --- | --- | --- |
| Group Number | Round One | Round Two | Improvement (Percentage) |
| 1 | 1068 | 620 | 41% |
| 5 | 840 | 840 | 0% |
| 7 | 2430 | 1120 | 53% |

**Table 6-15 Both Rounds Development Cost – Spain**

As it is shown in the above tables, the development time and cost of the groups are improved by a significant percentage in the second round using Set-Based Concurrent Engineering Model; however the improvement percentage of Group No5 is "Zero" due to reaching to the optimum design in the first round.

At the end of the game, some few questions about the game and Set-Based Model were prepared for players to give back some feedbacks about the game. The following figure shows the Set-Based Concurrent Engineering Questionnaire.

## Business Game Questionnaire

Having played the game, there are some questions about the game and different models that were applied within the game.

| | 0-40% | 40-70% | 70-100% |
|---|---|---|---|
| How much could you decrease your development cost in the game, using SBCE? | | | |
| How much could you decrease your development time in the game, using SBCE? | | | |
| | | | |

| | Not Effective | Effective | Very Effective |
|---|---|---|---|
| How much do you think SBCE can be more effective than PB? | | | |
| How much do you think Enabling Factors were effective during the game? | | | |
| Which Enabling Factors do you think are more effective? | Not Effective | Effective | Very Effective |
| Multiple Alternatives (Design Space) | | | |
| Narrowing Alternatives | | | |
| Trade-Off and Limited Curves | | | |

| Comments about the game |
|---|
| |

**Figure 6-10 Business Game Questionnaire**

In this short questionnaire, there are three different sections. The first one is related to the development time and cost improvement that the players experienced during the game. The second section is related about how effective Set-Based Concurrent Engineering is from players' point of view. Moreover which of the enabling factors they saw during the game are more effective. The last section is an open question which players can put any comment about the game.

Based on results gathered from players based on the above questionnaire, most of the players reported that there was an improvement of development time and cost about 0-40%. About the second section, most players agreed that Set-Based Concurrent Engineering model is "Very

Effective” than Point-Based Concurrent Engineering. In addition they also agreed that enabling factors could have a very effective impact on the development process. Trade-off, Limit Curves and Narrowing Alternatives are the most effective enabling factors from players’ point of view.

# 7 Chapter 7

## Conclusion

New Product Development Process is considered as a competitive advantage among the companies. Producing new products, from the starting of the project till production, consists of huge number of processes, activities, tasks, relationship between departments and partners involved in the project. All of them together will be considered as a bigger process aims at developing a new product. Based on complexity inside the NPD, companies are suffered by excessive cost and time. Redesigning, Modification, useless knowledge, lack of communication inside the company, low level of organizational integration and iteration are the most problems which result in increasing time, cost and decreasing the quality and innovation of the new product. Implementing a model which is smoothly able to progress till the production phase is being one of the most important factors in companies. Toyota Motor Corporation as an automobile company has been leading the market using an efficient product development model. Toyota has been delivering its products faster, cheaper and with a significant quality rather than its U.S competitors. U.S companies are trying to understand and follow Toyota's effective new product development model, Set-Based Concurrent Engineering; however this model is not known well enough and based on research and articles have been done till now, there are not so much documented papers about this model.

This thesis aims at providing adequate material for Set-Based Concurrent Engineering in order to introduce it more in details. Set-Based Model is a very wide area in terms of concepts and way of thinking. This model consists of many variables which all of them should be properly implemented in order to get the best results from it.

Having studied and introduced about the Set-Based Concurrent Engineering Model in the beginning of this thesis has theoretically proved that Set-Based Concurrent Engineering is more effective than the other models. Later on in the thesis, in order to reach this claim also in real market, a survey was carried out. This survey consists of several questions referring to the existing product development models within the companies and their effectiveness. According to those results gathered from the surveys, most of the companies have been applying the Point-Based Concurrent Engineering; however they also reported Set-Based Model as an effective model, even if all they enabling factors and principles of Set-Based Concurrent Engineering are not used by companies.

Further in the thesis, a business game was designed in order to introduce the Set-Based Concurrent Engineering Model through an educational game which enables players to understand what set-based model is, how it works and which enabling factors enables the product development process to be more efficient and effective.

As a general conclusion, there is a gap between Point-Based and Set-Based Concurrent Engineering. Some companies are following 100% set-based model such as Toyota and some others are using point-based model, combining with some of the enablers of set-based. Providing adequate information for corporations in order to improve their product development process has been one of the main goals of this work and through the business game, it hopes that companies have a more shift toward the Set-Based Concurrent Engineering principles and approaches.

# Appendix

## Interviewed Companies

The companies which were given the questionnaire to be evaluated in terms of effectiveness and efficiency in their product development process will be explained briefly in this section. As it is mentioned already in the related chapter, there are 14 companies. (The INDESIT Company also includes INDESIT IDD Division)

1. CAREL

   It was founded in 1973. One of the world's leading companies in the fields of Refrigeration, Air-Conditioning and Air Humidification, specialists in the development of control systems. (There are four Business Units: Air-Conditioning Controls, Parametric Controls for Refrigeration, Retail Solutions and Systems for Humidity Control)

   The most product/services of CAREL are PCO System, Air-Conditioning Parametric Controls, Refrigeration Parametric Controls, Software Solutions, Connectivity, Sensors and Protection Devices.

2. ABB

   It is a global leader in power and automation technologies that enable utility and industry customers to improve performance while lowering environmental impact. The ABB Group of companies operates in around 100 countries and employs about 130.000 people.

   The Product and Services of this company include Power Products, Power Systems, Discrete Automation and Motion, Low Voltage Products and Process Automation.

3. Dell'Orto

   Since three generations Dell'Orto is byword of alimentation systems: from the historic carburetors (PHBG) to the latest throttle bodies and electronic control units.

   Some products of Dell'Orto will be mentioned in the following table.

| Cars | Motorcycles | Industrial Use |
|---|---|---|
| Throttle Bodies | Carburetors | Carburetors |
| Diesel Throttle Bodies | Throttle Bodies | Throttle Bodies |

| | | |
|---|---|---|
| Manifolds | Oils Pumps | Fuel Pumps |
| EGR Valves | Compressors | |

4. STMicroelectronics

   It is a world leader in providing the semiconductor solutions. STMicroelectronics was created in 1987 by the merger of two long-established semiconductor companies, SGS Microelectronics of Italy and Thomson Semiconductors of France. The group has approximately 53,000 employees, 12 main manufacturing sites, advanced research and development centers in 10 countries, and sales offices all around the world. ST is among the world leaders in many different fields, including semiconductors for industrial applications, inkjet print heads, MEMS (Micro-Electro-Mechanical Systems) for portable and consumer devices, MPEG decoders and smartcard chips, automotive integrated circuits, computer peripherals and wireless.

5. INDESIT Company

   INDESIT Company is one of the European leading manufacturers and distributors of major domestic appliances. The Group's main brands are INDESIT, Hotpoint and Scholtès. INDESIT Company has 14 production facilities (in Italy, Poland, the UK, Russia and Turkey) and 16,000 employees.

   Products of the company are mostly Washing Machines, Dryers, Dishwashers, Fridges, Freezers, Cookers, Hoods, Ovens and Hobs.

6. SCM Group

   An industrial group which is leader in the creation, production and distribution of technologically advanced solutions to process a vast range of materials (wood, glass, stone, plastic, metals and composite materials), with specialist brands for specific technologies and centers of excellence expert in industrial components, present on all 5 continents for more than 50 years.

   Products of the company are Electro-Spindle, Fourth Rotary Axis Devices, Axis Robotized Machining Units, Aggregate Units, and Boring Units.

7. ASK Industries

   The ASK Group designs, develops, manufactures, and distributes high quality car audio and antennas systems - loudspeakers, subwoofer boxes, amplifiers, antennas, and cables. With a team of around 1700 employees, ASK is present in Europe (Italy, Poland, and Germany), South America (Brazil) and Asia (China).

   Loudspeakers and Boxes, Amplifiers, Antennas and Cables are the most common products of the company.

8. AUTEC

   AUTEC has established itself as a worldwide leader in Safety Radio Remote Control. AUTEC's systems have been applied to a wide range of machinery, such as industrial, construction, mobile hydraulics and industrial and manufacturing sectors. With more than 20 years' experience, AUTEC now boasts more than 150,000 installations across the globe.

   Transmitting Units and Receiving Units are the products of the AUTEC.

9. ALFA Laval

   Alfa Laval´s core of operations is based on three key technologies: heat transfer, separation and fluid handling. All three technologies have great significance for industrial companies and Alfa Laval holds leading global market positions within its fields of technical expertise. Alfa Laval´s products are sold in approximately 100 countries, 50 of which have their own sales organizations. The company currently has about 11,500 employees worldwide.

   The ranges of the products are divided into different classes.

   - ✓ Heat Transfer such as heating, cooling, heat recovery and condensation.
   - ✓ Separation such as Extraction and Treatment of Crude Oil
   - ✓ Fluid Handling such as Pumps, Valves, Tank Equipment and Fittings.

10. KONE

    KONE is one of the global leaders in the elevator, escalator and automatic building doors industry. It was founded in 1910. The main segments are residential buildings, hotels, office and retail buildings, infrastructure, and medical buildings. They have eight global production units located in their main markets, as well as seven global R&D centers. In addition, KONE has authorized distributors in over 60 countries. KONE's head office is in Helsinki, Finland.

Elevators, Escalators, Auto walks, Automatics Doors, Monitoring and Access Control Systems are the most common products of the KONE Company. In addition, KONE's services support each phase of a building's lifecycle from design and construction to building maintenance and modernization.

11. PRYSMIAN

    It is a leading player in the industry of high-technology cables and systems for energy and telecommunications. The PTYSMIAN Group is a truly global company, with subsidiaries in 50 countries, 98 plants, 22 R&D Centers and 22,000 employees.

    Industrial and Utilities such as Submarine, Network Components in the Energy Section and Telecom Solutions, Optical Fiber and Multimedia Solutions in the Telecom Section are some products and services of the company.

12. Black and Decker

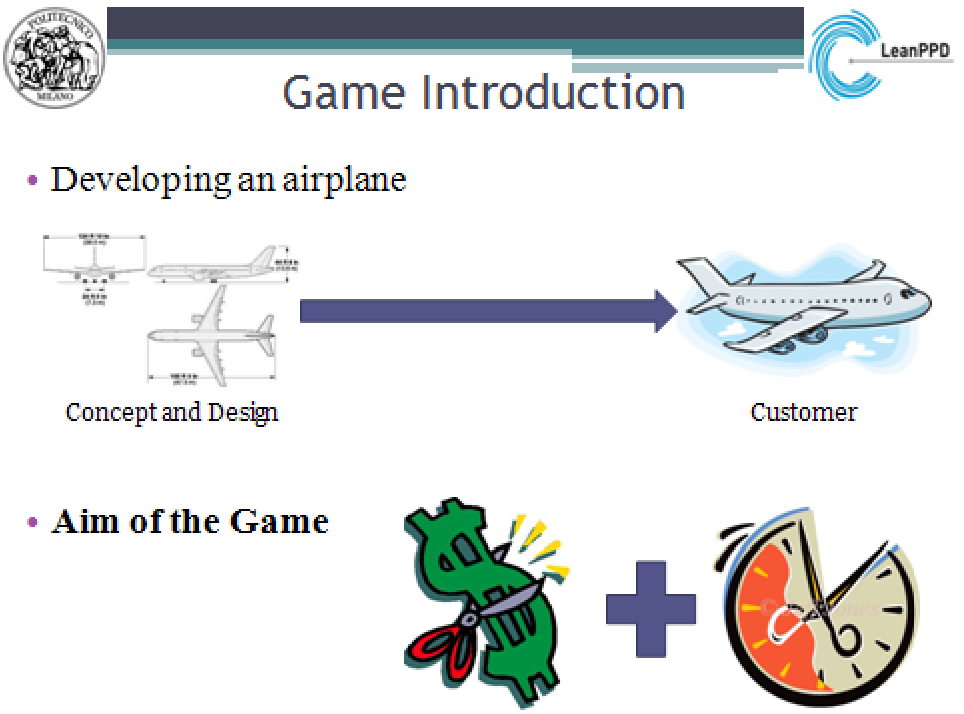
    Black & Decker is one of the nation's top makers of power tools and accessories, produced mainly under the DEWALT and Black & Decker names. It also makes electric lawn and garden tools, plumbing products (Price Pfister), specialty fastening and assembly systems, security hardware (Kwikset), and cleaning and lighting products (Dustbuster, SnakeLight, Scumbuster). Black & Decker markets its products in more than 100 countries; its largest customers include Home Depot and Lowe's. In 2009 the company agreed to be acquired by The Stanley Works.

13. ABOCA

    ABOCA was founded in 1978 and from the beginning its principal objective has been to bring to the modern consumer medicinal herbal products as tools to promote health and well-being. The first derivative products were alcohol extracts used to make drops and highly concentrated capsules containing the "Total Concentrate," another important company patent that consists of blending the dried extract with the micronized powder of the same herb, avoiding the use of inert excipients

## Game Presentation

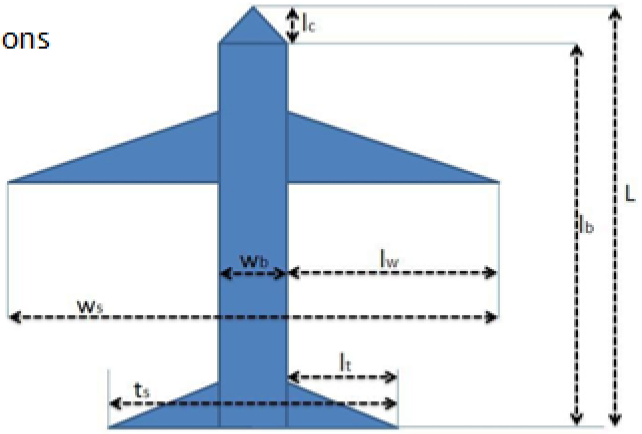
A PowerPoint file was prepared in order to present the business game during the class. The following pages contain the slides in which the game is explained.

# Game Introduction

## 1. Airplane Dimensions

- lb: Length of Body
- wb: Width of Body
- lw: Length of Wing
- lt: Length of Tail
- lc: Length of Cockpit




- Length of Airplane (L) = Length of Body + Length of Cockpit = lb + lc
- Wing Span (Ws) = 2*(Length of Wing) + Width of Body = 2* lw + wb
- Tail Span (Ts ) = 2*(Length of Tail) + Width of Body = 2* lt + wb

# Game Introduction

## 2. Customer Requirements

- Number of Passengers (NP): The number of people whom an airplane can carry during a flight.

NP = Number of Points on Body * Defined Number of Seats for each Single Point (equals to 3)

- Weight (W): Total weight of airplane

W = Weight of Airplane (wa) + Weight of Passengers (wp)

wa = Weight of Body(wb) + Weight of Wings(ww) + Weight of Tails(wt) + Weight of Cockpit(wc)

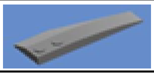
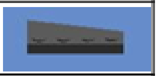
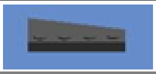
wp = NP * Average Weight of every Person (Considered as 60 Kg)

- Length of Airplane (L)
- Wing Span (Ws)
- Tail Span (Ts )

## Game Introduction

### 3. LEGO-Components of Airplane

| | Single Point |
|---|---|
| Capacity | 3 |
| Weight | 100 |
| Length | 1 |
| Width | 1 |

| Components | LEGO Parts |
|---|---|
| Body |  |
| Wing |   |
| Tail |  |
| Cockpit |  |

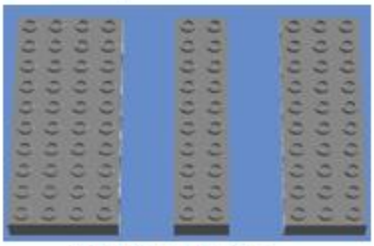
| Point Similarities | | Description | Number of Points |
|---|---|---|---|
| Body & Wing |  | number of points on both shapes | 6 |
| Body & Cockpit |  | | 4 |

## Game Introduction

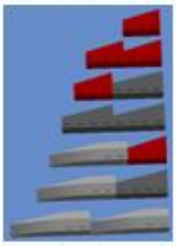
### 3. LEGO-Components Combination

Cockpit Combination

Tail Combination



BodyCombination



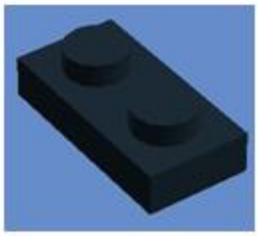
Wing Combination

# Game Introduction

3. LEGO-Joints for Airplane

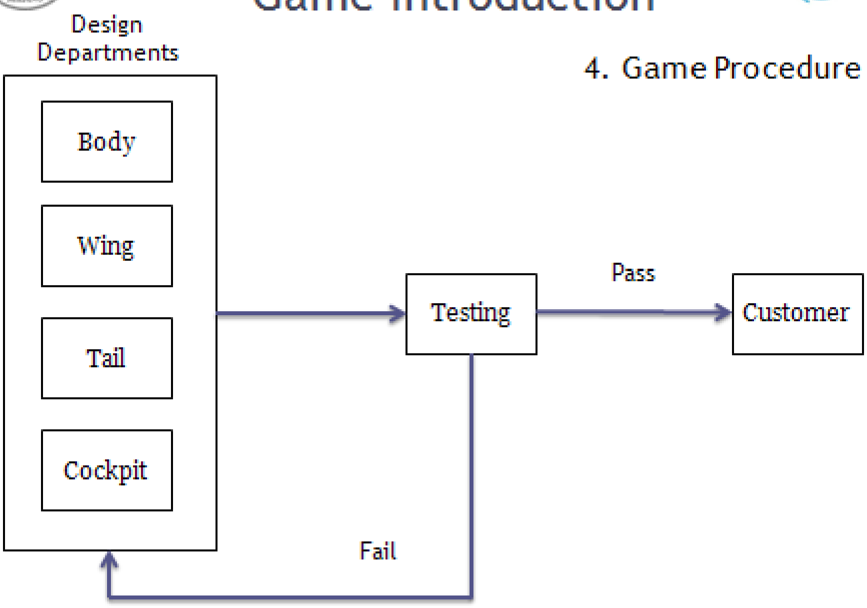
Joints for body components

Joint for connecting body with wing, tail and cockpit



# Game Introduction

4. Game Procedure



## Round One

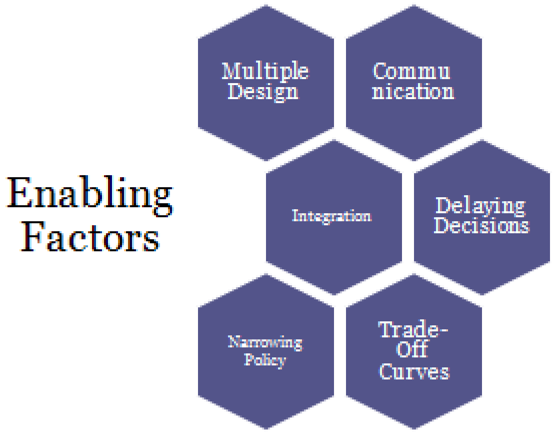
1. According to customer requirements, come up with your own best desing of your component.
2. Fill the related specifications into the component specifications sheet, when it is completed, give it to testing department.
3. Testing department will inform you about your airplane. In case of need, you should redesing and modify your airplane, it do increase the cost and time of your development process.
4. In case your design is fine, LEGO your airplane. The development cost and time will be informed to you.

## Main Problems

- Your design was not the optimum one!! It is possible to make it with less time and cost.
- Inconsistency between the airplane's components due to not enought integration and communication between the different departments.
- In case of inconsistency, there is iteration (redesigning) and it increases significantly costs and time.
- Inflexibile system due to fixing specifications of components early.

## Set-Based Concurrent Engineering

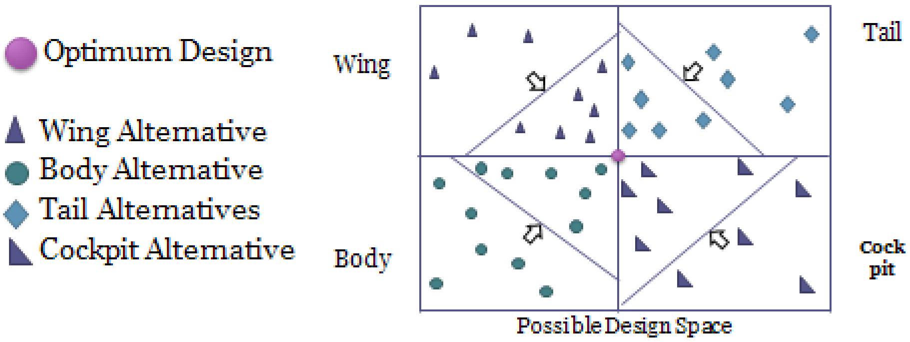
- Rare type of product development process model
- SBCE model is not efficient, thought by most companies
- Toyota spends less time and cost for development process with also higher quality using SBCE!




## Enabling Factors

### Multiple Alternatives (Design Space)

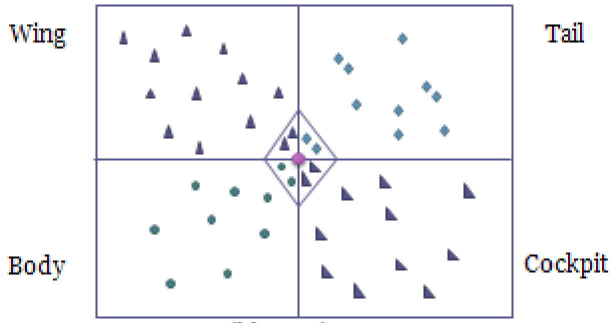
- More Alternatives VS One Alternatives
- Seems costly and time-consuming in the beginning
- Increase process flexibility
- Decrease total time and cost at the end



## Enabling Factors

- Narrowing Alternative Policy

- Eliminating the inferior solutions instead of choosing the best one

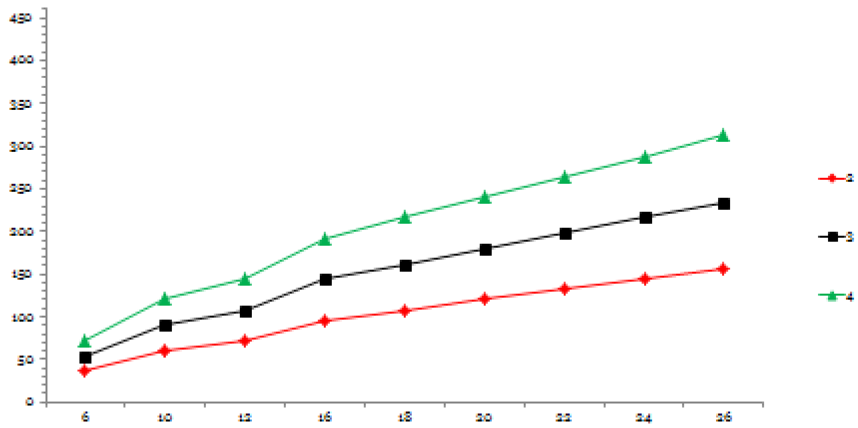



Possible Design Space

## Enabling Factors

- Trade-Off Curves

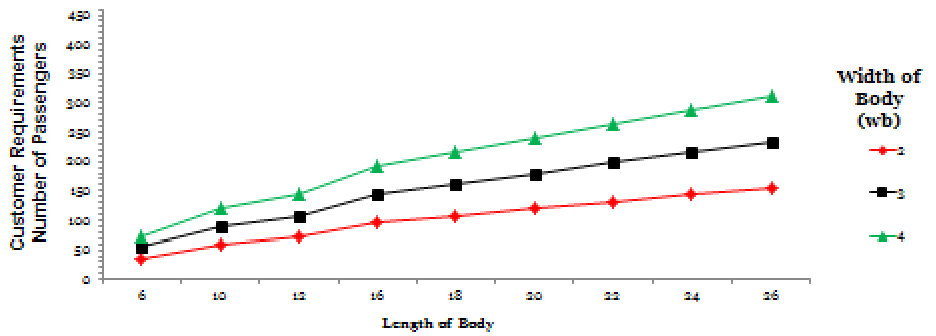
- Better understanding about the requirements of different functions
- Increasing the level of departments' compatibility
- Finding multiple design solutions



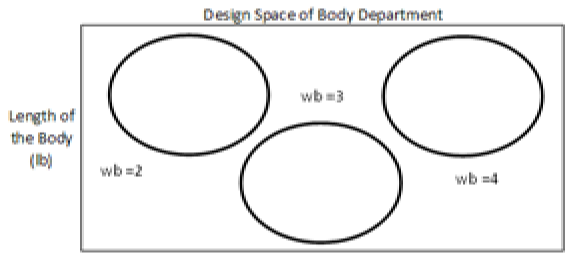
# Round Two

1. According to the customer requirements, find different design alternatives from the curves and fill your own design space sheet.
2. Share your alternatives and fill the Possible Design Alternatives Sheet together. Some of you might not have common alternatives!
3. Using excel sheets, try to create sets of possibilities. Each set represents a number of combinations which are using same «lb» and «wb».
4. Narrowing the possible solutions by using limited curves. Put the remaining solutions in the Feasibile Solutions Excel Sheet for each set.
5. Optimum solution can be found by comparing development time and cost of feasible solutions.
6. LEGO your optimum solution!

# Curves and Design Space Sheet




The possible solutions should be written inside the corresponding circles.



## Possible Solutions

Set of Possibilities

| | 1 | | | | |
|---|---|---|---|---|---|
| | lb | wb | lw | lt | lc |
| 1 | 12 | 3 | 3 | 3 | 3 |
| 2 | 12 | 3 | 3 | 4 | 3 |
| 3 | 12 | 3 | 3 | 6 | 3 |
| 4 | 12 | 3 | 4 | 3 | 3 |
| 5 | 12 | 3 | 4 | 4 | 3 |
| 6 | 12 | 3 | 4 | 6 | 3 |
| 7 | 12 | 3 | 6 | 3 | 3 |
| 8 | 12 | 3 | 6 | 4 | 3 |
| 9 | 12 | 3 | 6 | 6 | 3 |
| 10 | 12 | 3 | 7 | 3 | 3 |
| 11 | 12 | 3 | 7 | 4 | 3 |
| 12 | 12 | 3 | 7 | 6 | 3 |
| 13 | 12 | 3 | 8 | 3 | 3 |
| 14 | 12 | 3 | 8 | 4 | 3 |
| 15 | 12 | 3 | 8 | 6 | 3 |

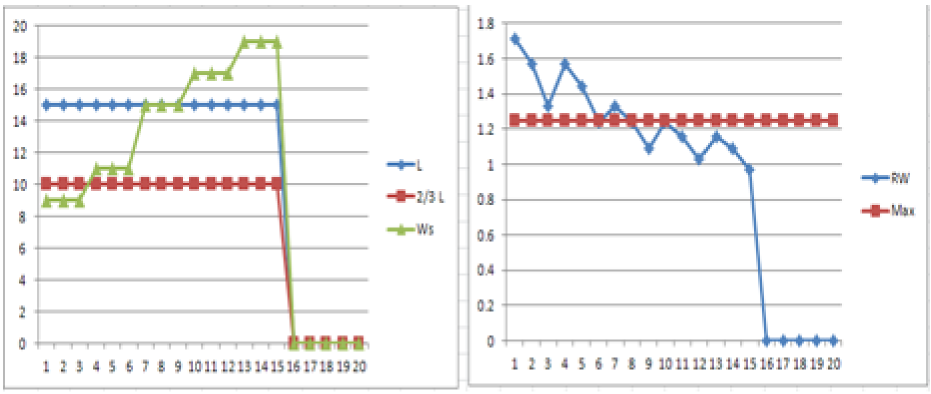
| | 2 | | | | |
|---|---|---|---|---|---|
| | lb | wb | lw | lt | lc |
| 1 | 16 | 2 | 3 | 3 | 2 |
| 2 | 16 | 2 | 3 | 4 | 2 |
| 3 | 16 | 2 | 3 | 6 | 2 |
| 4 | 16 | 2 | 4 | 3 | 2 |
| 5 | 16 | 2 | 4 | 4 | 2 |
| 6 | 16 | 2 | 4 | 6 | 2 |
| 7 | 16 | 2 | 6 | 3 | 2 |
| 8 | 16 | 2 | 6 | 4 | 2 |
| 9 | 16 | 2 | 6 | 6 | 2 |
| 10 | 16 | 2 | 7 | 3 | 2 |
| 11 | 16 | 2 | 7 | 4 | 2 |
| 12 | 16 | 2 | 7 | 6 | 2 |
| 13 | 16 | 2 | 8 | 3 | 2 |
| 14 | 16 | 2 | 8 | 4 | 2 |
| 15 | 16 | 2 | 8 | 6 | 2 |

| | 3 | | | | |
|---|---|---|---|---|---|
| | lb | wb | lw | lt | lc |
| 1 | 18 | 2 | 3 | 3 | 2 |
| 2 | 18 | 2 | 3 | 4 | 2 |
| 3 | 18 | 2 | 3 | 6 | 2 |
| 4 | 18 | 2 | 4 | 3 | 2 |
| 5 | 18 | 2 | 4 | 4 | 2 |
| 6 | 18 | 2 | 4 | 6 | 2 |
| 7 | 18 | 2 | 6 | 3 | 2 |
| 8 | 18 | 2 | 6 | 4 | 2 |
| 9 | 18 | 2 | 6 | 6 | 2 |
| 10 | 18 | 2 | 7 | 3 | 2 |
| 11 | 18 | 2 | 7 | 4 | 2 |
| 12 | 18 | 2 | 7 | 6 | 2 |
| 13 | 18 | 2 | 8 | 3 | 2 |
| 14 | 18 | 2 | 8 | 4 | 2 |
| 15 | 18 | 2 | 8 | 6 | 2 |

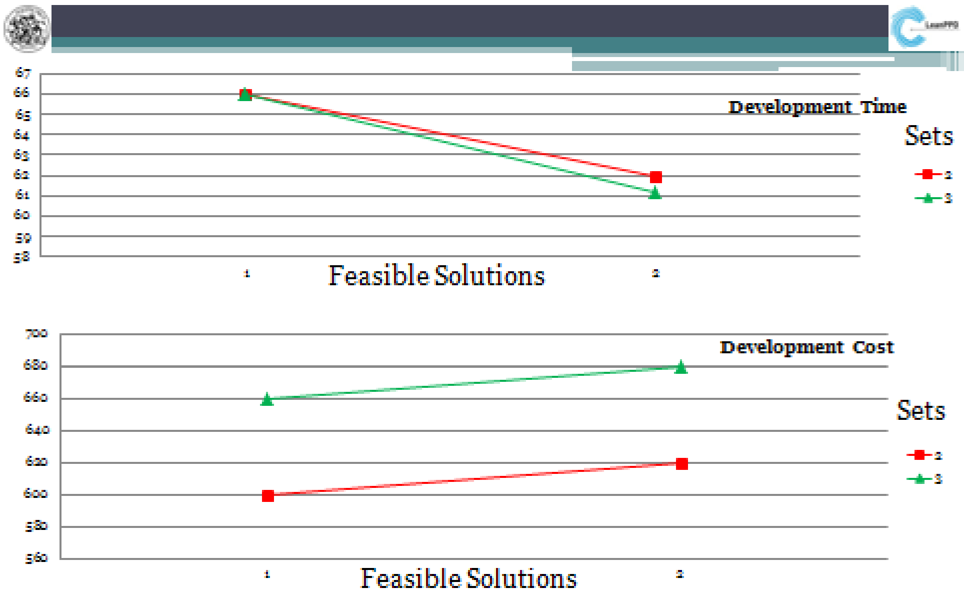
| | 4 | | | | |
|---|---|---|---|---|---|
| | lb | wb | lw | lt | lc |
| 1 | | | | | 0 |
| 2 | | | | | 0 |
| 3 | | | | | 0 |
| 4 | | | | | 0 |
| 5 | | | | | 0 |
| 6 | | | | | 0 |
| 7 | | | | | 0 |
| 8 | | | | | 0 |
| 9 | | | | | 0 |
| 10 | | | | | 0 |
| 11 | | | | | 0 |
| 12 | | | | | 0 |
| 13 | | | | | 0 |
| 14 | | | | | 0 |
| 15 | | | | | 0 |

- Possible solutions are combination of different components' alternatives which are extracted from the design space sheets.

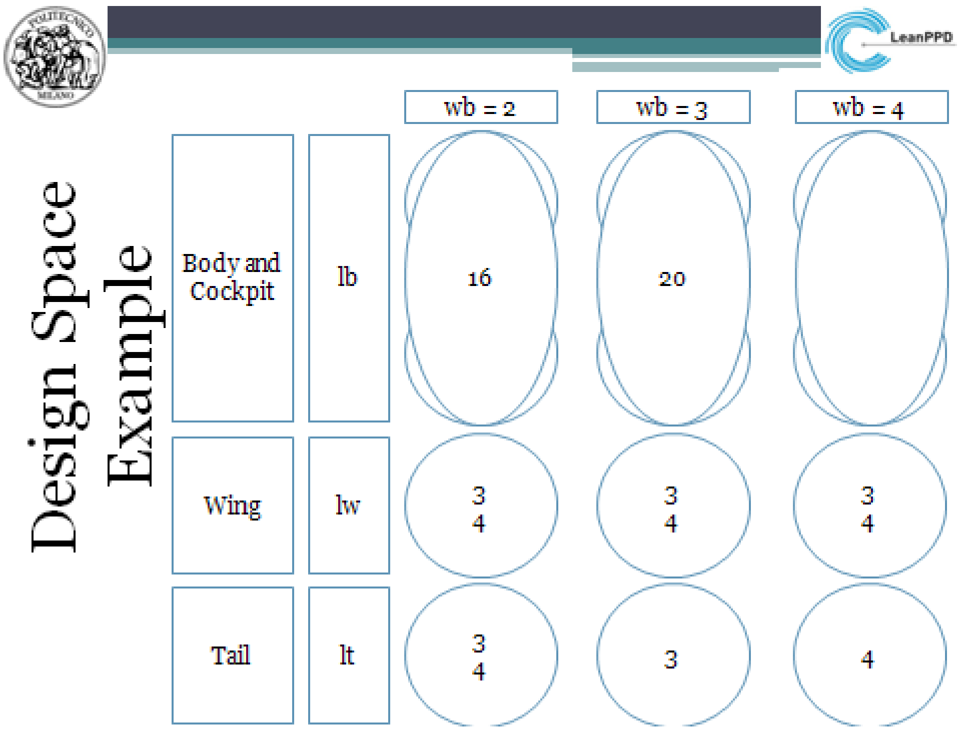
## Limit Curves




- From these curves you can eliminate the infeasible solutions and reach to optimum design.




- Having narrowed the solutions, the cost and time of the remaining feasible solutions will be graphically shown and the optimum solution can be selected.



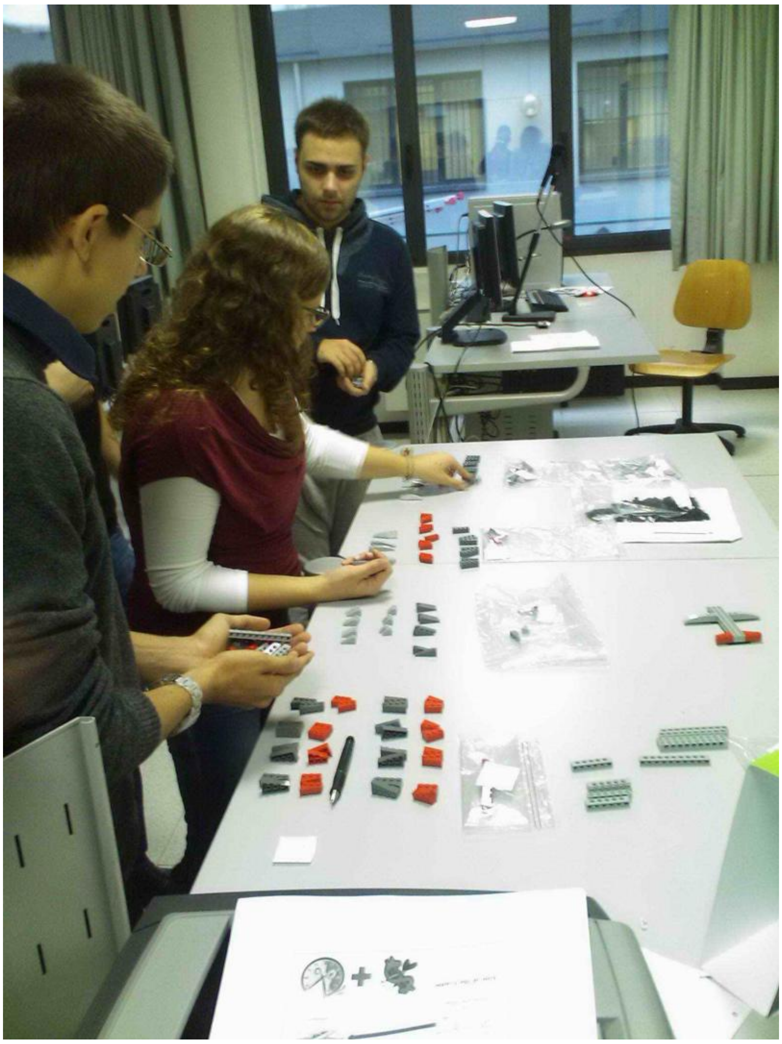
## Combination Example

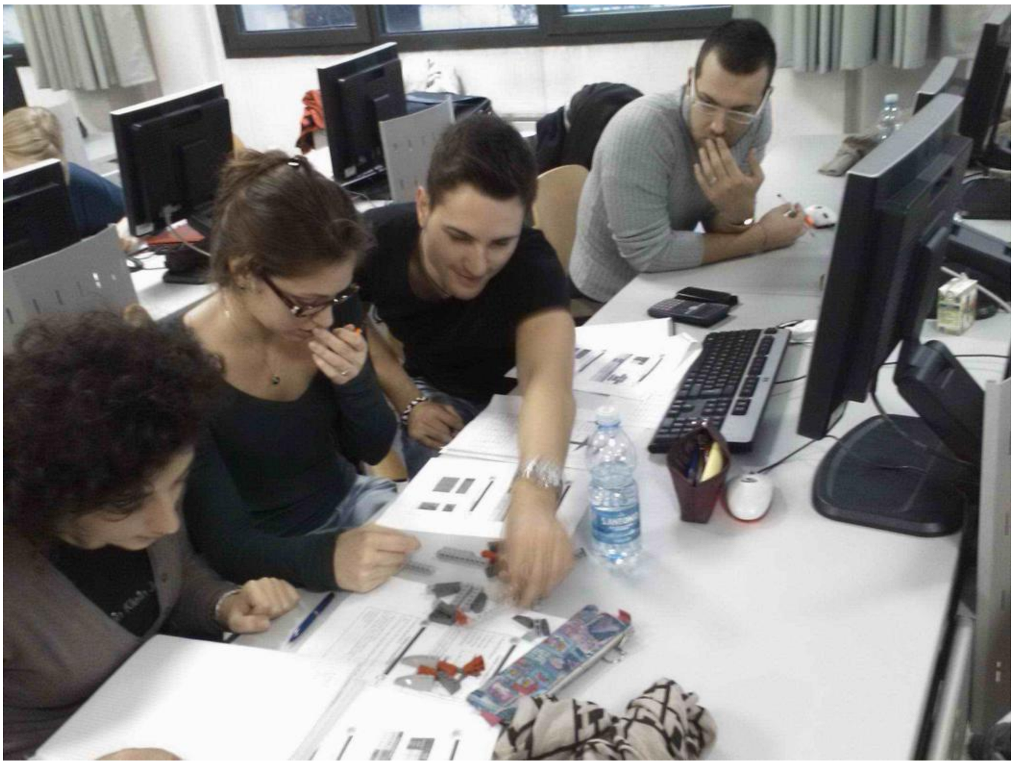
| Set 1 | | | | | |
|---|---|---|---|---|---|
| | lb | wb | lw | lt | lc |
| 1 | 16 | 2 | 3 | 3 | 2 |
| 2 | 16 | 2 | 4 | 3 | 2 |
| 3 | 16 | 2 | 3 | 4 | 2 |
| 4 | 16 | 2 | 4 | 4 | 2 |

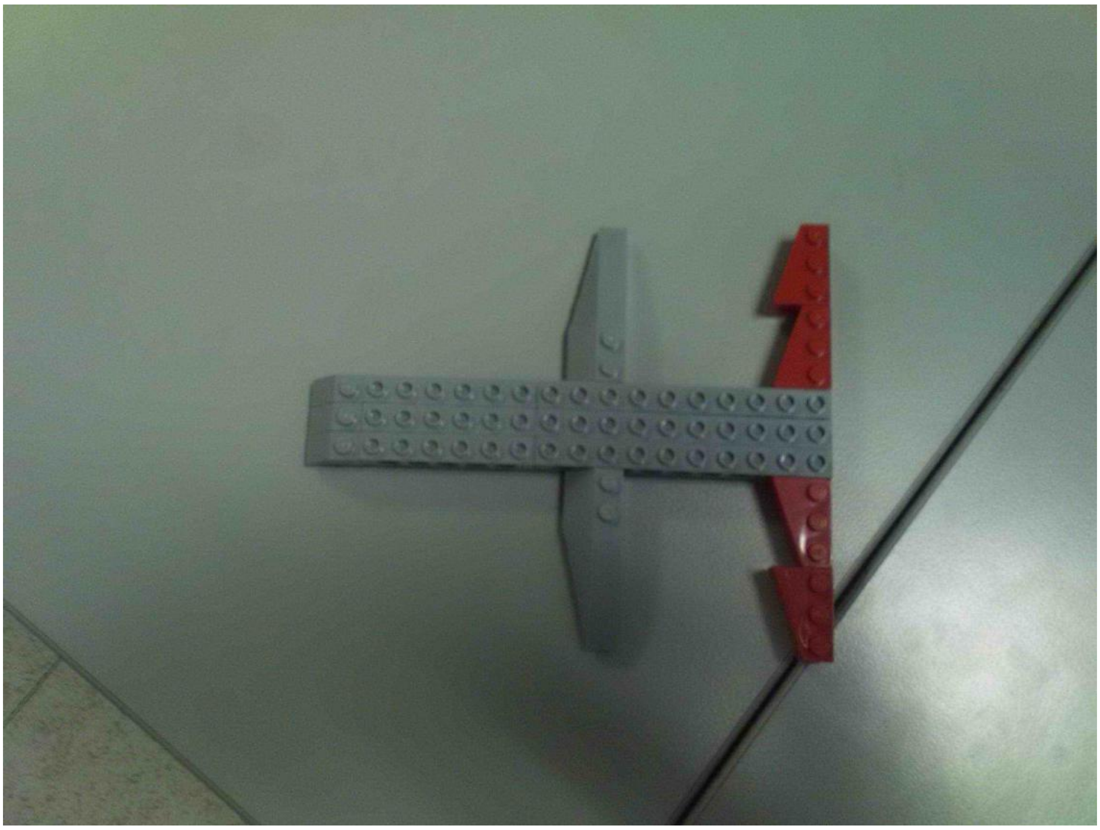
| Set 2 | | | | | |
|---|---|---|---|---|---|
| | lb | wb | lw | lt | lc |
| 1 | 20 | 3 | 3 | 3 | 3 |
| 2 | 20 | 3 | 4 | 3 | 3 |

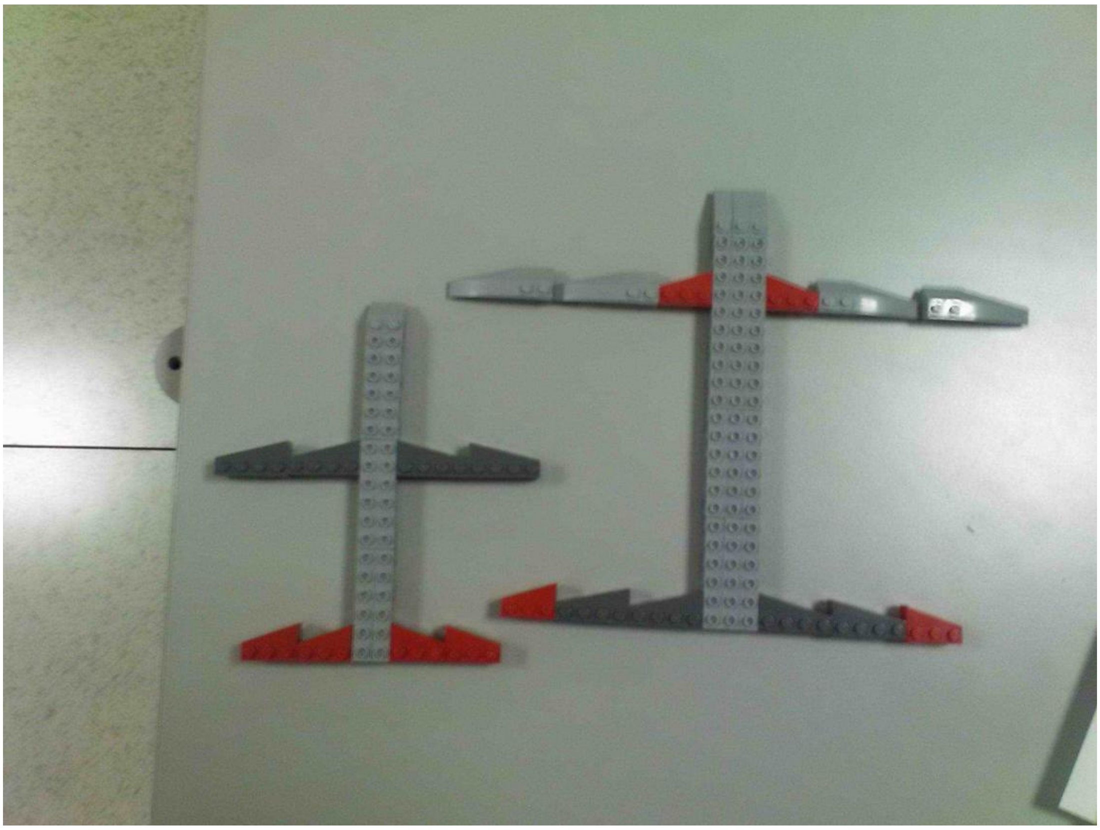
## Pictures of the Business Game in Italy

The following pictures were taken during the class, while the players were playing the Set-Based Concurrent Engineering Business Game.









## Pictures of the Business Game in Spain

## Business Game Questionnaire

| | 0-40% | 40-70% | 70-100% |
|---|---|---|---|
| How much could you decrease your development cost in the game, using SBCE? | X | | |
| How much could you decrease your development time in the game, using SBCE? | x | | |
| | Not Effective | Effective | Very Effective |
| How much do you think SBCE can be more effective than PBCE model? | | x | |
| How much do you think Enabling Factors are effective during the game? | | X | |
| Which Enabling Factors do you think are more effective in SBCE? | | | |
| Multiple Alternatives (Design Space) | | | X |
| Narrowing Alternatives | | X | |
| Trade-off and Limit Curves | | X | |

| | 0-40% | 40-70% | 70-100% |
|---|---|---|---|
| How much could you decrease your development cost in the game, using SBCE? | X | | |
| How much could you decrease your development time in the game, using SBCE? | x | | |
| | Not Effective | Effective | Very Effective |
| How much do you think SBCE can be more effective than PBCE model? | | | X |
| How much do you think Enabling Factors are effective during the game? | | | X |
| Which Enabling Factors do you think are more effective in SBCE? | | | |
| Multiple Alternatives (Design Space) | | x | |
| Narrowing Alternatives | | | x |
| Trade-off and Limit Curves | | x | |

| | 0-40% | 40-70% | 70-100% |
|---|---|---|---|
| How much could you decrease your development cost in the game, using SBCE? | x | | |
| How much could you decrease your development time in the game, using SBCE? | | X | |
| | Not Effective | Effective | Very Effective |
| How much do you think SBCE can be more effective than PBCE model? | | | X |
| How much do you think Enabling Factors are effective during the game? | | | X |
| Which Enabling Factors do you think are more effective in SBCE? | | | |
| Multiple Alternatives (Design Space) | | | X |
| Narrowing Alternatives | | | X |
| Trade-off and Limit Curves | | | X |

| | 0-40% | 40-70% | 70-100% |
|---|---|---|---|
| How much could you decrease your development cost in the game, using SBCE? | X | | |
| How much could you decrease your development time in the game, using SBCE? | x | | |
| | Not Effective | Effective | Very Effective |
| How much do you think SBCE can be more effective than PBCE model? | | | X |
| How much do you think Enabling Factors are effective during the game? | | X | |
| Which Enabling Factors do you think are more effective in SBCE? | | | |
| Multiple Alternatives (Design Space) | | x | |
| Narrowing Alternatives | | | X |
| Trade-off and Limit Curves | | | X |

| | 0-40% | 40-70% | 70-100% |
|---|---|---|---|
| How much could you decrease your development cost in the game, using SBCE? | X | | |
| How much could you decrease your development time in the game, using SBCE? | | X | |
| | Not Effective | Effective | Very Effective |
| How much do you think SBCE can be more effective than PBCE model? | | | X |
| How much do you think Enabling Factors are effective during the game? | | | X |
| Which Enabling Factors do you think are more effective in SBCE? | | | |
| Multiple Alternatives (Design Space) | | x | |
| Narrowing Alternatives | | | X |
| Trade-off and Limit Curves | | | x |

| | 0-40% | 40-70% | 70-100% |
|---|---|---|---|
| How much could you decrease your development cost in the game, using SBCE? | X | | |
| How much could you decrease your development time in the game, using SBCE? | x | | |
| | Not Effective | Effective | Very Effective |
| How much do you think SBCE can be more effective than PBCE model? | | | X |
| How much do you think Enabling Factors are effective during the game? | | | X |
| Which Enabling Factors do you think are more effective in SBCE? | | | |
| Multiple Alternatives (Design Space) | | | X |
| Narrowing Alternatives | | | X |
| Trade-off and Limit Curves | | | X |

| | 0-40% | 40-70% | 70-100% |
|---|---|---|---|
| How much could you decrease your development cost in the game, using SBCE? | X | | |
| How much could you decrease your development time in the game, using SBCE? | x | | |
| | Not Effective | Effective | Very Effective |
| How much do you think SBCE can be more effective than PBCE model? | | | X |
| How much do you think Enabling Factors are effective during the game? | | | X |
| Which Enabling Factors do you think are more effective in SBCE? | | | |
| Multiple Alternatives (Design Space) | x | | |
| Narrowing Alternatives | | x | |
| Trade-off and Limit Curves | | | x |

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