CHALMERS

Assessing Principles of Set-Based Concurrent Engineering Using a Design Game

Evaluating the application of one principle of Lean Product Development, Set-Based Concurrent engineering, using the Delta Design Game

By

Francesc Carbó Roma

Chalmers University of Technology
Department of Product and Production Development
Gothenburg, Sweden, June 2012

Assessing Principles of Set-Based Concurrent Engineering Using a Design Game

Evaluating the application of one principle of Lean product Development, Set-Based Concurrent engineering, using the Delta Design Game by L.Bucciarelli.

FRANCESC, CARBÓ ROMA. June 2012.

Examiner: Göran Gustafsson, Senior Lecturer.

Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Gothenburg.
Sweden
Telephone + 46 (0)31-772 10 00

Department of Product and Production Development
Gothenburg, Sweden , June 2012

Acknowledgments

Writing a thesis means that you are finishing your master and it is almost impossible to reach this objective without helps and advises.

I would first like to thank my tutor Durward K. Sobek II. He gave me the starting point for this thesis and without his advice, ideas and corrections I couldn't have got to print it. I would also like to thank you Kristofer Bengtsson and Ludvig Lindlöf that helped me in the second round with the game.

Since this thesis have been developed in Sweden I would like to thank you all my Erasmus family that helped overcoming the weak moments during these awesome, intense and short five months. Special mention for Dani, Eli, Màrcio, Tiri, Remi, Sonia and Jorge.

Looking back I would like to thank my degree mates in Catalonia, who have suffered with me during five years pursuing the same objectives. Turró, Enric, Miguel, Jordi, Joan, David, Gemma, Maria, Ernest, Sandra, Jonel, Yu-Han (and many others): maybe we could have made it all on our own, but having made it together has surely been the best of it all.

Last but not least I would like to thank my family, they pushed me to start this trip that now I finish proudly. Special mention to my parents that have always said me the right word at the right time, and my sister, who through her example and success has always pushed me to do my best.

Summary:

Assessing Principles of Set-Based Concurrent Engineering Using a Design Game
Department of Product and Production Development
Chalmers University Of Technology
Carbó Roma, Francesc

Product development is a strategic function in many companies and its management has been evolving throughout the industrial era. This project contributes to the emerging field of Lean Product Development, one of the current applied strategies that has high potential to manage the resources invested to bring new products to market. The objective of this thesis is to identify some of the key factors and practices to apply one of the Lean Product Development principles, Set-Based Concurrent Engineering. Although the Set Based Concurrent Engineering approach has been identified as one of the key practices to succeed in Lean Product Development, it doesn't exist a standard methodology for applying it despite of the industrial sector and the projects characteristics. In this thesis, experimental data were gathered through experimentation with groups of people using a design simulation called "Delta Design Game" originally developed at the Massachusetts Institute of Technology. The game is modified in order to reach conclusions during the research and to enable future pedagogical and research activities regarding set-based strategies applied in a multidisciplinary context. The thesis concludes with several recommendations and reflections about the important factors that enable or hinder set-based concurrent engineering.

Key words: Innovation, Product Development, Lean thinking, Lean Product Development, Set-Based Concurrent Engineering, Design game, Delta Design Game.

Thesis Structure

1. Introduction

1.1. Motivation

The market today demands all companies to improve their processes constantly and the current economic context makes this need even more critical. In recent years many efforts have been made to improve the basic processes developed in companies such as manufacturing. In that field, for instance, many companies have implemented lean manufacturing concepts that are focused in operations, achieving production results that usually justifying the investments. Nevertheless such improvements leading to excellent quality and productivity in operations does not guarantee market leadership or future business success.

Today, on average, 28,3 percent of companies' sales came from new products that are those ones that did not sell three short years ago (Kennedy 2011). This percentage grows to 100 percent in some dynamic industries and countless corporations such Apple owe their current success to their product innovation processes. These data show just how important innovation is, and using the words from Manish Goel, Operations VP in NetApp: "Those who innovate, will survive" (Goel 2012).

The dynamics of markets, the new technology, and the competition, have made new product development (NPD) one of the most powerful activities to make companies outstanding. The changes in the market and also in the society have forced companies to innovate improving their portfolio products but mostly to find new product lines. Since understanding innovation will be a keystone for the future success in most companies, it is mandatory to take a look at the innovation processes and how they can make a difference in the results.

The difference between the best innovators and the worst is high. According to the benchmarking studies done by R. G. Cooper a handful of companies do better than the others and much better than the worst ones. For instance the gap between the sales coming from new products is from 9% in the worst companies to 38% in the best, the commercial success rate goes from 37,6% to 79,5% and the rate used to assess if projects meet the profit objectives are 26,9% to 77,1% (Kennedy 2011). The lack of control of the worst companies, translated as a bad product development rates, contrast with the results of the best innovators that use specific and well-built product development processes. It is obvious that setting up a good product development process is mandatory for every company that wants to get the best innovation results and wants to take advantage of all the amounts of resources invested in NPD.

The differences between companies remain in how they manage the innovation process. Throughout the last century different approaches to the product development issue have been developed. In the beginning the focus was in the product, later it changed yielding to the customer needs focus. Modern NPD strategies blend these two approaches. One of this latest product development models is **Lean Product Development** (LPD), a model for development new products motivated by the systems used at Toyota Motor Corporation.

Womack and Jones (2003) argue that "lean thinking" should be applied to the whole company structure and subsystems but on the contrary the application of Lean Thinking during last twenty years have been focused mostly on improving the production lines and all the manufacturing process. **Lean Manufacturing** principles are currently really used in many companies, these principles are well proved and the investigation of its methods is deep. Even having a good knowledge about the Lean Manufacturing concepts there are a lack of information up and downstream about how to implement the lean methodologies in other companies' subsystems like sales or product development. This second one, Product Development (PD), is an area with high potential for realizing the Lean principles but the mere translation of lean manufacturing principles into Product Development doesn't means a good product development system.

Leon and Farris (2011) show that in the last years the number of publications related with LPD has increased significantly investigating different areas but they also insist that there are still a long way to go. Their paper describes the next steps to improve the knowledge in lean product development practices in different domains like performance and knowledge management amongst others.

The objective of this thesis is going ahead in the research assessing one of the Lean Product Development principles, set-based concurrent engineering (SBCE), using a practical methodology based on a design simulation.

1.2. Target Group

This research wants to be useful for students of engineering design who are interested in management. It is directed towards people who are interested in product development and especially to those ones who are interested in the Lean Thinking for the entrepreneurship. During the thesis it is assumed that the reader has the basic knowledge about lean manufacturing.

1.3. Personal Motivation

When I decided to study industrial engineering I already knew that my future would be related with management, thus I took the normal engineering degree with the management intensification. During the last few years I had the chance to work in a company called Enginyeria Teknics Sabadell in Barberà del Vallès (Barcelona – SPAIN). Our speciality was the industrial machinery for processes, for handling and assembling, for verification and inspection and so on. Our work needed to find out new solutions so innovate in every new project to satisfy our customer's needs. When I was looking for my project, after finishing my courses and my professional experience, I was interested in finding something blending both, innovation and management. With this project I found what I was looking for. During the thesis I've discovered a new way to define the innovation processes thanks to the lean thinking concepts, I'm sure that this new approach is going to be useful in my professional career.

1.4. Organization of the Thesis

The document is divided in five chapters. After the introduction, the second chapter deepen in the literature review where the Set-Based Concurrent Engineering concepts are introduced. The starting point is the general Product Development process for going ahead with the Lean Product Development characteristics that include the Set-Based approach. The third chapter describes the methodology used for reaching results; the research process is explained, the characteristics of the Delta Design Game, the process used to evaluate the designs and the materials developed for the practical sessions are widely described. After the methodology the chapter 4 focuses on the results and its discussion. An analysis of each round developed with the game is done; the expected results, the results obtained, the reasons and observations done. The last section in this chapter open a discussion about the results found.
Finally the chapter five sets the conclusions stated after the results discussion. The last part of this chapter includes a section dedicated to guide future research and game applications.

2. Literature Review

In this section literatures related with Lean Product Development and Set-Based Concurrent Engineering have been reviewed. In the first part the objective is to define the Lean Thinking and the Lean Product Development characteristics finding a holistic knowledge about the practices and the methods. The overview in Lean Product Development is going to be followed by the analysis of some LPD frameworks. In the second part the Set-Based concurrent engineering is going to be described in depth uncovering its approaches, its principles and its tools.

2.1. Product Development:

> "The process of creating or improving a product or service and managing it during all stages from design through marketing."
>
> (Cambridge Business English Dictionary 2011)

> "Innovations are products, services, solutions or processes that have no logical antecedent and are value-creating to a core audience."
>
> (White, 2005)

. . .

There exist many definitions about innovation and product development. In business and engineering New Product Development (NPD) is the term used to describe the global process to bring new product to the market. These products can be tangible (something physical) or intangible (services, experiences or belief). All the products we use every day have emerged from a product development process to reach the market being at the beginning just a simple idea. NPD is much more than a few brainstorming sessions and an engineering design; both of these are critical points in the process but just a part. The NPD process has to be a systematic process, through which thoughts and ideas have to be collected, organized, evaluated and processed with an innovation culture and atmosphere.

Every company wants to reach the best strategic position and consolidate sales in the global markets and one of the key factors to ensure the future prosperity in any business is the success in innovation, thus innovation has become the point to focus the improvement efforts for many companies (Letens, Farris, & Van Aken, 2011). The potential benefits of adopting a good product development process may be really significant in the next years and innovation can be the way to overcome the current global crisis, "When you can't make cheaper products neither products with higher quality, the only alternative is do different things, innovate." (Sala-i-Martín, 2011). Companies want to launch new products to the market with best success rate as possible, that means having the higher odds as possible to develop products that become commercial successes when launching. Some specific objectives are reducing the time-to-market but doing this on the initial budget, bring to the market products that reach the initial revenues objectives and with quality.

Cooper et al. (2004) identify three critical factors for successful innovation:

- A good culture and climate within the business in support of product innovation.
- The active role of high management in innovation. Behaviours, engagement and commitment.
- The project teams and how they are organized. How companies manage the resources and processes.

These points define three common aspects that discriminate the best innovator companies from the worst ones. The first point, promote a good innovation climate, is seen as a key factor for success in innovation and it has to be supported with some practices and specific programs designed to promote a positive climate, for instance avoiding punishment for failure or simply bringing the necessary resources for a creative job. The second point focus in the senior management commitment as a driver for success in NPD, the support of high management has to be strong and has to be represented with participation in all the development process. The last point is about how the teams are organized to ensure the accountability and the success in the NPD process.

These points link with the need to define an overall framework with the best practices in NPD, a framework that defines how to manage the people but also how to define processes and which are the tools to succeed in product development despite companies' nature. There are different methodologies that have tried to answer this question and one of them is the Lean product development model.

2.2. Lean Product Development

2.2.1. Lean Thinking

> "Lean is the search for perfection through the elimination of waste and the insertion of practices that contribute to reduction in cost and schedule while improving performance of products"
>
> (Walton, 1999)

> "Lean is a way of thinking, with a commitment to achieve a totally waste-free operation that's focused on your customer's success […] It is achieved by simplifying and continuously improving all processes and relationships in an environment of trust, respect and full employee involvement […] It is about people, simplicity, flow, visibility, partnerships and true value as perceived by the customer."
>
> (Hogg, 2008)

. . .

Lean Thinking is a highly evolved method of managing an organization to improve the productivity, efficiency and quality looking for perfection. The term "Lean" was introduced for the first time in 1990 on the book "The machine that changed the World" by Womack, Jones and Roos that explains the use and the evolution of lean manufacturing practices in the automobile industry. The term Lean was conceived in 1984 as a new paradigm for production management contrary to the prevalent mass production system that in this moment justified the large inventories understanding that "much is better". While mass production justifies the cost reductions with the scale economies, the lean approach emphasizes flexibility of response to the customer changing needs and excelling in quality in every step of the production stream.

Lean thinking suggests taking a close look to companies and organizations to understand its value streams and then minimize waste while maximize customer value. All organizations complete complex processes that generate value, the whole of these actions are what lean thinkers call a "value stream". Lean thinking removes all non-value adding activities in the value stream and constantly aligns all required activities through all the processes to the

external but also to the internal costumers. The final results are short lead-times, reduced requirements for human and financial resources, and products suited to fulfill customer requirements (Womack and Jones, 2003).
To accomplish this, lean thinking changes the rules on management. The products go horizontally across departments and technologies changing the current way that was focused in optimizing the products with a vertical structure. Lean thinking points in customer needs upstream and downstream of all the processes that have to *"pull"* their needs instead of pushing making then the products *"flow"*. "Pull" is the concept of each process pulling the incoming work from the upstream process when needed and in the amount needed. Pull is the opposite of push where the creator pushes his outputs without regard for the need of the receiving station (Oppenheim, 2004). The term *"flow"* denotes the uninterrupted motion of work pieces at a steady pulse of time through all processes of the line with no backflow or rework, for instance from raw materials into hands of the costumer, from order to deliver or from design to launch time. While doing this companies are more capable to respond with quality and low cost to the changes.

To guide the Lean techniques there are **five basic principles** that were categorized by Womack et al. (2003), these principles link with the last paragraphs:

Define customer Value: Define value precisely from the perspective of the end customer.

Identify the value stream: For each product or service identify the needed actions for developing and thus eliminate waste such non-added value steps.

Flow the products: That means making the steps flow during all the enterprise eliminating non-necessary waiting times.

Pull: Let the customers pull value from the next upstream step in all the production process.

Pursue perfection: When value stream and customer needs are well defined and flow and pull concepts are introduced the process begins again and continues until a state of perfection is reached.

Lean thinking has wide applicability to a large range of processes, people and organizations, from concept design to the factory floor, from the labourer to the upper management, from the customer to the developer (Walton, 1999). Lean concepts have been implemented first in manufacturing processes improving the production lines but thinking that Lean is just about manufacturing could be an error. Lean thinking should affect every process in an organization and correspondingly to all the processes developed on companies. Lean thinking is not a program to reduce cost but a way of thinking and acting for the entire of the organization. Working with Lean philosophy in all the branches of the company should be the final objective for all the companies that want to implement a holistic Lean process and get the major benefits as possible.

2.2.2. Lean PD vs. Lean Manufacturing

Lean is usually related with manufacturing enterprise because as said above the principles were implemented firstly in the factories; realize that the principles definitions have a production sight. Also, the Lean concepts have been usually identified by the “just-in-time”(JIT) concept but this is just one of the several tools that Lean manufacturing applies. Despite of these confusions, as said above, lean thinking can be applied outside manufacturing operations and product development is one area with high potential for realizing the benefits of Lean Principles (Hoppmann, et al., 2011).

Product development plays a key role in defining customer’s value, hence make sense that if all the process should be planned for satisfying customer’s needs this area has to be important in all the process, also for improving other processes downstream like manufacturing. Some authors go further and defend that the impact on cost, quality, and manufacturing lead-times of lean principles applied in product development are bigger than the concepts applied in lean manufacturing (Hoppmann, et al., 2011). The rules applied during last decades to change the factories’ floors to Lean manufacturing are valid but now the question is: “How has the lean thinking to be applied in product development?”. While many scholars have studied the Lean Manufacturing practices on contrary the lean product development (LPD) research is just in the beginning of the journey. It has been necessary to understand the Lean principles but also finding a new way to work with them in a new environment dominated by uncertainty like innovation. Lean principles are clearly related with production and finding the way to apply them into Lean Product Development has been one of the objectives for different authors that have tried to succeed in this challenge with two different approaches.

The first one is taking the Lean Manufacturing process as a model to define the LPD practices assuming that lean manufacturing principles can be applied to product development. Lean concepts were introduced for the first time in Toyota Production System (TPS) that has become the base of all the concepts that have defined the Lean Thinking. The objective of this first approach has been to find direct analogies between LPD and TPS to define the best LPD practices. For instance Ladas defined SCRUMBAN that is a direct application of KANBAN, a manufacturing tool used in TPS like JIT is used in Lean Manufacturing (Liker and Morgan, 2009). SCRUMBAN is now used in Software Product Development and is really useful to face the constant changes in product’s specifications making the development process more agile.

The second approach in LPD research is to figure out how Toyota, which as said above become the model for Lean manufacturing, makes its own product development process. Toyota has been the world leader in many product development performance measures and many books documented various aspects of Toyota’s Product Development System (TPDS) analysing one or more of the classical product development management domains such people, strategy, process, portfolio management, performance evaluation and market research. For instance Ward et al. (1995) observed and defined the SBCE.

One element of lean thinking is about reducing waste. The waste identification within the organizations has been a challenge for all the companies due to the importance of identifying it in order to apply the lean practices. Analysing the different approaches to the wastes from both perspectives, manufacturing and product development, is an interesting exercise to understand the limitations of applying Lean-manufacturing practices in LPD processes. Both approaches share the lean principles but the application of these could be quite different or at least not automatically. The main difference between the wastes in manufacturing versus product development is that manufacturing concerns the flow of materials whereas the most important flows in product development are of information.

Table 1 below summarizes seven common "wastes" in manufacturing and their corollaries in product development.

Type Of Waste	Manufacturing	Product Development
Transport	Non-necessary movements of products.	Non-necessary flow of information and bad communication. Not standards based.
Inventory	Existence of materials and products not being processed	Redundant information in data bases and not well defined. Unsynchronized processes.
Motion	People moving too much to perform the process	Wrong flow of information through teams and people.
Waiting	Existing times between stages and processes	Late delivery of information. Information created too early. Unavailable information.
Overproduction	Production ahead of demand.	Non-necessary information generation.
Over processing	Existing processes that can be eliminated due to a bad design or wrong tools	Too much information and detail. Extra analysis and studies. Redundant information development.
Defects	Product defects have to be detected fast and fixed	Wrong tests, inaccurate data. Incomplete or ambiguous information.

Table 1 - Comparing Manufacturing and Product development approach through the types of waste.

Reinertsen and Shaeffer (2005) described four main differences between Manufacturing and Product Development. First, while manufacturing is a repetitive and sequential activity where the variation has to be minimized, even eliminated, in PD the objective is finding good variations or eliminate bad variations instead of eliminate all of them. Secondly, every manufacturing stage adds value to a physical product that can be in one place at a time leading to an inherent sequential process. On contrary the Product Development works with information that can be treated in parallel leading the possibility to work non-sequentially and using feedback. Thirdly, the manufacturing processes are strictly defined, with a specific start and a desired end. In contrast the PD managers have to choose the best alternative assessing the economic gain against economic cost. Fourthly and last the risk management. Taking rational risk is crucial in Product Development because is inherent to the innovation activity, if we try to eliminate any possibility to failure we also close some doors to new technologies with uncertain prospects.

2.2.3. Lean Product Development (LPD)

"LPD is not just using tools and techniques of Lean manufacturing in product development processes. On the contrary LPD has been considered as a process improvement concept by adapting lean thinking into product development by maximizing utilization of people, processes and technology."

(Liker & Morgan 2006)

"LPD is viewed as a cross-functional design practices (techniques and tools) that are governed by the philosophical underpinnings of lean thinking – value, value stream, flow, pull, and perfection – and can be used (but are not limited) to maximize value and eliminate waste"

(Leon and Farris 2011)

. . .

While it exist wide consensus about how to define Lean Manufacturing, Lean Product Development has not yet a clear definition. The definitions above are a general suggestion that stress the use of the Lean Thinking in product development to improve the design process eliminating wastes, which as seen above, are related with knowledge and information.

Implementing Lean Product Development practices can bring companies to two major competitive advantages. First, LPD is an enabler to reach the next level in Lean enterprise; hence it can be a perfect complement for those companies that are currently using the lean manufacturing tools and practices. Secondly, the LPD improves product development performance increasing the quality of designs, the market response and reducing the lead times.

2.2.4. Lean Product Development Frameworks

The Lean Thinking was uncovered as a result of the studies that had revealed the better performance of Toyota versus the European and the American car manufacturers. Since nineties many authors have tried to define a definitive framework for LPD.

In "The machine that changed the world" under the title "Techniques for lean design" Womack et al. (1990) identified four major differences between the mass production companies and the lean ones such Toyota. These differences become the first LPD framework and were; a powerful project leader with strong authority, teamwork, early and controlled communications, and simultaneous development or concurrent engineering.

In the book "Product Development for the Lean enterprise" Michael N. Kennedy (2003) creates a fictitious world to explain the potential benefits of the lean product development in an imaginary company, in that book the traditional Structure-based product development processes (Mass process) and the Knowledge-based process (LPD) are compared. While the basis of the structure-based system is the management of the operational activities increasing the amount of bureaucracy the basis of the engineering in the knowledge-based system are the knowledge of individual workers and the knowledge management. The book stressed the importance of having a holistic development environment rather than a process in the traditional way and emphasizes four keystones for the LPD; the designer Entrepreneurial Leadership, the expert engineering workforce, the responsibility-based planning and control, and the set-Based concurrent engineering.

Many frameworks for LPD are defined but no one of them are the last one, some studies seek for a newer and more developed frameworks to define both lean product development practices and new tools. It is not the objective of this study to identify all the approaches for the LPD, anyhow all the frameworks are build using the exposed lean thinking principles and even being the ideas some times common what it is really important to underline is that simply implementing one or two LPD tools in the complex product development processes could be worthless. LPD is about how people are managed and how you manage the processes in a general point of view. It is important to understand that Lean is a different way to see the entrepreneurship and that implies a holistic change to reach the aimed benefits in PD process. The effort for change is bigger as bigger and more complex is the organization and the changes to reach the objectives implies modifications in teams' organization, in every worker performance, in processes and also using new tools and techniques.

The first attempts on describing a framework evolved during the years being more specific and practical focused; Leon and Farris (2011) summarized some of these attempts. Their work is reproduced in Table 2, with the addition of more recent work by Hoppmann et al. (2011).

Framework Name (Authors)	Study Motivation	Framework Elements	Definition/Description
Lean Design Techniques **(Womack, Jones, and Roos, 1991)**	To do a better job faster with less effort	**Leadership**	Related to the "large project leader" who designs and engineers a new product and gets it into production
		Team Work	Cross-functional team guided by a "heavyweight" leader. Team knowledge lies in the shared viewpoints and experiences of team members
		Communication	Direct and upfront conflict confrontation, strong commitment to accomplish team agreements, and effort management
		Simultaneous Development	Process involving overlapping activities. It requires understanding and intensive communication among activities
LPD Techniques **(Karlsson and Ahlström, 1996)**	To develop products faster with less effort	**Cross-functional teams**	Team members are selected rom different functional areas with the intention of integration functional aspects of the product since the beginning. The team structure is mostly "heavyweight" leader oriented
		Strategy	Projects are guided by a vision and objectives rather than detailed technical specifications
		Supplier involvement	Active supplier participation since the beginning of the project instead of being involved on already-defined specifications for subcontracted parts.
		Simultaneous engineering	Parallel performance of different development activities, concurrent engineering
LPD Subsystems **(Liker and Morgan, 2006)**	To provide systemic view of the TPS for PD	**People**	Includes the chief manager, cross-functional teams, balance of expertise and development of technical competence, continuous supplier integration, continuous learning environment, and the culture of excellence and continuous improvement.
		Process	Comprises all tasks and sequence of tasks used to bring a product concept to SOP. Underlying principles include: customer-value oriented processes, front- loaded (exploration of multiple solutions while maximizing the design space), levelled process flow, process standardization and flexibility
		Tools and Techniques	Set of tools that enable people to execute and improve the PD process, which include technology adaptation to people and processes, organization alignment through visual communication, tools for standardization and organizational learning.

Table 2 - Frameworks for LPD. Page 1/2 (modified from Leon and Farris 2011)

Framework Name (Authors)	Study Motivation	Framework Elements	Definition/Description
LPD Principles **(Ward, 2007)**	To create profitable operational value streams predictably, effectively, and efficiently through usable knowledge	**Value-focus**	Value is what customers want and concentrates on two main streams: the development Value stream and the operational value stream
		Entrepreneurial System Designer (ESD)	Typified by the chief engineer who creates and communicates the operational value stream vision, inspires developers, controls the process and provide technical guidance
		Teams of responsible experts	Expertise is developed by continual learning (data into usable knowledge) and decays rapidly when learning stops
		Set Based Concurrent Engineering	Simultaneous explorations of multiple solutions for every product subsystem and avoidance of converging to a solution until it has been proven
		Cadence, pull and flow	Cadence refers to the repetitive rhythm of the development process. Flow is related to knowledge and material availability when needed. Pull means responding directly to the needs of costumers when required
Framework for Organizing LPD (Joern Hoppmann, Eric Rabentish, Uwe Dombrowski 2011)	Integrate the existing approaches into a single and coherent general framework	**Chief engineer**	Establish the role of an experienced project manager who leads the projects. The CE is the ultimate responsible for delivering value to the customer.
		Specialist career path	Make use of technical specialists with dedicated expertise in a particular field.
		Workload levelling	Unlevelled workflow can carry on a drop in the quality of the PD activities and increase the lead times. Is necessary to plan the resources available and chose the right projects.
		Responsibility-Based Planning and Control	The chief engineer sets only the major milestones and the dates to deliver are negotiated with the design teams. It generates high accountability and motivation, more robust schedules, higher responsiveness and continuous improvement.
		Cross-project Knowledge transfer	The knowledge has to be properly captured and has to be useful for the future projects.
		Simultaneous or Concurrent Engineering	The phases on the PD are conducted in parallel reducing the lead times. To promote this a good tool is defining cross-functional design teams.
		Supplier integration	The suppliers are integrated into the product development process at an early stage and work closely with the development engineers.
		Product variety Management	Use the old products to define the new ones. Pats between products should only differ if this is justified by a perceivable value-added for the costumer.
		Rapid prototyping, Simulation and Testing	Emphasize the simulation and the testing processes contribute to a high performance product development system.
		Process Standardization	There are activities that are consistent across the projects. These ones have to be identified and standardized.
		Set-Based Engineering	Use a large number of possible solutions for each subsystem during the design process. Instead of quickly narrowing down the set of possibilities engineers test and analyse different solutions in parallel.

Table 2 - Frameworks for LPD. Page 2/2 (modified from Leon and Farris 2011)

Understanding that creating a repetitive environment for experimentation similar to a company is almost impossible, we take advantage of a small environment created with a game to evaluate the effectiveness of the Set-Based concurrent engineering pointed as a framework element for LPD by Kennedy (2003), Morgan and Liker (2006), Ward et al. (2007), Brown (2007), Schuth et al (2008) and Hoppman et al. (2011) (see León and Farris, 2011). The next section explains the characteristics and the principles of SBCE.

2.3. Set-Based Concurrent Engineering

Set-based Concurrent Engineering (SBCE) is about how the project teams reach the final product or solution. The process made by traditional designers, sometimes called "point-based design", begins with a brainstorming that generates a handful of possible preliminary solutions. These solutions are analysed superficially based on expertise and subjective criteria in order to choose the best alternative that has to be developed in deep. During the development process this alternative evolves, and after some (perhaps many) modifications, a product emerges from the process. If the designers do not choose the right option the design can become unfeasible and the process starts again. The "point-based design" process can be seen as a funnel where the wide range of options rapidly converges in one solution that crosses sequentially all the departments implied in the design (see Figure 1). Those alternatives that are not selected at the beginning of the process are often eliminated even having high potential. Thus, it is critical how the designers chose the first option to develop but doing so is not easy, mostly because at the beginning of the project it is impossible to have all the required information for choosing with warranties. Usually the design process requires several narrowing iterations and applying the "point-based" approach some problems arise when all the development teams have to find a holistic solution and define the final product. Every team has its own perspective of the problem so different constraints. These constraints are many times difficult to solve in accordance between all the teams because the feasible solution for one is out of the range of possibilities from the others and so on. This problem appears more often as more complicate and critical is the design causing many changes and loopbacks that result in an expensive rework.

To reduce the loopbacks companies usually work using the "Concurrent engineering" (CE) that promotes the analysis of the chosen solution in the early stages of the process by all the teams. The aim is to detect the incompatibilities between development departments as soon as possible reducing as maximum the loopbacks. The CE improves some aspects of the design process, for instance the development process usually is faster and the performance of the teams improves because of the shared information. Even improving the serial point-based design the CE doesn't solve all the problems because the design teams still work just with one alternative of design.

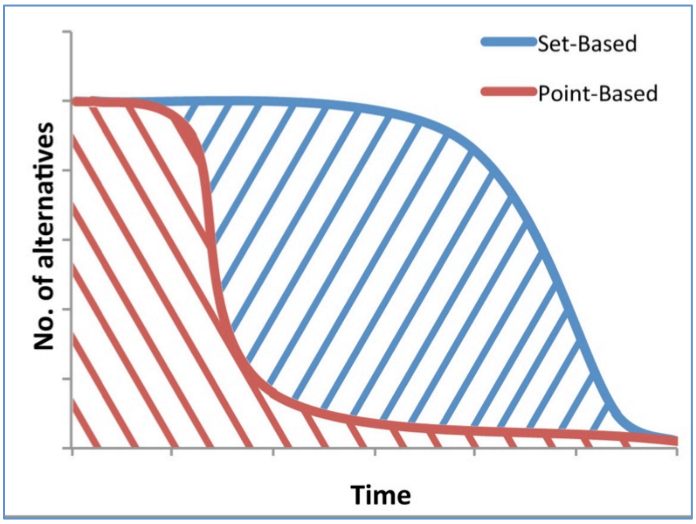


Figure 1 - No. of alternatives used while designing vs. Project time for SB and PB approaches.

Set-based Concurrent Engineering considers any solution as an intersection of a several parts or sub-systems. Each one of these sub-systems has to be developed as much as possible understanding the main constraints derived from the other subsystems but seeking for as many feasible solutions as possible before making any eliminatory decision. SBCE stresses the need to allow the decisions to be delayed and the design options to remain open as much as possible to select the best solution at the end of the process (Figure 1). During the development process every design team generates a set of solutions for every sub-system that are exposed to the other teams, as the design progress each team narrow its range of solutions thanks to the other teams' inputs.

Looking again at Figure 1, the area defined under the lines could represent the work needed to succeed in each one of both approaches so it seems that the efforts made using the SBCE are bigger than the efforts made in the point based approach. But these efforts made finding several options in the design space are not a waste of time and resources if understanding that in this process the potential loopbacks are reduced and almost eliminated. The cost of the loopbacks done with the traditional system choosing one alternative at the beginning of the project are many times bigger than the costs derived from seeking many different possibilities early in the development process. The area plotted for the point-based approach is just true in a perfect world with no loopbacks and developing a good set of solutions for one project can lead to faster convergence in following projects. This affirmation is even truer if the companies are able to save the knowledge for the future projects in a right way linking then two of the LPD practices, the SBCE and the knowledge management that should allow the cross-project knowledge transfer (Hoppmann 2011). If the knowledge is saved in a right way a big part of the area defined for the SBCE curve should be already explored since the starting point.

One way to capture knowledge is through "trade-off curves". These are comparative mapping graphs of the important design data for the system performance with other subsystems' characteristics. The trade-off curves are tools to provide the design teams with knowledge to create the sub-system designs, this knowledge has been generated in previous projects and is saved in the curves that are continuously updated to use the on-going knowledge for future projects.

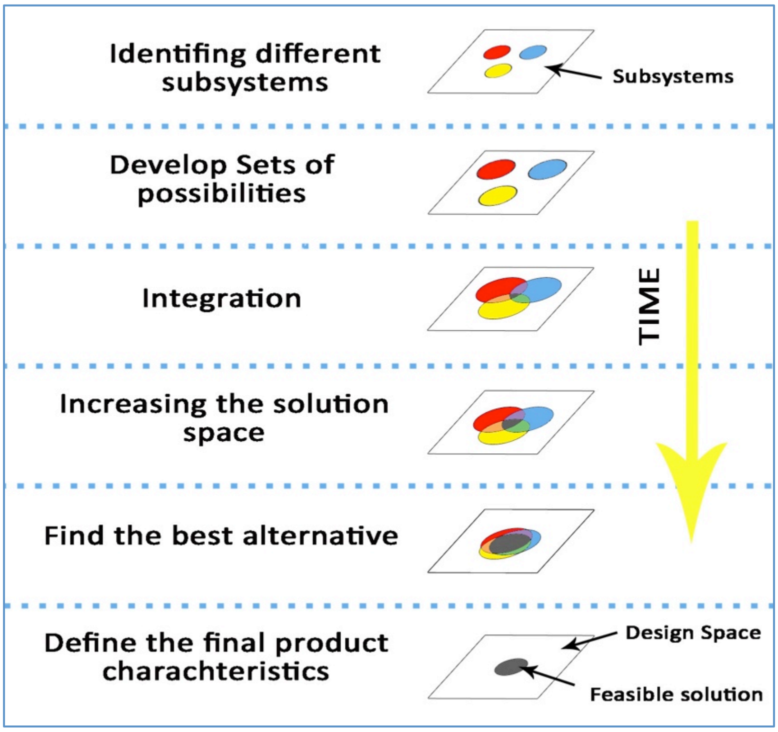


Figure 3 represents the design process when working with the set-based approach. First identifying the different sub-systems to develop them and integrate seeking a set of solutions to choose as late as possible the best option among the different alternatives.

Figure 2 - Set-Based Concurrent Engineering scheme process

(Sobek 1997) compares the point-based and the set-based approaches with nine basic functions of a design process which are reproduced in Table 3.

Functionality	Point-Based Approach	Set-Based Approach
1. Search: How to look for design options	Iterate on existing ideas. Brainstorm new ideas	Define feasible regions
2. Communication: What (ideas) to communicate the others?	Communicate your best idea	Communicate sets of possibilities
3. Integration: How to integrate the system?	Pass the idea among the team members for critique.	Look for intersections
4. Selection: How do you determinate which idea is best?	Elaborate formal schemes for selecting the best alternative. Make prototypes to confirm that the solution works	Design in parallel on each alternative until it is not worth pursuing further. Look for low costs tests to prove infeasibility.
5. Optimization: How do you optimize your design?	Analyse and test the design Modify as necessary to achieve objectives/improve performance	(Same as previous)
6. Specification: How do you constrain others with respect to your own subsystem design?	Maximize constraint in specification to ensure functionality and interface fit.	Use minimum critical specification to allow optimization and mutual adjustment.
7. Decision risk control: How to minimize risk of "going down the wrong path"?	Establish feedback channels Communicate often Respond quickly to changes	Establish feasibility before commitment. Pursue high-risk and conservative options in parallel. Seek solutions robust to physical, market and design variation.
8. Rework risk control: How to minimize damage from unreliable communications?	(Same as previous)	Stay within sets once committed
9. Management: How do you control de process?	Review designs and manage information at transition points	Manage uncertainty at process gates

Table 3 - Benchmarking PB approach and SB approach

The SBCE approach have some theoretical advantages. It allows the design teams to defer the critical decisions to the last moment when they have the best information as possible. It explores different designs at the same time increasing the odds to find a better solution. Exploring different possibilities also increase the flexibility therefore the response capability to changes in product specifications. With the SBCE teams converge to the final design more quickly non-exceeding the dead lines in the projects. Communicating about sets of solutions increase the richness of communication while decreasing the length and frequency of meetings.

2.3.1. Principles of Set-Based Concurrent Engineering

Based on their in-depth research of Toyota's product development system Sobek, Ward and Liker (1999 defined in detail the SBCE. The authors analysed Toyota's practices in order to define the characteristics of its product development process and described three principles that set the nine functions in Table 3. These principles are explained with more detail below.

Principle 1 – Map the Design Space

It is necessary to investigate and communicate different design alternatives to define a region of feasible solutions. The goals are both; understand the set of possibilities that solve the studied problem and capture the knowledge generated during the process by the designers.

- Define feasible regions

To define the feasible solutions each design team develop, in parallel and relatively independently, the preliminary design constraints for its subsystem. To define this first constraints the engineers use the previous knowledge that is saved in standardized platforms. In Toyota two of this platforms are the "*trade-off curves"* and the *"checklists"*. The checklists explicitly define current capabilities and are used by designers to define quickly the first characteristics' of each subsystem. These are continually updated with the engineers' expertise guaranteeing the success and the functionality of them. During the design process engineers use the checklists to guide the design and make the reviews, after the product development process is completed they abstract their experience to modify and complete the checklists for future opportunities. Failure to do this means the knowledge remains in every single worker and the knowledge is not widely shared.

- Explore Trade-Offs by Designing Multiple Alternatives

Every subsystem is analysed in many different alternatives. These alternatives are tested defining feasible solution spaces that are summarized in the trade-off curves. The trade-off curves usually define the relation between different and important variables for the design or the process. Whenever it is possible engineers try to generalize the results of testing and prototyping in mathematical definitions but if it's not possible different test and results are used to interpolate relationships and define a framework to make future decisions. Spending resources generating trade-off curves even not being necessary for the current processes has to be seen as an investment for future applications and products, not as a waste.

- Communicate sets of possibilities

The engineers have to communicate to the team sets of possibilities rather than just one possibility. Doing that the process is more flexible and it is easier to reach a solution fulfilling all the subsystems requirements, if every single design group present just its best option it is easy that this one, even being well in one perspective, become unfeasible for the others. Communicating different alternatives helps the other actors in the design process to understand your constraints, thus the process to reach the solution becomes a dialogue to find the best holistic solution rather than a battle of arguments where everybody defends one option. In Toyota the design teams use different tools to ensure the communication of its constraints to the other design members, the two major mechanisms to promote the simultaneous engineering are the module development teams (MDT) and the Obeya or Big Rooms. MDTs are cross-functional teams defined at the beginning of the project that are responsible of different subsystems, they have to negotiate how to achieve the performance characteristics defined at the early stage of the process. The Obeya is a room where the important meetings take place; on the walls of the room the leaders of each design teams post the latest information of the project as well as drafts, simulations and test results thereby enhancing cross-functional collaboration (Hoppmann 2011). In Toyota these drafts used to summarize the main constraints for a process or a design are called A3.

Principle 2 – Integrate by intersection

- Look for intersection of feasible sets:

Communicating sets of possibilities allows the teams to look through the solutions space seeking an intersection space where all the subsystems accomplish the requirements and finding a feasible solution. Working this way the design teams participate in the process at the same level and create consensus since the beginning and more commitment in the project. The communication has to be clear and bidirectional between all the design teams, if all the design actors understand the consequences of one decision from different perspective the intersection of feasible solutions is more optimized. That concept of communications sets of alternatives goes deepen in the set-based approach. We are seeing the design space as a space with a set of solutions, but after analysing the intersection among subsystems we are seeking for a set of feasible solutions to fill the gaps between sub-systems, so attacking the problems in a set-based minded way.

- Impose minimum constraints

In SBCE it is important to ensure flexibility in the design process. One of the key factors to ensure that is not to define constraints while it is not necessary. Working like this design teams can find more design options, thus increase the set of possibilities and also the odds of finding a better solution. Maintaining little constraints help during the integration process because different design options can be modified with freedom thus it is easier to find an integrated solution.

- Seek conceptual robustness

One design is robust if it remains functional even changing the environment characteristics such physical variations, manufacturing variations and so on. Design teams have to seek for robust designs understanding the interactions with the other subsystems and minimizing the impact of external changes on its designs.

Principle 3 – Establish feasibility before Commitment

- Narrow sets gradually while increasing Detail

Defining sets of possibilities allows looking for a solution among many options. Instead of picking one option to develop until the end in SBCE the process to reach the final product is a progressive process where the different design possibilities are eliminated while the knowledge increase. Working like this helps to understand better the real constraints thus the important considerations before committing to a design. The different sets of possibilities defined by design teams are all reduced in parallel ensuring a holistic solution feasible for all the subsystems.

- Stay within Sets Once Committed

Changing the initial sets of possibilities can generate loopbacks and reengineering, to avoid that the design teams have to stay within the original set of options once committed. An important part in the process is redundancy. A subsystem solution which the team knows that works is always one of the possibilities if the set of solutions.

- Control by Managing Uncertainty at Process Gates

Instead of control the design process with rigid schedules in SBCE the uncertainty is controlled and reduced crossing different gates during the design process. To control the uncertainty level the responsible of design and the chief engineer have to evaluate the set of feasible solutions in each gate and the knowledge acquired about them, thus the rules are easy and based on expertise. For instance if the set of feasible solutions has just one solution but this one is well defined the process could be at the final stage and the product almost defined, on the contrary if the set has one solution but this one it is not well defined the conclusion is that the set of possibilities is too small and it is necessary to find new alternatives.

With the SBCE section the literature review is concluded. A general knowledge on lean thinking and its practices has been developed and next chapter focus on the methodology used throughout the practical exercises for stating conclusions related with the application of the SBCE principle.

3. Methodology

This chapter starts with a brief explanation about the process carried on throughout the thesis execution. This introduction is followed by the analysis of all the materials used during the practical sessions, starting with an overview to the original Delta Design game and continuing with the materials used in the practical activities.

3.1. Thesis research process

The main objective for this thesis was defined at the beginning; evaluate one of the Lean Product Development techniques, the Set Based Concurrent Engineering, in order to understand which practices were needed for its application. The original plan was doing it using the Delta Design game. Thus, the first steps to face were both exploring the game and deepen into the LPD knowledge as have been done with the previous literature review.

The research started with the objective to identify the characteristics of the Lean Product Development. The aims were to understand how Lean principles work in Product Development environments and the current state of LPD. Once the LPD was covered the next step was deepen into the characteristics' of set-based concurrent engineering. Concurrently the Delta Design Game, originally developed by Louis Bucciarelli (1991) at the Massachusetts Institute of Technology, was evaluated to identify its possibilities and how it could be used for the thesis. These preliminary research processes were followed by the definition of the strategy for the practical analysis; how to use the game with different groups of people, how to evaluate the results, and how to extract conclusions.

The study had three game sessions or rounds. Between these sessions the way to present the game and the way to define the design process changed to extract conclusions. These changes were defined thanks to the preliminary study of the game and thanks to the feedback of all the participants in all the sessions. After the three sessions all the findings were blended to extract general conclusions for the thesis.

3.2. The Delta Design Game

3.2.1. Why a Design Game?

The design process involves communication, negotiation and compromises between designers and design teams. Thus, design is a complex process executed by people and the process management is a cornerstone for success. To facilitate the studies in the design process design games appear in different forms to help analysing different aspects of the design. In every game everything is abstracted and stylized to eliminate the functional knowledge and experiences that designers have and usually bring to their work. The games provide an environment that is manipulable and well bounded (Eva Brandt 2006). By playing the games it is possible to learn about different concepts depending on different game approaches. Both, the manipulability of the environment and the elimination of the functional knowledge during the design were the main reasons to use the design games as a study tool.

The Delta Design game is an exercise originally designed to demonstrate to students that design is a process of negotiation among several conflicting disciplines and requirements. Its author, Louis L. Bucciarelli, wanted to illustrate how different disciplines can define different modes of representation, modes to think, and to act through a same design or reality. In engineering design, design members see the object of design in different ways according to their individual responsibilities and technical interests (Bucciarelli, 1999).

The game was developed in 1990 but it has been used in different studies with different purposes. For instance, Smith, Eppinger and Gopal (1992) used the game to evaluate the differences between two iterative design processes. Smith and Tjandra (1998) used the game again to observe the iteration processes in a general point of view. Lloyd and van de Poel (2008) used the game to teach ethics in a completely different field.

3.2.2. The Game

The Delta design game is a role game that requires only basic mathematical knowledge to play it. The final objective is to design a house following the rules of the fictitious Delta world. The different roles implied in the design process have their own objectives and their own technical knowledge; thus, each role is responsible of different parameters and constraints. The game defines a period of training for all the participants where each player becomes familiar with their own role. The design process follows the training phase, in that the participants work together to negotiate and complete the house design.

The universe of the game is imaginary but retains some parallelisms with the real world to make it easier to understand. The imaginary world where the game takes place is called the "Deltoid Plane" or "DeltaP" and is different from our world in several key aspects; for instance, it is two-dimensional instead of three-dimensional. The original game takes around 3 hours time that are used for both to learn about each role and to develop the engineering design task. That task requires the collective efforts of all the four roles which are: the **architect**, the **project manager**, the **structural engineer**, and the **thermal engineer**. The design of the house has to be done meeting as best as possible requirements related with cost, thermal habitability, structure specifications as well as customer taste. The original version presents the game to all the roles in two different dossiers. The first one is common to all the roles and explains the general rules in the imaginary environment; the second one explains the specific constraints and considerations that each role has to take into account.

In the next section the environment and the responsibilities of all the roles are summarized,. For more information see Appendix A where the original game source is provided.

Experimental Environment

Delta design takes places in an imaginary world in two dimensions with specific rules. The houses are built in the plane and are made of equilateral triangles called "Deltas" (see Figure 4). In delta world the meaning of right angle change and it measures 60º instead of 90º, thus the equilateral deltas have three right angles in delta world. The units to measure all the physic proprieties are specific from the delta space to emphasize the world singularity. For instance, time is measured in wex instead of seconds, distance in lyn not meters, force in din instead of Newton, and so forth.

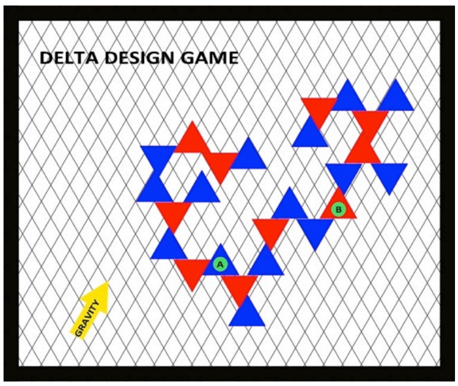


Figure 4 - House design example in Delta world.

The triangles that make up the buildings can be of two colours, blue and red, each having its own thermal proprieties. Blue ones are thermal passive pieces, while the red ones generate heat that increase the dwelling temperature that has to be controlled by the thermal engineer. Deltas are subject to gravity and the cement between deltas has a mechanical resistance limit. The structure has to be anchored to the plane with two anchors with a limit capacity load. The responsibility of guaranteeing the stability of the houses falls on the structural engineer. The price of the cement varies on the quantity and the type of it; the cement needed to joint two blue deltas is not the same that the cement used to joint two red deltas or one blue delta with one red delta. The cost of joining all the structure derived from the cement costs, the deltas cost and other factors that have to be controlled by the project manager. In DeltaP the aesthetic design principles are also special and it is responsibility of the architect to define the design characteristics when possible. The summary of the Design specifications is in the Table 4.

Specification	Limit Value
Functional internal area	>100 Qd (Quarter Delta)
Maximum Blue Delta's	[60,70] %
Average Internal Temperature	[55,65]º Nm (Degrees nin)
Indiv. Delta Temparature Range	[20,85]º Nm (Degrees nin)
Maximum load at the anchors	20 Din (Force)
Maximum internal moment	40 Lyn*Din (Dist. x Force)
Total Budget	1400! (Currency)

Table 4 - Summary of Delta Design game specifications

This is an overview of the complex world that the players of the game face when they read the game specifications. All the roles have their own tools to control its constraints and it is easy to understand that all the players are in the same position when the game starts, that gives sense to the comparative results analysis between groups and sessions.

Design Roles

All the constraints for each role are summarized in Table 5. The

Roles	Objectives	Constraints	Evaluation Parameters
Project Manager	- Minimum cost - Minimum lead-time.	- Cost of single elements. - Cost of blocks. - Cost of assembling. - Building Times	- Total Cost - Construction Time
Architect	- House form aesthetic -Internal/external ratio - Space Functionality	- Aesthetic concept in DeltaP. - Colour distribution - Exterior façade	- Internal Area - Blueness parameter - Blue dispersion - I/E Ratio
Structural Engineer	- Prevent the structure to collapse. - Define the anchor points	- Mechanical laws in DeltaP. - Gravity force and assembly joints resistance.	- Maximum load at anchor points. - Maximum internal moment
Thermal Engineer	- Keep average temperature acceptable. - Avoid hot and cold spots	- Thermal laws of DeltaP world: conduction and radiation.	- Average internal temperature - Maximum temperature

Table 5 - Summary of objectives, constraints and evaluation parameters for each role.

responsibilities for each role during the house design process are pointed in the second column, defined as objectives. The second column lists the variables that affect the objectives, while the third column lists the parameters that are used to evaluate design quality. These evaluation parameters are used to rate the final designs with an overall mark using a linear function as will be explained in more detail below.

Unplanned Events

In a real design process the changes in the product specifications are unfortunately a reality. The game facilitators can, if they choose to do so, introduce changes midstream in the design process to simulate unplanned events. The two primary mechanisms for doing that are gravity changes and overhead factor changes.

The initial budget is of !1400 (! Is the symbol of Zwig, the currency in DeltaP) and the cost has to be controlled by the Project Manager. The total cost is calculated with the next formula:

$$Total\ Cost = K\ x\ (Delta\ cost + Cement\ Cost + Module\ Cost)$$

Equation 1 - Total cost

The K is a constant that can be modified to make the budget objective heavier or softer. That value usually is around 1,4 at he beginning of the game but it can change for instance to 1,8. Then the budged becomes an important constraint and the design has to be adapted to the new situation.

In the DeltaP world the gravity has the direction of one of the plane axis but its direction can change suddenly to the other axis with the Gravity Waves. The structural characteristics of the house are closely related with the gravity direction. One of the objectives of the Structural Engineer has to be to define the anchors that are used to set the house taking care of these potential changes.

3.2.3. Design Quality Evaluation

The final designs of the clusters are evaluated using a linear function that relates all the evaluation parameters and adding one extra point to assess the design in an aesthetic point of view. This function is used to compare the design quality of the final solution generated by each team in the practical sessions. The results show which group have met better the design objectives and brings the opportunity to extract conclusions about the processes and tools used during the activity. The function has been developed taking all the criteria into account and giving equal weight to each role. Each role of the game is rated over 5 points that are distributed among the different factors for which each is responsible. The general form of the evaluation function is shown below:

A_i = Architect *PM_i = Project Manager*
SE_i = Structural Engineer *TE_i = Thermal Engineer*

$$FP = 5 \times (A_1 + A_2 + A_3 + A_4 + A_5 + PM_1 + PM_2 + SE_1 + SE_2 + TE_1 + TE_2)$$

Equation 2 - Linear equation for quality evaluation

The addition of all the factors is up to 20 points but the Final Punctuation (FP) multiplies this result by five to bring the total up to 100 points for more intuitive reading and analysis.

The parameters in the Equation 2 are explained below. The criteria used to define the equations for each parameter have been defined taking care of the original game specifications and the expertise in the game.

Architect parameters

A_1 - This parameter evaluates the internal space of the designed houses. Fewer than 100 Quarter Deltas (QD - Area unit) means not satisfying the minimum imposed by the original game. If you satisfy the minimum you have at least 0,2 points and the teams get the whole point if the area is over 160 QD.

	Range	Related Param.	Branch	Formula
A_1	[0,1]	Internal Area (IA)	IA < 100 QD	A1=0
			100 QD ≤ IA ≤ 160 QD	$A1 = 0{,}2 + 0{,}8 \times \left(\frac{IA - 100}{60}\right)$
			160 QD≤IA	A1 = 1

A_2 - This parameter evaluates the colour distribution. The percentage of blue deltas in the design has to be as higher as possible but between 60% and 70%. Being out of the range means 0 points, inside of the range means at least 0,5 points and teams get more points as more percentage of blues.

	Range	Related Param.	Branch	Formula
A_2	[0,1]	Blueness ratio (B)	B < 60% or B > 70%	A2=0
			60% ≤ B ≤ 70%	$A2 = 0{,}5 + 0{,}5 \times \left(\frac{B - 60}{10}\right)$

A_3 - This parameter evaluates the relation between the external façade and the internal façade. The design is better as higher is the relation so if the internal façade is longer than the external. A relation higher than 1,4 means the whole point, a relation of 1 or lower means 0 points.

	Range	Related Param.	Branch	Formula
A_3	[0,1]	Internal/External ratio (IE)	IE ≤ 1,4	$A3 = \frac{\vert 1 - IE \vert}{0{,}4}$
			IE > 1,4	A3 = 1

A_4 - This parameter evaluates the blue dispersion so the number of joints between two blue deltas. Its value is directly the blue dispersion parameter that is defined in the original game but divided per hundred to express it as a part per unit.

	Range	Related Param.	Formula
A_4	[0,1]	Blue dispersion (BD)	A4 = BD/100

A_5 - This parameter is the only one that represents a subjective analysis of the designs. These are analysed from an expert point of view. It is used for evaluating matters such symmetry and the rooms concept. This last concept was introduced in the first round and it is explained below in the methodology analysis of the first round. The parameter's range is [0,1].

Project Manager parameters

PM_1 - This parameter evaluates the cost of the designs. Being over the maximum budget (!1400) means 0 points, being under the half represents the whole punctuation.

	Range	Related Param.	Branch	Formula
PM_1	[0,3]	Total Cost (TC)	TC > 1400	PM1 = 0
			!700 ≤ TC ≤ !1400	$PM1 = 3\ x\ \left(\frac{1400 - TC}{700}\right)$
			TC < !700	PM1 = 3

PM2 - This parameter evaluates the time to build the designs. A really bad design in terms of time is being over 200 wex (Time unit). Thus, being over 200 wex means 0 points and designs have better punctuation as less time is needed to build them.

	Range	Related Param.	Branch	Formula
PM_2	[0,2]	Time (T)	T ≤ 200 wex	$PM2 = 2\ x\ \left(\frac{200 - T}{200}\right)$
			T > 200 wex	PM2 = 0

Structural Engineer parameters

SE_1 - This parameter evaluates how well are the anchors placed. If the anchor load overcomes the limit of 20 din (Force unit) its value is 0. If does not then is 2,5.

	Range	Related Param.	Branch	Formula
SE_1	[0,2'5]	Max. Load at anchors (ML)	ML ≤ 20 din	SE1 = 2,5
			ML > 20 din	SE1 = 0

SE_2 - This parameter evaluates the structure as a whole group using the internal moments analysis. Each joint has a load limit depending on the contact length between deltas, if any of the joins is not properly designed the punctuation is 0, if not is 2,5.

	Range	Branch	Formula
SE_2	[0,2'5]	Bad designed joints > 0	SE2 = 0
		Bad designed joints = 0	SE2 = 2,5

Thermal Engineer parameters

TE_1 - This parameter evaluates the success controlling the global temperature in the cluster. The global temperature (T) has to be between 55º nin and 65º nin (Temperature unit). Being out of the range means 0 points, being inside of the range means at least 1,5 points. Designs get better mark as nearer from the middle of the range (60ºnin) is the global temperature.

	Range	Related Param.	Branch	Formula
TE_1	[0,3]	Global Temperature (T)	T < 55ºnin or T > 65ºnin	TE1 = 0
			55ºnin ≤ T ≤ 65ºnin	$TE1 = 3\ x\ \frac{(10 - \lvert 60 - T \rvert)}{10}$

TE_2 - This parameter evaluates the success controlling the high temperatures in the cluster. The particular temperatures of each delta (T) have to be between 20º nin and 85º nin. Being out of the range means 0 points, being inside of the range means at 2 points.

	Range	Related Param.	Branch	Formula
TE_2	[0,2]	Maximum Temperature (Ti)	Ti < 20ºnin or Ti > 85ºnin	TE2 = 0
			20º nin ≤ Ti ≤ 85ºnin	TE2 = 2

3.3. Practical sessions

The methodology followed during the practical sessions is explained in this section. During the research a total of three rounds of the game were played, each one of them had its own specific objective, schedule and population, game presentation and data gathering process. The original “Delta Design Game” was modified during the research process depending on the objectives in each round. The specific objectives of the second and third rounds were developed based upon the outcomes of previous rounds. The results and the objectives of each round are not detailed in this section but in Chapter 4.

3.3.1. First round

The first session was designed to play the game making the teams work with different methodologies, with this purpose the activity teams worked following different preliminary instructions about the number of alternatives at the beginning of the design process. The objective was to analyse the convergence process and the final quality performance results to evaluate the differences of working with different number of alternatives during the design process. The schedule was designed using as a base the original game but making some modifications in order to fix the problems related with the learning process detected in the preliminary study of the game.

The framework for the first session was a course of “Set-Based Concurrent Engineering” gave in Chalmers University of Technology by Durward Sobek. The participants were people familiarized with the SBCE concepts, some of them working in different industry fields and others from the academic world, university teachers or PhD students. The number of participants during the activity was 12 so three teams played the game.

The activity started with a general introduction to familiarize the participants with both the Delta World environment and the objectives of the activity. After, the participants were divided by roles to make the training sessions where the players got the specific expertise. Figuring that the learning process could be a bottleneck in the activity because there were not specific tutors for each role, as was suggested in the original game instructions, the learning activity was supplemented with some practice exercises (See Appendix D for the exercises). To guide the first steps in the design the architects received the **design brief** for the design task. When the activity was finished a discussion was opened while participants answered a questionnaire. Both activities, the discussion and the questionnaire were designed to catch the feelings of the participants during the design game. Figure 5 shows the plan for the first session; the time gave to each activity, the groups’ organization, and the materials given to the participants.

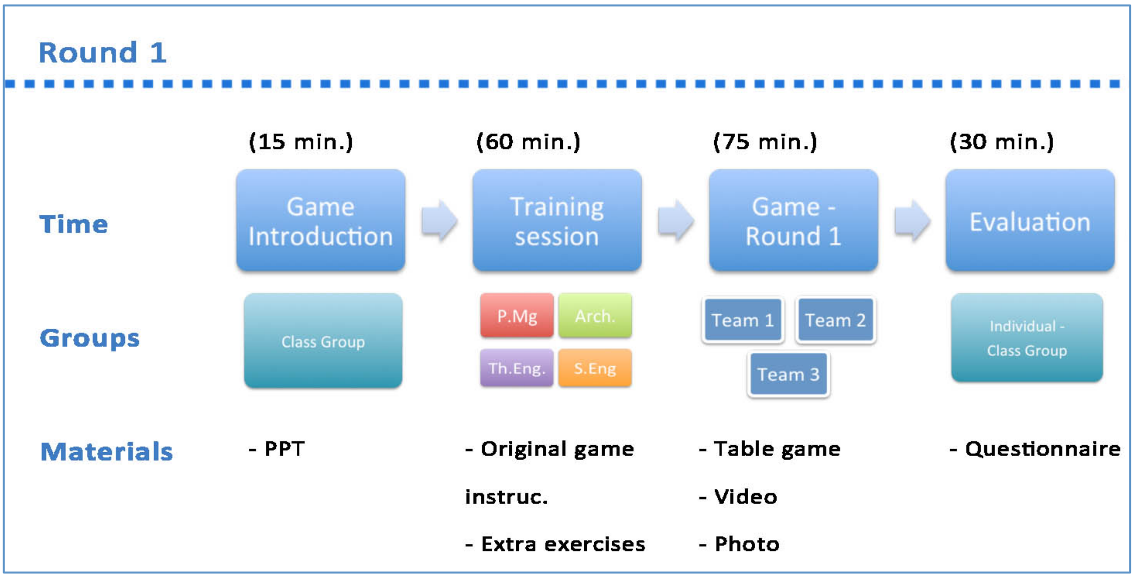


Figure 5 - Schedule Round 1

Below the extra materials generated for the first round are detailed and the way to evaluate the activity explained.

- Design Brief

To make the teams work with different alternatives, three different starting points were given to the architects. The same design brief was given as a starting point for the design but changing one sentence between teams; the first group would start with at least two design alternatives, the second with at least three and the third with at least four alternatives. The design brief included some additional objectives not included in the original papers. The house design had to have a minimum number of spaces to accommodate the dwelling for 6 Deltans. This modification was introduced to restrict the solution space and make the easiest task (the architect one) a little more complex.

- Extra Practical Exercises

The practical exercises for this first session were conceived mostly for having an experience before starting with the design process. The exercises were designed for the engineers in the game (Thermal and Structural) and for the project manager. During the activity all the players with the same role worked together in order to share conclusions and knowledge. To guide the activity two tutors took care of two roles, one working with the project managers and helping the architects with the preliminary designs and one working with the engineers. The role of both tutors during the practical activity was to resolve doubts and giving some advice for the design activity through the exercises' results if needed.

All the exercises asked for an analysis of some clusters of progressive complexity. Each cluster had to be analysed for reaching some results. For instance in the next figure the example for the first exercise for the structural engineer with the general wording.

Structural Exercices:

Ex 1) Evaluate the next structure following the gravity rules of Delta World. Identify the cluster load. Decide where to put the anchors (A and B) and find the weaker points in the structure. The results will change depending on your decisions so try to experiment and make questions if needed.

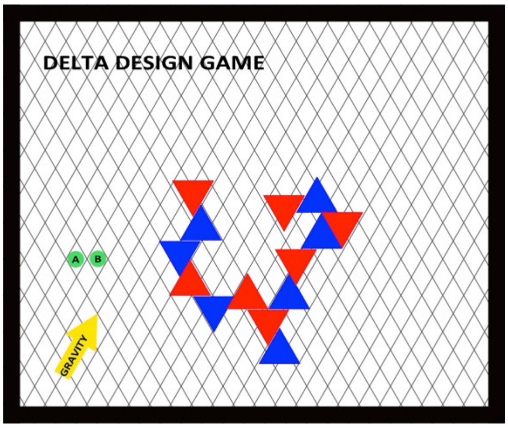


Figure 6 - Exercise 1 Structural Engineer

- Data Collection

Data were gathered in three different ways.

- Design quality results: (pg. 28)
- Questionnaire feedback (Appendices B & C)
- Video tape/photo review and open discussion

Taking advantage of the knowledge about SBCE of the players, the questionnaire was designed to catch the potential application of the SBCE tools during the game. The questionnaire promoted the reflexive analysis of all the participants that thought about their own practices and the decisions made by the group. The objectives were to evaluate the implication of the designers during the development process, understanding which level of co-operation and coordination the groups reached, and which group managed better the knowledge always.

The discussion opened at the end of the first round allowed the participants to explain better the problems appeared during the game and the obstacles found for reaching the initial objectives. The review of the videos and the pictures was used to understand better the problems appeared and for the posterior quality analysis.

3.3.2. Second Round

The results obtained in the first round defined the plan to follow in the second. These results were not the expected ones because the teams found it impossible to work with more than one alternative for reasons that are going to be detailed in the analysis chapter. Thus, the second round was designed in order to find solutions to solve those problems that had appeared, most of them closely related with the knowledge and the complexity for assessing the quality of the designs. For fixing those problems some lean concepts were considered. The objective for the second round was to develop a part of these possibilities and if possible evaluate them not missing the final objective, allowing the set-based approach.

The population in the second round was a subset of the first round, so only two teams of four participated. Due to the knowledge achieved for all the participants in both the game and the SBCE principles, the round started with a preliminary group activity for developing a couple of the lean concepts considered for changing the activity results.

The activity group was followed by a second round with the game and a new discussion about the results, this time without questionnaire.

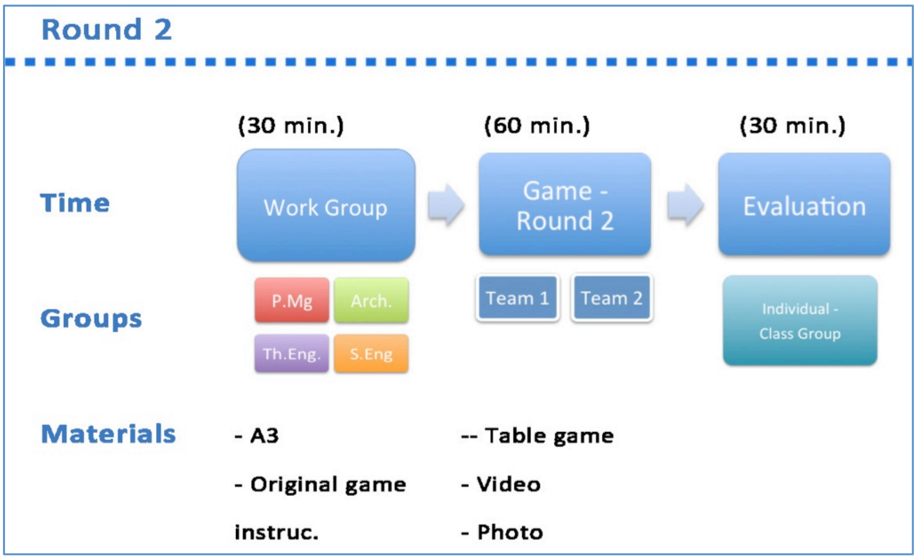


Figure 7 - Schedule Round 2

This second round was presented mostly in the same way than the first round but adding a couple of modifications. A key modification was to replace the training session with a working session where "Rules of Thumb" were developed in each of the disciplinary areas. The concepts developed during the activity group were obviously used in the second round. A schedule for the design process was suggested to promoting the set-based approach as well.

Below the extra materials generated for this second round are detailed and the way to evaluate the activity explained.

- Work Activity Group – Developing "Rules of Thumb"

In the work activity the participants defined a simplified explanation about their roles and the "Rules of Thumb". These rules were defined for three reasons, while defining the rules the players were going deeper in their knowledge, the rules themselves were useful to explain to the others the main constraints for each role, and the rules were useful during the design process making it faster and more flexible. After the group activity the conclusions reached were exposed to all the players in the board for sharing knowledge (Figure 8).

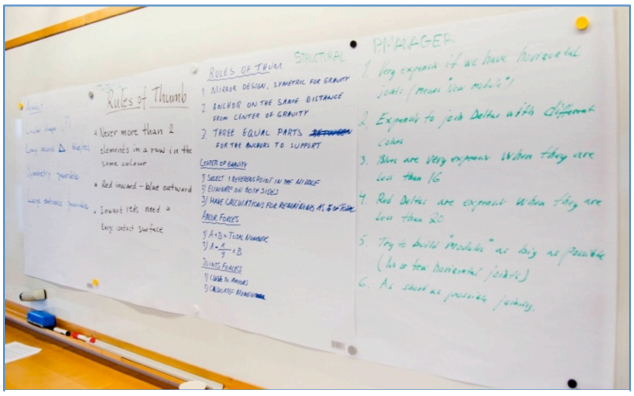


Figure 8 - "Rules of Thumb" Generation

The results achieved for each group are exposed and extended below with some extra "Rules of Thumb". These extra rules were defined after the second round and used for the third round. The rules developed primarily are detailed in Appendix E.

(*Obs: The "Thumb rules" are concrete sentences and easy to understand while having the game background, the reader could not understand some of the next points if not read*)

Project Managers Group:

1. Build modules as big as possible. Avoid horizontal joints if possible ("new modules").
2. Alternate Blue-Red joints with Red-Red or Blue-Blue if possible. Expensive to joint deltas with different colours.
3. Make a cluster with more than 16 blue Deltas if possible.
4. Make a cluster with more than 20 red Deltas if possible.
5. Make joints as short as possible.

Structural Engineers Group:

1. Make the cluster as more symmetric as possible.
2. Dwelling anchors at the same distance of the centre of gravity.
3. Three equal parts for the anchors to support.
4. Free Branches

Thermal Engineers Group:

1. Never 3 or more elements in a row in the same colour.
2. Never 2 inward reds together.
3. Inward reds need a large contact surface, minimum 1,5 lyn.

Architects Group:

1. Alternate Red Deltas with Blue Deltas if possible.
2. Internal area >100QD
3. Big entrance.
4. Dwelling for 6 inhabitants.
   a. At least 3 small spaces for suitable for an occupancy of two Deltans. (>6 QD)
   b. At least 2 medium-sized spaces that all 6 Deltans can occupy at once. (>10QD)
   c. At least 1 large space to accommodate the Deltan family and guests. (>16QD)

- Second Round Design Schedule Suggestion

In addition, a rough schedule was given to the teams to encourage a more set-based mindset during the design run. The schedule (outline below) suggests working with a set of different design options and working with sets of solutions to fill the gaps found during the analysis of each alternative.

1. Share thumb rules and goals.
2. Identify conflicts and synergies between roles.
3. Generate Design Alternatives.
4. Rough evaluation of the preliminary designs.
5. Identify Gaps.
6. Generate Sets of ideas to close gaps.
7. Evaluate and decide changes in designs.
8. Choose last design.
9. Evaluate the chosen design.

- Data Gathering

The data gathering process for the second round was the same than in the first round but skipping the questionnaire.

3.3.3. Third Round

After the first and the second rounds, the third round was designed for finding a new way to present the game. The new presentation was focused on making the design process more Lean in order to allow once and for all the application of the SBCE. The new way wanted to simplify the concepts in the game just stressing the main constraints for each role. The original game papers were modified and some extra material to support the design process were designed. This material was designed thinking in some lean tools used in LPD such the A3, the "Trade-Off" curves and the Obeya rooms.

The activity was planned working with two PhD students who had been players in the first rounds, Kristofer and Ludvig. Both of them were developing their PhD's at Chalmers University of Technology so the players in the third round were two groups of masters' students at the university. All of them were familiar with the Lean principles, some of them because they studied the general principles in some master courses and the others because Kristofer introduced them in his lectures. The game schedule was similar than in the first round but the time planned for each activity was increased and one step between the training session and the game execution was introduced, as shown in Figure 9. The objective of this step was to force the players to communicate the others their knowledge and constraints using a new tool designed for this third session, the A3 summary sheets.

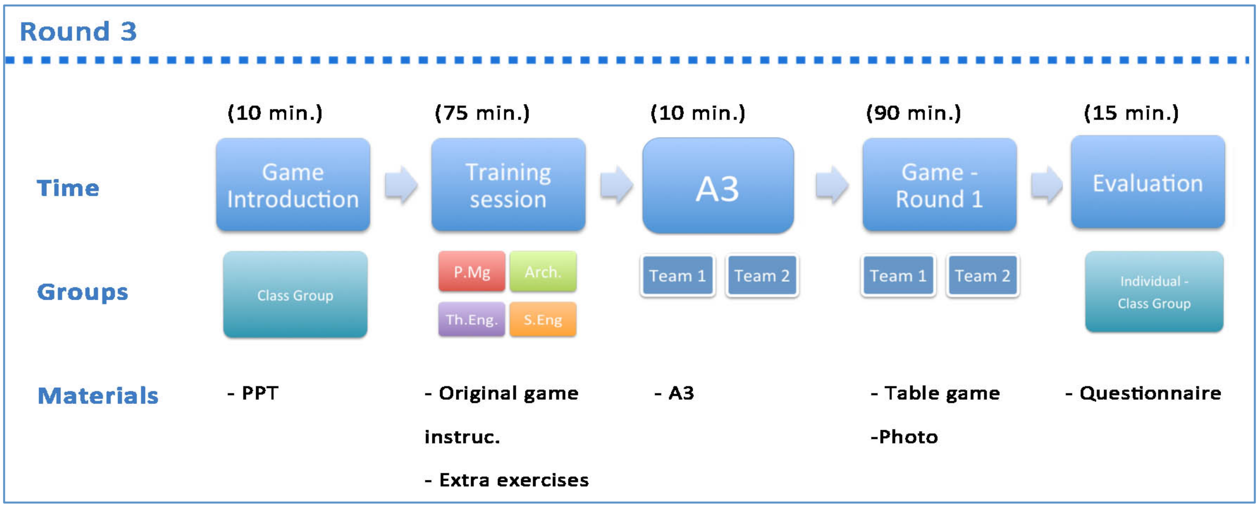


Figure 9 - Schedule Round 3

The third round proposed a significant change in the presentation of the game. The new materials were designed to facilitate the design process and to overcome all the difficulties appeared before. Thus, the objective was to increase the analysis speed during the game and help the teams to understand all the roles constraints and their interaction. The new materials wanted to be the representation of all the knowledge acquired during the first sessions and making the parallelism with the real world wanted to represent the way to save knowledge within the companies.

Below the extra materials generated for the third round are detailed and the way to evaluate the activity explained.

- Enhanced Training Materials

In the first rounds the players spend too much time trying to understand the main constraints of their roles and, as it is exposed later in the analysis chapter, sometimes they were in the design phase without understanding what their actions could involve. The original game instructions were used as a base for the new version after making some modifications. Generally the main explanation was preserved but all the irrelevant information was eliminated, this way, the reading could be faster and easier.

The first part of the documentation that was common for all the roles was left unchanged. However, the role-specific instructions were modified to allow the application of the SBCE approach skipping all the appeared problems with the original game presentation in the first two rounds.

The engineering roles in particular needed fasters methods for doing preliminary evaluation of the designs as evaluation of their parameters became the bottleneck in previous design rounds. Thus, it was necessary to focus in improving these roles analysis mostly because the other two already worked. The modifications were done to speed up the analysis trying to sharpen in the roles' concerns.

Structural Engineer Paper Changes:

- Rules of thumb: The rules were added in the instructions as a tool for assessing the designs quickly.
- Free branches analysis: The free branches were those parts of the cluster that were not part of the main skeleton (the main stream of Deltas between anchors). Depending on the contact length in the branches a safety maximum of supported deltas was defined. Placing more deltas than the safety number in a branch implied the specific analysis of this one. In Image 4 an example with three branches.
- Define approximated method for finding the centre of gravity and fast equations for finding the anchor support loads.

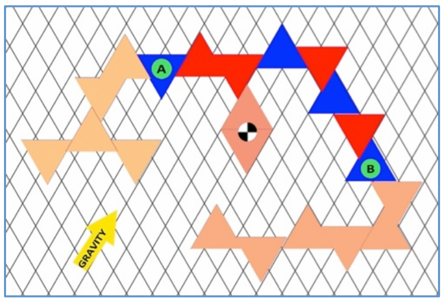


Figure 10 - Free branches concept.

Thermal Engineer Paper Changes:

- Rules of thumb: The rules were added to the instructions as a tool for assessing quickly the designs.
- Equations simplification. The mathematic operations were simplified. That means that the complex theoretical formulas were simplified but also that the difference between making rough calculations and exact ones was stressed. Below one example, in this case the equation's objective is for finding the T* (Temperature of radiating deltas). As it is easy to figure it is faster to work with absolute magnitudes directly referred to the designs than with averages. Making changes while working with averages imply recalculations for every simple modification spending too much time.

N_R = Number of red deltas
N^* = Number of radiating deltas
L^* = Average rad. length of deltas with free nodes;
q_o = Heat produced red deltas
k_r = Coefficient of radiative transfer

$$N_R \bullet q_o = T^* \bullet N^* \bullet L^* \bullet k_R$$

N_{red} = Number of red deltas
L_{out} = Tot. lenght of the outward pointing deltas

$$T^* = \frac{N_{red} \times 160}{L_{out}}$$

Equations 3 & 4 - Temperature radiating deltas. Left original one, right enhanced one.

- Trade-off curve for the inward red deltas.

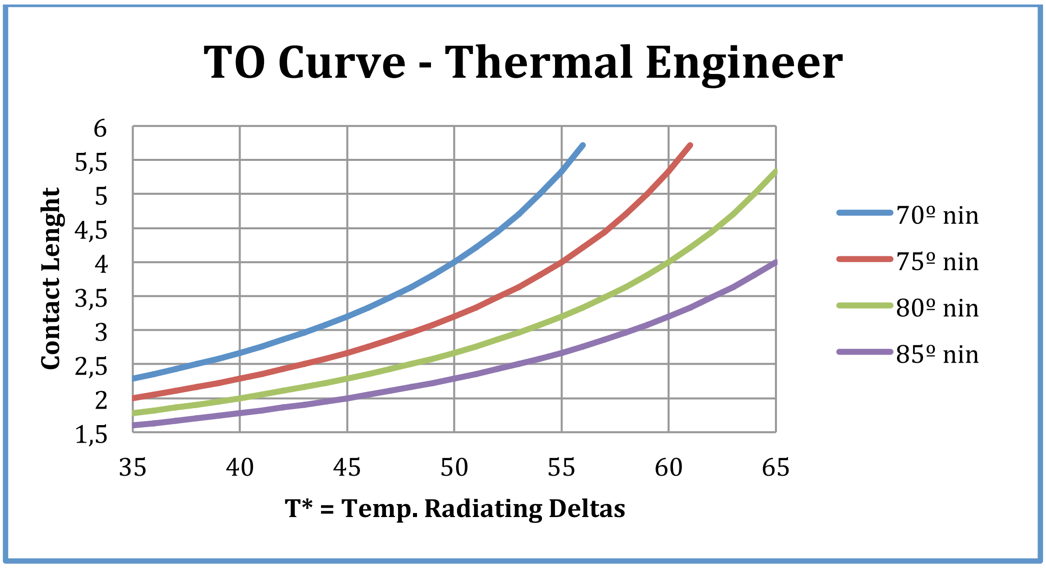


Figure 11 - Trade-off curve for the inward red deltas

Architect Paper Changes:

- Defining the room concept and the rooms needed in the design task.
- Starting design point. The "Rules of Thumb" of other roles are introduced to guide the first designs exploration.

Project Manager Paper Changes:

- Rules of thumb: The rules were added in the papers as a tool for assessing quickly the designs.

All the modified papers are reproduced in the Appendix A.

- A3 Reports

The A3 reports were designed for helping all the participants in the design process but also for facilitate the share of knowledge inside the teams. The documents summarized the constraints for each role in a single sheet of paper. Four different A3 reports were created. One for the Structural Engineer, one for the Thermal Engineer, one shared between the Project Manager and the Architect and one extra to show the conflicts between all the roles. All the A3 are reproduced in detail in the Appendix F.

The structure of the A3's was similar for each role, as illustrated in Figure 12. Under the title the responsibilities and the evaluation parameters, on the right and in the main position the thumb rules. The resting space was filled with different elements like calculations, rough calculations, simplifications, examples and so on depending on each case.

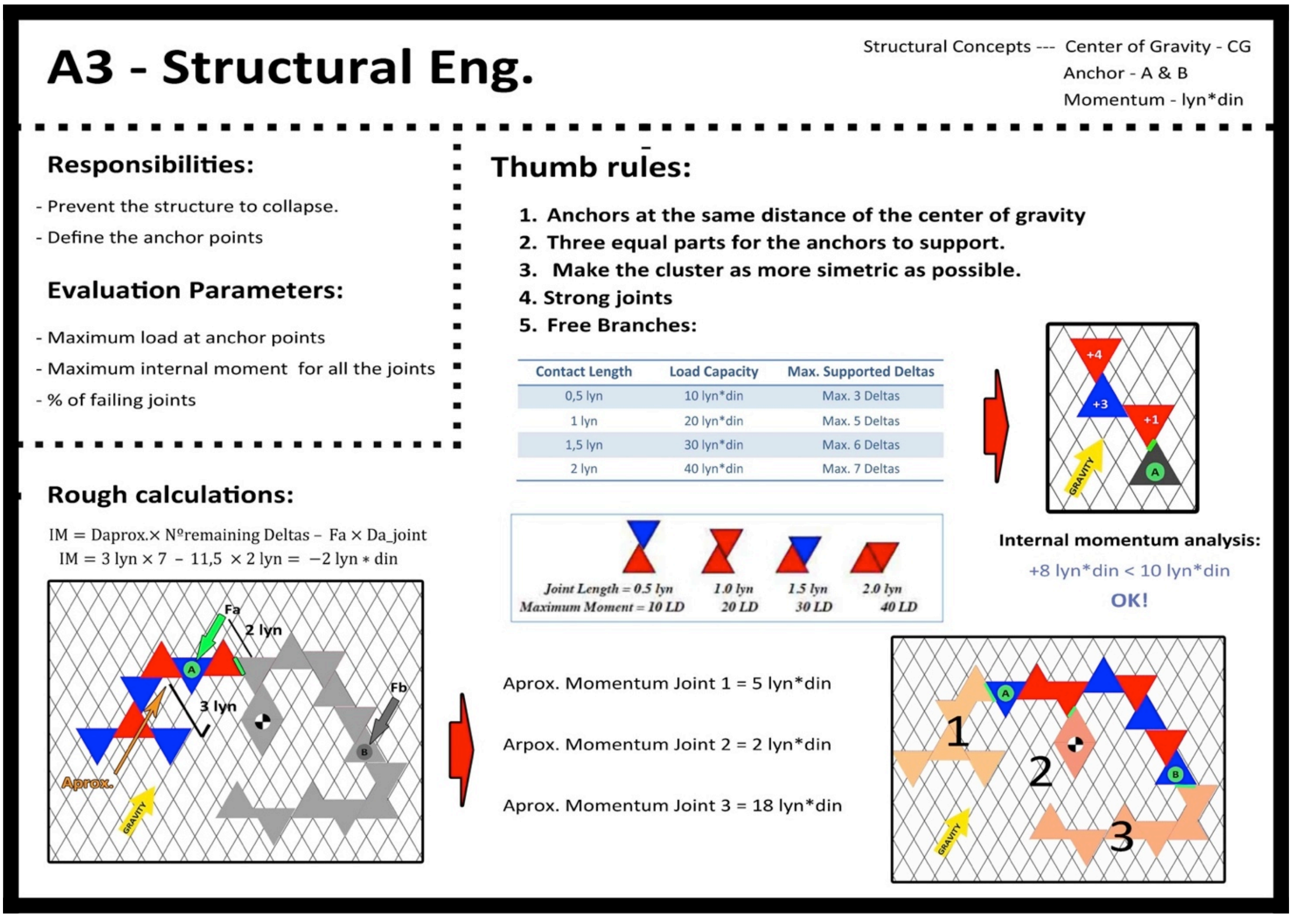


Figure 12 - A3 Report Structural Engineer

Above the A3 report for the structural engineer and next the table introduced in the conflicts A3 report. This table was created for the roles to quickly understand which were the negotiation targets inside the team and identifying how the other roles modifications could affect the design in different points of view.

Role	Role Interests – "Rules of Thumb"	Conflicts: Structural Engineer	Conflicts: Project Manager	Conflicts: Architect	Conflicts: Thermal Engineer
Structural Engineer	Strong Joints		Increase Cost	Constraint Design	Better Conduction
	Free Branches Control		Optimize Cost		
	Symmetrical Cluster Concept			Constraint Design	
Project Manager	Modules As Big as Possible	Higher momentum		Constraint Design	
	Blue-Blue and Red-Red Joints			Blue dispersion ratio	Never more than two in a row
	Use more than 16 Blue Deltas			Blueness ratio	Low Temperature
	Use more than 20 Red Deltas				High Temperature
	Short Joints	Colapse possibility			Bad Conduction
Architect	Alternate Red with Blue Deltas		Increase Cost		Reduce Hot Spots
	Internal area >100 QD	More branches More Analysis			
	Big Entrance	More branches More Analysis			
	Dwelling Spaces	More branches More Analysis			Control Inward Deltas
Thermal Engineer	Never 3 in a row same colour		Increase Cost	Ok. Alternate colours	
	Never two red inward together		Increase Cost	Ok. Alternate colours	
	Large Contact for red inwards	Better joints	Increase Cost	Constraint Design	

Table 6 - Conflicts A3 Report

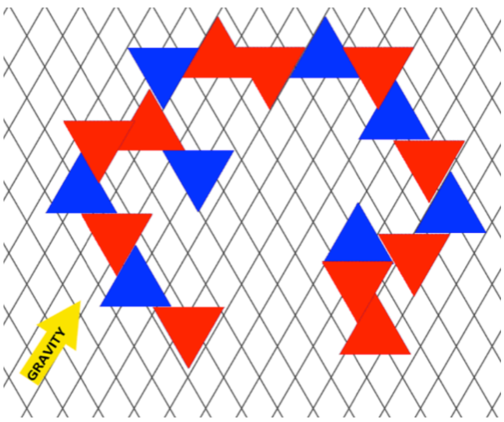
Practical Exercises V2

Some new practical exercises were defined with similar structure as the exercises in the first round. But for this third round the exercises were designed to show how different small changes could change the final analysis result. In this case the results of the exercises were given to promote the self-learning process. In this round there were three tutors so all the roles had a specific teacher improving the learning process. Below some examples of the exercises designed for the thermal engineers. See Appendix D for more details about the exercises.

> Evaluate the next structures following the thermal rules of Delta World. Find the average Temperature of the radiating deltas (T*), the temperature of the interior deltas if needed, and the average temperature of the entire cluster. State if the clusters are well designed and if not suggest solutions.

General wording for thermal engineers.

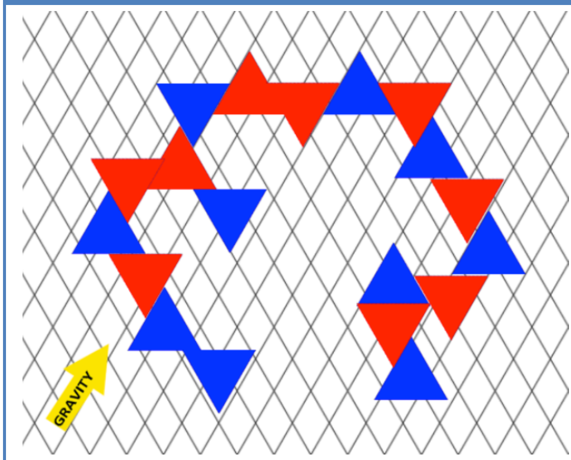
Exercise 4:



Results: NOK

Lout=32
T*= 55
Ti1 = 95 Ti2=81,7 Nn
T = 62,7 Nn

Exercise 5: Changing two red deltas.



Results: OK

Lout=32
T*= 45
Ti1 = 85 Ti2=71,7 Nn
T = 52,7 Nn

Table 7 - Exercises 4 and 5 Round 3

The data gathering process for the third round was similar than in the first round but adding some questions to the questionnaire related with the new materials introduced.

3.4. Analysis Methods

The data gathered during the three rounds have been blended and analysed to extract conclusions following different methods.

Video and Photo analysis: The visual media have been revised several times for catching the participants' feelings and the processes followed for each team in each round. The photos have been used for extracting conclusions and for the quality design analysis. These pictures have been used for reproducing the design with image software for easy analyse them.

Quality design analysis: After each round the results on quality of each team were exposed by the participants, based on these data the first analysis just in time to evaluate the quality were done during the sessions using the quality formula. After each session the design results have been analysed again with precision to extract definitive conclusions about the design performance. These results have been compared looking the general results but also the results in each role independently. Thanks to the results extracted some graphs have been plotted and conclusions reached.

Questionnaires analysis: The questionnaires have been analysed using basic software for data base analysis. The results have been extracted using the means in each round and the standard deviation for each analysis.

4. Results and Discussion

4.1. First Round

The original plan for the first round was to evaluate convergence in the design process. That means to identify how teams eliminate design alternatives and when they choose one option as a final solution. Thus, the session was videotaped in order to figure out when teams eliminate the alternatives and then analysing the convergence process to the final solution. As said in the literature review the SBCE is about working with a set of alternatives but also about making eliminatory decisions as late as possible.

The game started with the architects' preliminary designs but the first attempts were really far from a holistic feasible solution, what it was good for the architects was really bad for the others. The time took for making the preliminary designs was wasted because when the engineers and the project manager started the first analysis the results were completely out from the feasible solution domain for at least one of the roles. All the teams just took the best option among the bad ones to improve it. The example in the Figure 13 shows the problem; in this case the Thermal Engineer rejected the solutions 1, 3 and 4 automatically so the team finally developed just the option 2.

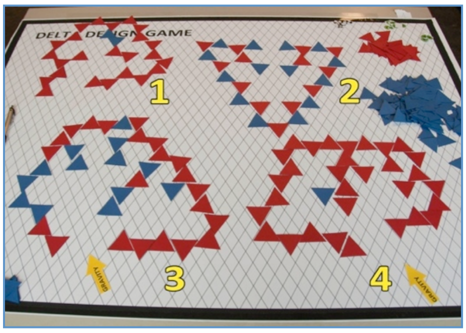


Figure 13 - Preliminary designs Round 1

The convergence process was developed working serially. After the elimination of these designs that were really far from the solutions domain the teams iterated to improve the picked solution in turns. First analysing from one perspective, modifying to meet that set of constraints and then moving to the next perspective. The time took for analysing was too long in all the roles but exaggeratedly in the engineers so the teams could not make many cycles. Any process to follow while improving the design was defined but it was made serially because it was not possible to fully understand what was going to happen after some changes looking from different perspectives.

The quality design analysis showed the bad performance in the first round; no one of the groups overcame fifty points, they did not reach even half punctuation. The designs picked and improved by all the teams were good in some domains but bad in the others, they were inside some requirements but it did not exist any design improved globally. The results are summarized in the next table where (R) means round and (G) group.

Parameter	Units	R1G1	R1G2	R1G3
Internal Area	QD	128	144	146
Blueness (%)	%	55,2	50,0	46,2
I/E ratio	-	1,0	1,2	1,2
Blue dispersion (%)	%	93	100	100
Expert Evaluation		0,8	0,8	0,8
Total Cost	zwigs	1148,0	1302,0	1310,4
Construction Time	wex	106,0	164,0	20,0
Max load at the anchors	din	16,9	17,2	14,0
Internal moments	-	NOK	NOK	NOK
Global Temp. (T)	ºnin	61,2	80,6	64,2
T_{max}	ºnin	88,4	138,0	96,0
Final Punctuation		47,5	31,5	47,5

Table 8 - Quality evaluation Round 1

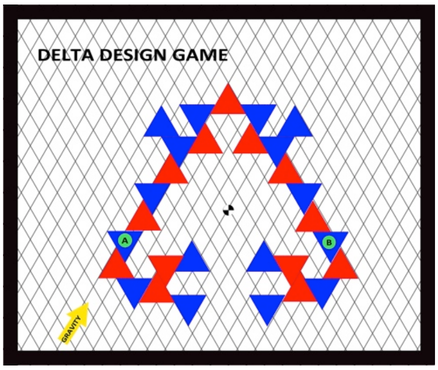


Image 14 - Design Round 1 Group 1

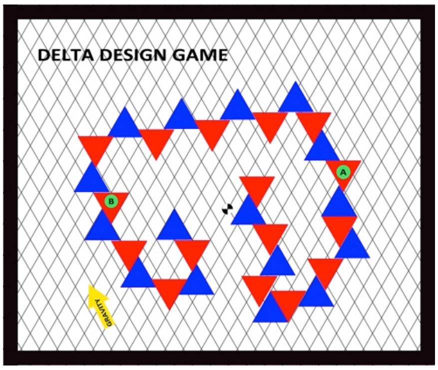


Image 15 - Design Round 1 Group 2

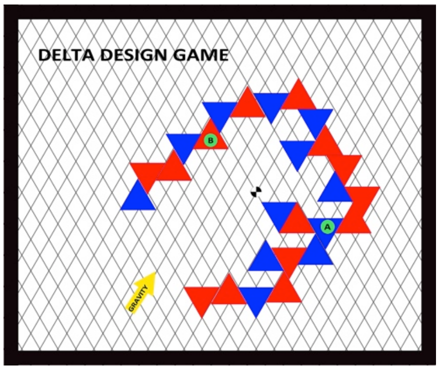


Image 11 - Design Round 1 Group 3

The wrong starting point was one of the causes why teams just worked with one alternative, all the teams quickly carried out the point-based approach instead of using the set of alternatives but then during the design refinement they neither look for a set of alternatives to improve the chosen design.

The questionnaires analysis from 10 participants in the game that rated the parameters from 0 to 9 stressed the lack of knowledge during the game. The particular knowledge of the own roles was low thinking that when finished the game the players should be experts in their fields. However, the main problem was the lack of knowledge in the other fields. Next some results. The entire analysis is in Appendix C.

Parameter	Mean	Standard Deviation
Your performance as a design group.	5,50	2,55
The co-operation within the team.	5,80	2,20
Your role knowledge	6,5	2,72
Average of Knowledge of other domains of expertise	2,58	1,93
How well your team attempted to apply SBCE	1,50	1,58

Table 9 - Questionnaire results Round 1

The discussion opened at the end of the session expressed the feelings of the participants that reflect the frustration and the difficulties found during the design in the same direction as the questionnaire;

- "We were looking the reality just from our perspective"
- "We didn't care about the others"
- "Teams had make absolutely Point-Based approaches"
- "I don't know what happens if something changes"

These results were not explained just for the bad designs at the beginning of the process. Mostly because all the teams, even starting with different number of alternatives, picked just one choice quite fast so they had certainly enough time to improve it later. The designs could not be improved because of the design analysis process and for the process used to improve the design. The teams had problems for assessing the designs; the quality but also the implications of the potential modifications. It was impossible to imagine sets of different designs neither sets of possibilities to modify one design because players did not know which were the potential implications of any modification, for the other roles but even worst for their own roles. The convergence process followed blended with the lack of knowledge in the other fields generated a slow improvement or refinement, sometimes making changes but later going back. The teams converged fast and iterated slowly in their approaches.

Even though the desired results from the first round were not achieved, the analysis of the first session had positive points. The activity was good in terms of realism, the design process was complex and the knowledge was the key factor to overcome the difficulties that constantly appeared. It was not easy to reach a solution that agreed with all the roles' specifications and it was really important to find the way to share the knowledge inside the team to improve the results. All these reflexions gave a set of possibilities for going ahead in the project.

The poor results stressed some errors when setting up the activity. Some participants felt that the instructions and the exercises designed for practicing and learning were not adequate, or at least the materials were not well conceived. It was concluded that most of the problems were due to the knowledge management: the way to present it, the way to share it and the way to use it. It was necessary to apply some changes that would allow performing the set-based approach. Some tools to explore in order to make the design process more agile were defined during the open discussion after the design run:

- **"Trade-off curves";** explore and generate trade-off for facilitate the decisions.
- **"Thumb rules";** defining the main constraints for each role and stating a starting point for the design process.
- **Simplified analysis**; define how to make rough calculations and when to use them. Define the boundaries of each calculation and each role clearly. Make the calculations easier for increase the design iterations so the alternatives in the design.
- **Modularity;** exploring the possibility of redefining the game using modules instead of deltas as a construction elements. The objective was to make the design analysis easier.
- **Capture knowledge** to reuse it. Generalize knowledge. Creation of A3. Obeya rooms.

4.2. Second Round

The objective in the second round was focused on improving the learning process, guiding the activity for promoting the set-based approach and developing some of the ideas discussed after the first session. For this last purpose the second round started with the activity group explained in detail during Chapter 3 (pg. 34). The main aim was to simplify the game for allowing the quick analysis during the design process and to facilitate the communication among the roles simplifying the calculations and creating the "Rules of thumb".

The reasons for creating this materials were related with the SBCE practices; all the materials would help defining feasible alternatives so for defining the solutions space, the agility while analysing should took into a fast iteration process allowing working with sets of solutions, the instructions should be simply so the specifications defined for each role minimal and critical allowing making robust first preliminary designs.

The materials generated after the group activity ("Rules of Thumb" and simplified calculations) improved significantly the communication but not the speed of analysis. The general design process in the second round improved in different aspects like the knowledge management and the designs quality. Thus, two of the errors detected in the first round were fixed; the teams started with coherent designs and the knowledge was extended and shared.

It was clear that the groups started trying to apply the set-based approaches; actually one of them started developing the design with modules as an idea to explore different solutions. The concept was promising but during the game was not enough time to make the research in that field, finally the first modules became a whole cluster to be developed. Both teams started making three different designs considering the general expertise and one group used the backup of the first session saved with the smartphone to have at least one feasible design since the beginning. This was in accordance of the set-based approach that suggests having at least one feasible solution while exploring the set of alternatives. The design process within teams was this time more dynamic and the chaos experimented in the first round went down.

The convergence process was again far from the set-based approach and the teams continued applying the convergence in series. Anyhow, this time, the modifications proposed for one role were discussed inside the team nor like in the first round. The starting point was better in all the groups so all the preliminary designs generated were roughly analysed, not directly eliminated, but finally just one picked. The engineers guided the convergence process, in both groups the dynamic were to analyse the picked design from an engineer perspective (often the thermal perspective) who proposed an improvement, this modification was evaluated thinking in the other roles criteria for accepting or rejecting.

The results on quality expressed the improvement on performance but in this case due to three possibilities; the effect of all the knowledge shared between members, the expertise achieved after two rounds by all the participants or probably a combination of these two.

Parameter	Units	R2G1	R2G2
Internal Area	QD	182	186
Blueness (%)	%	41,9	54,3
I/E ratio	-	1,1	1,1
Blue dispersion (%)	%	100	100
Expert Evaluation		0,8	0,8
Total Cost	zwigs	887,6	1234,8
Construction Time	wex	34,0	6,0
Max load at the anchors	din	18,0	22,0
Internal moments	-	NOK	OK
Global Temp. (T)	ºnin	72,0	53,8
T_{max}	ºnin	138,0	81,0
Final Punctuation		67,9	61,7

Table 10 - Quality evaluation Round 2

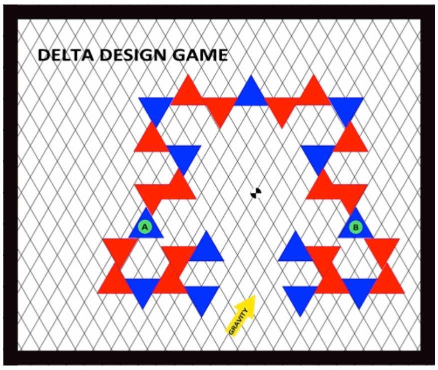


Figure 12 - Design Round 2 Group 1

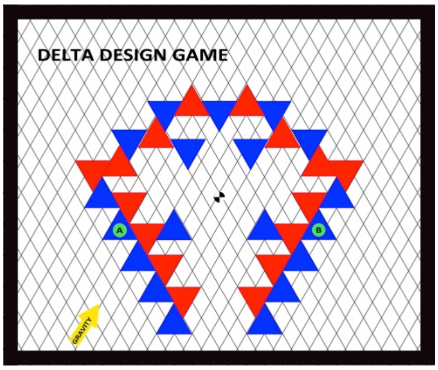


Figure 18 - Design Round 2 Group 2

All the improvements on performance and the efforts for applying the set-based approaches were not translated again in the real application of the set-based approach. The design schedule suggested to promote the set-based approaches was not used for the teams. Both of them missed some steps, for example the second step, identifying conflicts and synergies between roles, was skipped. In this round the teams were able to analyse the designs but the analysis process still took too much time limiting the possibility to iterate and explore the designs' possibilities. The working session was supposed to develop simplified procedures. It seems they were helpful for the thermal guys, but not for the structural guys. The teams were able to identify the boundaries of the solution space but not to explore it.

The slowness in the analysis created fear to changes; do not know what was going to happen after a small change in the cluster, not from a role point of view but in a general, blocked the teams that couldn't explore more than one alternative in detail avoiding the set-based approach.

It was clearly necessary the simplification of the analysis process to allow the exploration of different alternatives so the solutions space. Teams should be able to work with preliminary designs with confidence, even not having all the exact numbers of each alternative these ones had to be analysed roughly with guaranties.

4.3. Third Round

The third round started defining all the new materials brought to the players. The objective was to given complete knowledge about the game and doing it faster and easier than in the first two sessions. It was necessary to create the understanding of how each role performed, their constraints and boundaries and find the way to present it to the other team members. The analysis speed had to go up for allowing the possibility of working with different alternatives, this asked for both, simplified analysis and defining how and when to use rough calculations instead of exact ones. The roles needed tools such the "Rules of thumb" with the purpose of quickly reject different modifications and having some guidance to figure which changes in the design could be okay or not. The design process had to be improved for skipping the fear to changes so to allow the alternatives exploration.

It was decided to continue developing some lean product development tools for reaching the objectives and the ideas generated after Round 1 were developed. The groups worked in a LPD environment similar to the Obeya rooms used in Toyota with the A3 reports as a guide for exposing the potential problems during the design and the thumb rules to follow. All these materials wanted to represent the knowledge saved in the first two rounds of the game keeping some parallelisms with the knowledge saved in the real world after any project developed in any company. The Obeya rooms and the A3 reports were applied for promoting the SBCE approach; the integration, so looking for the intersection among possibilities between roles' perspectives, the specification, so using minimum information for allowing the general optimization, and for making easily the solutions space exploration, working with sets.

The learning process for each role worked better than in the first sessions, as we can see in Figure 17 the results on design stress the improvement throughout the games in both engineer domains.

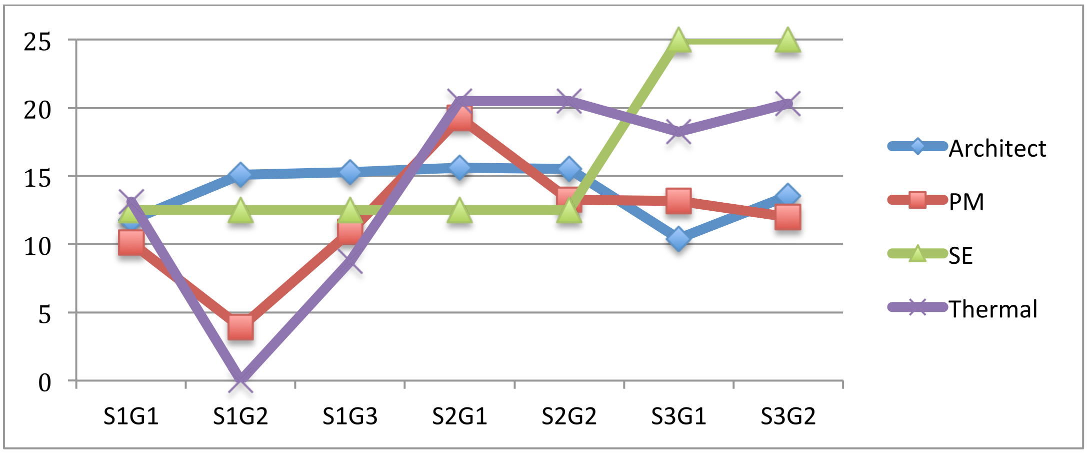


Figure 17 - Quality Results by roles in each role and group.

The questions made during the practical exercises phase went directly referred to the analytical aspects due to the skipped overwhelming data from the original papers. Both teams started with four alternatives as a starting point but the Group 1 quickly choose one solution to develop. For this group the developing process at the beginning was random, the group made some changes taking pictures of the previous state to have a backup in case of falling in a worst solution. After some iterations this group started to work with more attention with the A3 and the refining process went pretty fast but still in a point-based approach so serially.

The Group 2 applied the set-based approaches since the beginning of the activity and almost until the end. As said above the group started with four alternatives that were analysed at the beginning for all the roles. The group used post-its to identify each design and state the main characteristics using a visual and intuitive platform. The group was quite fast in the rough analysis and this gave them time to discuss about the weak and the strong points of each structure while exploring different changes to close the gaps. The environment in this group was working in a clear set-based approach until ten minutes before the game finished. The near dead line broke the process and the team finally chose one option among the analysed four, since that moment to the end the approach was point-based.

The table below shows the quality results for the third round.

Parameter	Units	R3G1	R3G2
Internal Area	QD	104	122
Blueness (%)	%	54,5	57,7
I/E ratio	-	1,1	1,2
Blue dispersion (%)	%	94	88
Expert Evaluation		0,8	0,8
Total Cost	zwigs	1009	1176
Construction Time	wex	104,0	56,0
Max load at the anchors	din	11,0	16,3
Internal moments	-	OK	OK
Global Temp. (T)	ºnin	55,5	56,8
T_{max}	ºnin	83,6	83,8
Final Punctuation		66,8	70,8

Table 11 - Quality Evaluation Round 3

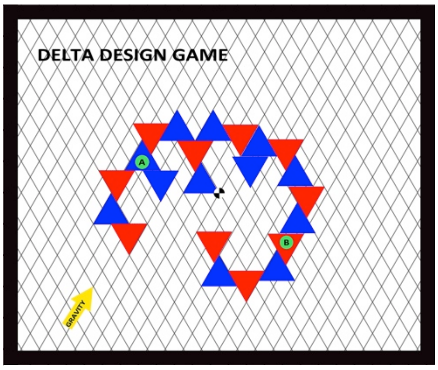


Figure 18- Design Round 3 Group 1

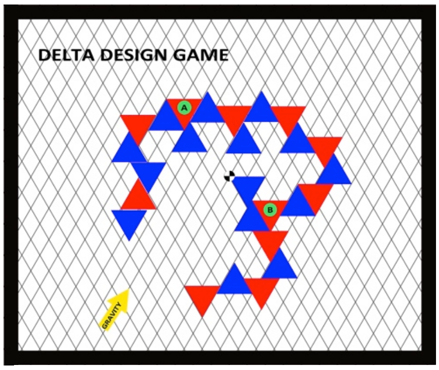


Figure 19 - Design Round 3 Group 2

In this third round the results were in both groups acceptable even being the first time playing the game for all the players. The evaluation of each role performance shows that the solutions were found thinking in a holistic point of view so all the roles were implied in the design process and in the negotiation. The evolution of results on the quality show the progressive improvement in design through the rounds and the questionnaires stress the usefulness of the new provided materials so the importance to generate tools to define the design map widely.

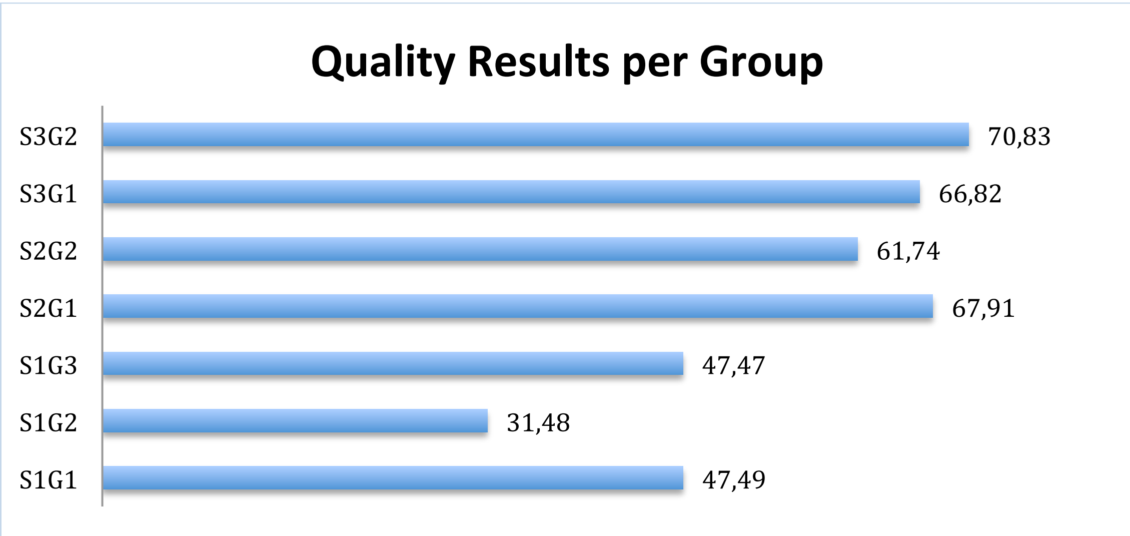


Figure 20 - Evolution Quality Results

The next table summarizes some questionnaires' results. As said in the methodology chapter the questionnaire for this third round had several equal questions as the questionnaire used in the first round, these ones are compared and three others focusing in the new materials provided, are analysed independently. The first column corresponds to the average of all the answers of all the players in the first round, the second column to the average in the third round, the third column is the difference between these two averages and the last column is the difference between the two groups in the third round.

Parameter on study	Mean Round 1	Standard Deviation R1	Mean Round 3	Standard Deviation R3	Mean R3 Vs. Mean R1	R3 Group 2 Vs. R3 Group1
Your performance as a design group.	5,50	2,55	7,00	1,00	1,50	1,17
The co-operation within the team.	5,80	2,20	6,86	1,07	1,06	0,83
Quantity of knowledge shared between members.	3,90	1,37	6,43	1,40	2,53	0,42
How well your team attempted to apply SBCE.	1,50	1,58	4,86	1,46	3,36	-0,33
Your knowledge of the four domains of expertise:						
Architect	4,30	2,71	5,43	2,52	2,37	1,58
Thermal Engineering	3,60	2,59	4,71	2,31	2,38	2,25
Project Manager	4,10	3,11	5,43	2,08	1,99	0,42
Structural Engineer	2,20	2,30	4,86	1,15	1,77	1,42
Own role Knowledge	6,5	2,72	7,43	1,13	0,93	-
Utility of The PPT introduction	-	-	5,71	1,60	-	-1,25
Utility of the written papers	-	-	7,43	0,98	-	-0,17
Utility of the A3	-	-	5,57	2,15	-	1,92

Table 12 - Questionnaires analysis

The results in the questionnaires were the consequence of a subjective perception about the activity but looking the fifth column it is clear that, as said above, the teams felt that they were sharing better the knowledge in the third round. One of the objectives of the new materials were to increase the knowledge in each domain and it was reached, the general knowledge of all the roles increased with the new presentation at least in 1,11 point in each role and 0,93 points on the own role. Looking at the last three lines in the table and comparing the results between the two groups in the last session that worked with different approaches some differences are stressed. The group that worked with the Set-Based approach give more value to the A3 and less to the introduction papers that stress the importance of using the simplified analysis and the visual platforms for applying the SBCE approaches. This group also reached a higher level of knowledge than the group in the same activity, the global result of the design was better and the results on the questionnaires reflect that second team members felt that they had learnt more about the other roles than group one, for instance the difference for the thermal characteristics was 2,25 points.

This round was useful to realize that it was possible to work with a set-based approach but for really being able to do it until the end of the design process it was needed more time in the design phase. The management of the time during the convergence process appeared as an important point for applying the set-based approach, it was clear that for applying the SBCE the preliminary study of the game asked for more analysis and simplification. This analysis asked for introducing some extra lean tools to allow the application of the SBCE approach.

4.4. Results discussion and Alternative Explanations

The results have been obtained using a design game. As said before the objective of the design games is to reduce the design environment in order to facilitate the analysis but at the same time this simplification can lead to a non-reliable representation of all design processes.

The conclusions have been stated using a small analysis population due to the small groups playing the game and using the participants' feedback, thus the incidence of each subjective opinion could be important.

The evaluations of the SBCE performance done by the participant could not be defined in the same criteria scale. The participants in the first two rounds had a higher level of knowledge about the SBCE due to the assistance to the course so they could be more critical.

The results on quality have been improving progressively during the rounds, this improvement could be due to different factors, as said above one option could be the better knowledge sharing inside the teams but other factors like the expertise introducing roles or the expertise running the game could influence leading to a better game flow in the third round.

Comparing the results on quality among the first and the third round with the second round can lead to errors in the conclusions. The players in round 2 had much more time to assimilate the intrinsic game concepts and more time expertise. Anyhow, all the conclusions stated using the quality results as a base have been supported mostly by the comparison between the first and the third round.

The function developed for assessing the design quality could be developed using different criteria leading to different results. It has been chosen to give the same importance to all the roles but this criterion could change and then the results.

The simplifications and modifications made to the game for the third round have been done for facilitating the analysis but could be seen as a problem engineering simplification so like a trick in the game. Anyhow the final evaluation parameters for all the rounds have been the same so this simplifications if represent an engineering reduction the results on design should be affected.

In this exercise the visual platforms such the A3 and the trade-off curves have been used to save knowledge and improve the design process. These are two valid tools but maybe not the only ones that can work to drive the design process and facilitate the SBCE application.

5. Conclusions

The conclusions chapter is divided in two parts. First some general conclusions about SBCE application are stated. Secondly and thanks to the experience after playing the game three times some conclusions about how to run the game, how to use the game for future research and how to use the game to teach SBCE principles are exposed.

5.1. General Conclusions

The game, even representing a small and virtual design environment, stressed the need of applying more than a single lean tool to reach the lean performance. In this case it has been necessary to use tools such the trade-off curves and the A3 to create the Obeya rooms environment to allow the set-based approach. At the beginning it was thought that being the game more simple than the real design environment it could be possible to apply simply the SBCE, but even with its relative simplicity it was not possible. The quality results analysis stress that using a set of tools for finding a good way to present the information allows getting better results.

For applying the SBCE approach it is necessary to create an atmosphere for sharing information between teams or design actors. This space has to be useful for skipping loopbacks and converge to a final solution realistic from all the designs points of view. Sharing knowledge is needed to find a balanced solution among the design perspectives.

To apply the SBCE successfully it is convenient to find a valid way to save the knowledge within the entrepreneurship and one valid option is using Lean tools. It seems useful to abstract one's knowledge about the problem or solution space into a suitably general representation that can be applied to other designs.

To apply the SBCE it is important to define the main constraints for each person or department implied in the design process, so defining the desing boundaries. The definition of these boundaries has to be clear and intuitive for the other people and at same time as less restrictive as possible. That has to allow defining flexible, feasible and robust preliminary designs leading to the definition of feasible solutions spaces as wide as possible. If these boundaries are not defined correctly it is easy to spend time and resources generating non-reusable knowledge.

After this study it is not clear, due to the reduced number of rounds played, that applying the SBCE implies better results in the design but at least it implies better understanding of the problem by the designers. This better knowledge is in both, the own field of knowledge and in other fields of knowledge.

It is critical to apply SBCE to find rapid ways to evaluate designs or proposed modifications, to either kill them quickly or inform other modifications. Not finding tools for analysing fast enough lead to blocking the design process.

The fear to changes also blocks the design teams. The application of SBCE approach ask for different analysis so for changing perspectives. It is necessary to clearly understand what is going to happen when making changes, if not teams can remain trapped with no direction loosing time and resources. In the same direction it seems necessary to work with confidence with the preliminary designs, if not the design teams can get lost in the solution space and explore alternatives out from it.

To apply SBCE it is necessary to present the information using as more visual platforms as possible. These platforms have to be intuitive, useful for communicating, analysing and increase the designers' implication.

The relative proximity to the dead line of the project is a critical point to keep into account for those who want to apply SBCE. While having the dead line far teams are able to look for different alternatives and exploring sets of solutions, when the time press then is easy to chose quickly one option falling again in the point-based approach. The changes when the deadline is near can be made randomly so the time management and the convergence process have to be studied and cleared when applying SBCE.

It is not possible to apply the SBCE approaches without assuming extra time at the beginning of the project; this time has to be made up during the convergence process. It is just possible to skip this extra time if the amount of saved knowledge is huge and it is useful for the particular case.

Even needing more effort at the beginning of the design, applying the SBCE doesn't imply more overall effort if using the saved knowledge. If knowledge is saved properly and it is used in future design applications the effort done in exploring different design options is clearly an inversion.

5.2. Future Research and Game Applications

This section wants to give both, few guidance for future applications with the game and few ideas for future research. The characteristics of the original Delta Design Game promoted clearly the point-based approach. The modifications after three rounds facilitated the exploration of the design space so to be able to apply the set-based approaches. The results in the last round allow being optimistic about future applications of the game to assess different SBCE aspects.

It has concluded that to generate the environment and promote the SBCE approach using the Delta Design Game it is necessary to use the materials generated throughout this thesis, if not, the same problems to apply the principles are going to be found. One of the initial ideas for this thesis were to assess which principles or practices related with LPD could be taught with the game and how can be used it to teach the SBCE principles. Some conclusions have been stated but further research can be developed using and taking advantage of the new way to present the game.

Future research in SBCE:

- **Analyse the convergence process vs. Quality results**: This study could see the differences of working with different number of alternatives, the results based on quality and the loopbacks generation. Analyse when the teams eliminate alternatives and based on what.
- **Analyse the response to customer requirements changes**: Analyse the situation and the different design processes followed by different teams before and after introducing the uncertainty factor in the game. As have been exposed before the game has a couple of tools to introduce this factor, the overhead multiplication factor and the gravity waves. If this second one is considered too radical it is possible to introduce other changes, for instance the requirements about the rooms in the dwelling.

Using the game to teach SBCE:

- **Two phases activity to teach SBCE**: The activity could have the objective of teaching the SBCE plying first the game with the original papers for later giving the material generated in this thesis. The time in this case could be critical for the success so could be interesting to present the activity in a course framework as an activity divided between sessions for not having the time pressure.

Among all the ideas proposed to fix the knowledge problematic after the first session just one have not been explored deeply in the next two sessions, the modularization. The modularization should imply a new way to present the game. In this presentation instead of using the deltas as structural elements some different structural elements could be defined, two, three or whatever. It would be a new way to present the game so it has to be deeply studied, during this thesis the process has been started but just with preliminary studies, some conclusions are exposed next.

Modularization:

Each designed module has to be defined just with one orientation or if not its characteristics have to be defined in six different options. This options have some characteristics in common and some different depending on the number deltas pointing outward or inward, the cluster orientation respect the axis, the symmetry and so on.

On next pages three possible examples of modules with its six possible orientations and some characteristics that should be used later for assembling, there exist unlimited alternatives when defining modules, for instance one of the players in the first round suggested making a cluster hexagonal shaped consisting of 6 deltas.

The future steps in the modularization research study are to define how the modules communicate between them and defining rules for assembling them. After defining these rules it could happen that the game was less complex than the original one. Playing with modules open a van of possibilities to modify the original game and make new studies. For instance, using it could be possible to balance the relative complexity between roles applying new rules on cost for using the modules so increasing the complexity for the project manager.

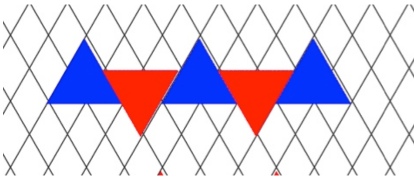
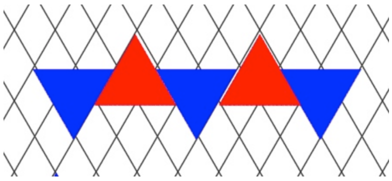
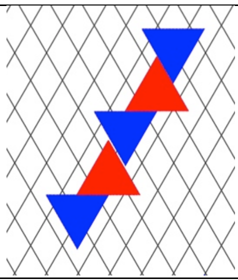
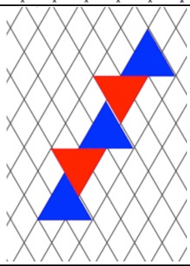
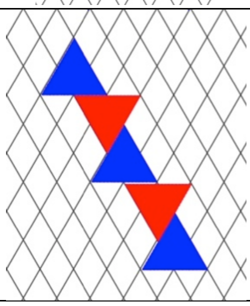
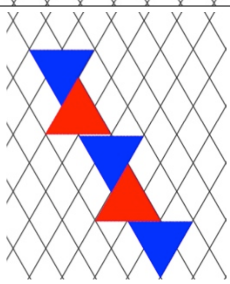
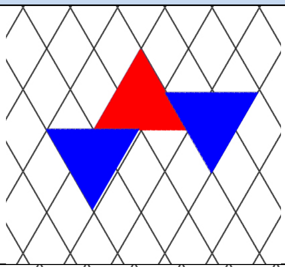
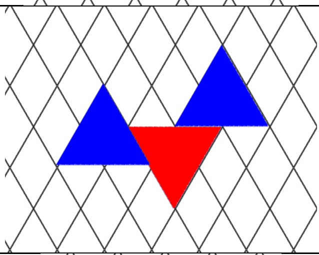
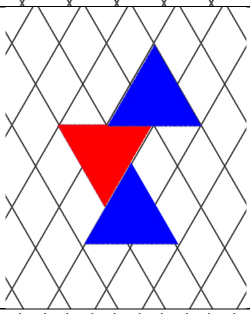
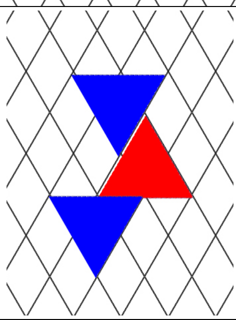
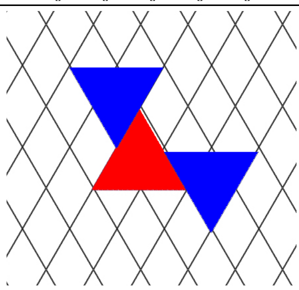
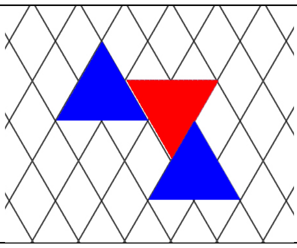
Module 1			
Orientation Alternative	Role	Results	
	Project Manager	Cost=	!130
		Time=	6 wex
	Thermal	T*=	40 ºnin
		T_{max}=	80º nin
		T_{avg}=	56º nin
	Structural	Y	19 lyn/din
		X	16 lyn/din
	Project Manager	Cost=	!130
		Time=	6 wex
	Thermal	T*=	80º nin
		T_{max}=	80º nin
		T_{avg}=	80º nin
	Structural	Y	16 lyn/din
		X	19 lyn/din
	Project Manager	Cost=	!170
		Time=	28 wex
	Thermal	T*=	40 ºnin
		T_{max}=	80º nin
		T_{avg}=	56º nin
	Structural	Y	2 lyn/din
		X	19 lyn/din
	Project Manager	Cost=	!170
		Time=	28 wex
	Thermal	T*=	80º nin
		T_{max}=	80º nin
		T_{avg}=	80º nin
	Structural	Y	-2 lyn/din
		X	16 lyn/din
	Project Manager	Cost=	!170
		Time=	28 wex
	Thermal	T*=	80º nin
		T_{max}=	80º nin
		T_{avg}=	80º nin
	Structural	Y	-2 lyn/din
		X	19 lyn/din
	Project Manager	Cost=	!170
		Time=	28 wex
	Thermal	T*=	40 ºnin
		T_{max}=	80º nin
		T_{avg}=	56º nin
	Structural	Y	2 lyn/din
		X	16 lyn/din

Table 13 - Module 1 / Modularization

Module 2			
Alternative	Role	Results	
	Project Manager	Cost=	!88
		Time=	16 wex
	Thermal	T*=	15 ºnin
		T_{max}=	15º nin
		T_{avg}=	15º nin
	Structural	Y	3 lyn/din
		X	7 lyn/din
	Project Manager	Cost=	!88
		Time=	16 wex
	Thermal	T*=	24º nin
		T_{max}=	64º nin
		T_{avg}=	37º nin
	Structural	Y	6 lyn/din
		X	5 lyn/din
	Project Manager	Cost=	!88
		Time=	14 wex
	Thermal	T*=	15 ºnin
		T_{max}=	15 º nin
		T_{avg}=	15 º nin
	Structural	Y	6 lyn/din
		X	0 lyn/din
	Project Manager	Cost=	!88
		Time=	14 wex
	Thermal	T*=	24º nin
		T_{max}=	64º nin
		T_{avg}=	37º nin
	Structural	Y	3 lyn/din
		X	4 lyn/din
	Project Manager	Cost=	!86
		Time=	14 wex
	Thermal	T*=	24º nin
		T_{max}=	64º nin
		T_{avg}=	37º nin
	Structural	Y	-2 lyn/din
		X	19 lyn/din
	Project Manager	Cost=	!86
		Time=	14 wex
	Thermal	T*=	15 ºnin
		T_{max}=	15º nin
		T_{avg}=	15º nin
	Structural	Y	3 lyn/din

		X	7 lyn/din

Table 14 - Module 2 / Modularization

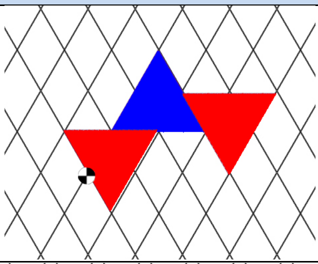
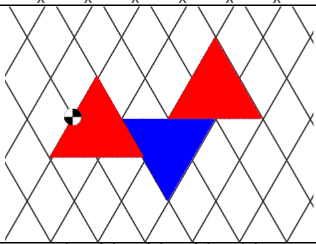
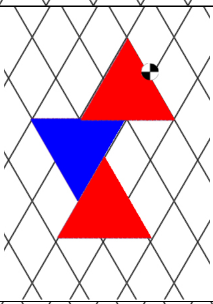
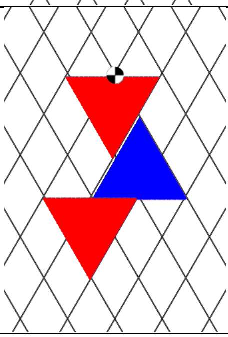
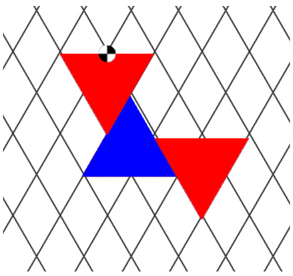
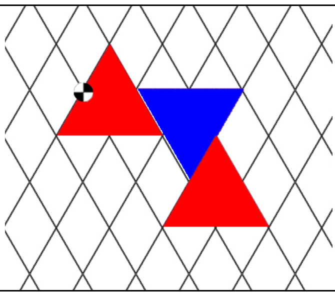
Module 3			
Alternative	Role	Results	
	Project Manager	Cost=	!86
		Time=	16 wex
	Thermal	T*=	40 ºnin
		T_{max}=	40º nin
		T_{avg}=	40º nin
	Structural	Y	3 lyn/din
		X	7 lyn/din
	Project Manager	Cost=	!86
		Time=	16 wex
	Thermal	T*=	64º nin
		T_{max}=	64º nin
		T_{avg}=	64º nin
	Structural	Y	6 lyn/din
		X	5 lyn/din
	Project Manager	Cost=	!86
		Time=	14 wex
	Thermal	T*=	40 ºnin
		T_{max}=	40 º nin
		T_{avg}=	40 º nin
	Structural	Y	6 lyn/din
		X	0 lyn/din
	Project Manager	Cost=	!86
		Time=	14 wex
	Thermal	T*=	64º nin
		T_{max}=	64º nin
		T_{avg}=	64º nin
	Structural	Y	3 lyn/din
		X	4 lyn/din
	Project Manager	Cost=	!66
		Time=	14 wex
	Thermal	T*=	64º nin
		T_{max}=	64º nin
		T_{avg}=	64º nin
	Structural	Y	-2 lyn/din
		X	19 lyn/din
	Project Manager	Cost=	!66
		Time=	14 wex
	Thermal	T*=	40 ºnin
		T_{max}=	40º nin
		T_{avg}=	40º nin
	Structural	Y	3 lyn/din
		X	7 lyn/din

Table 15 - Module 3 / Modularization

Bibliography

Bucciarelli, Louis. L., "*Delta Design: Seeing/Seeing as*", Proceedings 4th Design Thinking Research Symposium on Design Representation, Massachusetts Institute of Technology, Cambridge, MA, April, 1999.

Brandt, Eva., *"Designing Exploratory Design Games: a framework for participation in participatory design*?", Proceedings Participatory Design Conference, Copenhagen, 2006.

Cooper, Robert. G., "Winning at New Products: Creating Value Through Innovation", Basic Books, New York, 2011.

Cooper, Robert G., Edgett, Scott J., and Kleinschmidt, Elko J., "*Benchmarking best NPD practices-I*", Research Technology Management, Arlington, VA, Jan/Feb 2004.

Goel, M., "*Diners"* Sunday supplement in "*La Vanguardia"* from Sunday February 5th, Barcelona, 2012.

Hogg. David, P.Eng, Director of Consortium Development, AME Conference, Toronto, 2008.

Hoppmann J., Rebentisch E., Dombrowski U. and Zahn T., "*A framework for organizing Lean product development*", Engineering Management Journal, Vol. 23, No. 1, 2011.

Kennedy, Michael N., "*Product development for the lean enterprise: why Toyota's system is four times more productive and how you can implement it*", Oaklea Press, Richmond, Virginia, 2003.

Kennedy, Michael N., Harmon, K., and Minnock, E., "*Ready, Set, Dominate*", The Oaklea Press, Richmond, Virginia, 2008.

León H.C.M. and Farris J.A., "*Lean Product Development Research: Current State and Future Directions*", Engineering Management Journal, Vol.23, No.1, 2011.

Letens, G., Farris, J.A., and Van Aken, E.M., "*A Multilevel framework for Lean Product Development System Design*", Engineering Management Journal, Vol.23, No.1, 2011.

Liker, J. K., and Morgan, J.M., "*Lean Product Development as a System: A case Study of Body and Stamping Development at Ford*", Engineering Management Journal, Vol.23, No.1, 2011.

Liker, J.K., and Morgan, J.M., "*The Toyota way in Services: the case of Lean Product Development*", Academy of management perspectives, 20:2, 2006.

Lloyd P. and Van de Poel I., *"Designing games to Teach Ethics*", Springer Science+Business Media, 2008.

Oppenheim, Bohdan W., "*Lean Product Development Flow*", Systems engineering, 7:4, Department of Mechanical Engineering, Loyola Marymount University, Los Angeles, CA, 2004.

Prudhomme G., Boujut J.F., and Brissaud D.,*"Toward reflective practice in engineering design education"*, International Journal Engineering, Vol. 19, Great Britain, 2003.

Reinertsen, D., and L. Shaeffer, "*Making R&D Lean*", Research Technology Management, 48:4, 2005.

Sala-i-Martín, X., Columbia University, Department of Economics, Professor of Economics, Traduced from his blog http://salaimartin.com/, April 2nd , 2011.

Smith R.P, Eppinger S.D., and Gopal A., "*Testing an Engineering Design Iteration Model in an experimental setting*", Massachusetts Institute of Technology, Cambridge, MA, February 1992.

Smith R.P., and Tjandra P., "*Experimental Observation of Iteration in Engineering Design*", Research in Engineering Design, 1998.

Sobek II, D.K., "*Principles that shape Product development Systems: A Toyota-Chrysler comparison*", PhD Dissertation, University of Michigan, UMI, Ann Arbor, MI, 1997.

Sobek II, D. K., Ward, Allen C., and Liker, J.K., "*Toyota's Principles of Set-Based Concurrent Engineering*", MIT Sloan Management Review, 1999.

Walton, M., "*Strategies for Lean Product Development*", Massachusetts Institute of Technology, Cambridge, MA, 1999.

Wang L., Ming X.G., Kong F.B., Li D. and Wang P.P., *"Focus on implementation: a framework for Lean product development"*, Journal of Manufacturing Technology Management, Vol.23, No.1, 2012.

White, Ian. "*Clarifying Innovation*", Urban Mapping LLC, DMI News, Fall 2005.

Womack, James P., and Jones, Daniel T., *"Lean Thinking: Banish Waste and Create Wealth in Your Corporation"*, Simon & Schuster UK Ltd., London, 2003.

Womack, James P., Jones, Daniel T., and Roos D., "*The machine that changed the world: Based on the Massachusetts Institute of Technology 5-Million-Dollar 5- year study on the future of the automobile*", Rawson Associates, New York, 1990.

Womack and Daniel T. Jones, "*Lean Thinking: Banish Waste and Create Wealth in Your Corporation*", Simon & Schuster UK Ltd, London, 2003.

APPENDIX A – The Game Instructions

Original Game

Below, the active link for finding the original game when this thesis was finished.

“http://ocw.mit.edu/courses/civil-and-environmental-engineering/1-101-introduction-to-civil-and-environmental-engineering-design-i-fall-2006/delta-game/ “

Modified Game

Next the modified papers for the third session are reproduced. First the general introductory paper and next the specific papers for each role.

If the reader is interested in the materials used during the practical sessions such as the game table, the practical exercises, the A3 reports the image documents and so on to modify or use them, feel free to contact;

Francesc Carbó Roma
cesccarbo@gmail.com

The Delta Design Game

Introductory Paper

1 Introduction

Congratulations! You are now a member of an expert design team. Your collective task will be to design a new residence suitable for inhabitants of the imaginary Deltoid plane.

These written materials, provided to help you prepare for this task, are organized in three sections. The first provides an **overview** of life on the Deltoid plane, it describes your team characteristics and your design task. The second section explains **in detail** the main constraints of your role and how to develop your task. The third section promotes the practice with different exercises that will help you to go deeper in your role responsibilities and will give a way to communicate your design desires to your team mates.

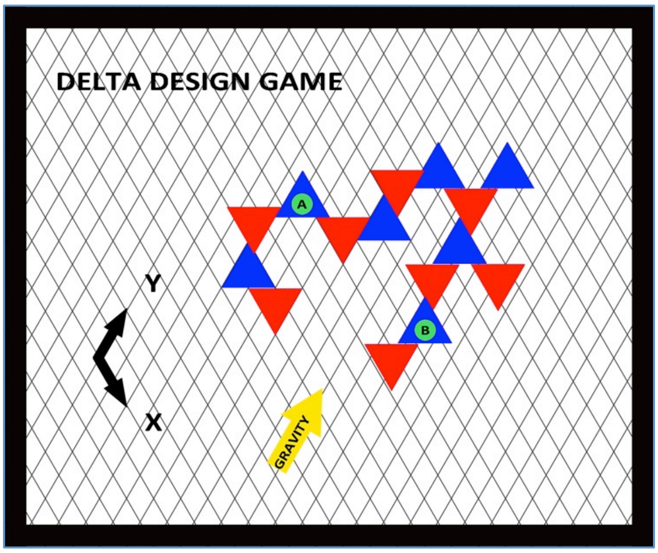
1.1 Life on DeltaP

Life on DeltaP, residential and otherwise, is quite different from what you have grown accustomed to here on Earth. First off, DeltaP is a plane, not a planet, so your team will be designing in two-dimensional rather than three-dimensional space.

Deltoid space has unfamiliar relations between the "x" and "y" axes as well. What we think of as "perpendicular" is hopelessly skewed to a Deltan, and vice-versa. In our units, a right angle on DeltaP measures 60° or $\pi/3$ radians. Thus all sides of an equilateral triangle form lines considered perpendicular to all others.

In this flat though angular world, residents construct their artifacts strictly with discrete triangular forms. Of these, the equilateral triangle --with its three perpendicular sides (!)-- is considered the most pleasing. Accordingly, your team will design the residence by assembling into a cluster the most prized building materials on DeltaP, equilateral triangular components called "deltas."

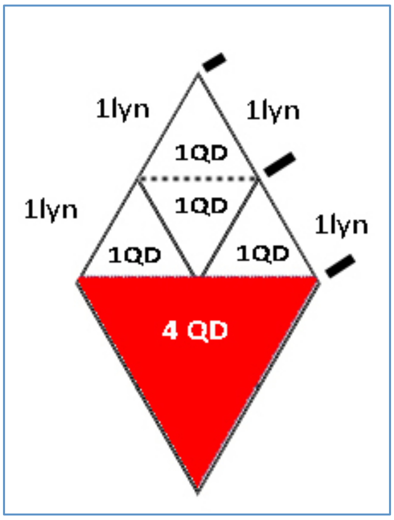
Next an example of a work in progress:



Deltan systems of measurement are as unfamiliar as that for spatial coordinates. Table 1 summarizes the measurement schemes on DeltaP that you will need to know to carry out your design task.

Measurement	Unit of Measurement	Symbol
Time	Wex	wx
Distance	Lyn	ln
Area	Quarter-Delta	QD
Heat	Deltan Thermal Unit	DTU
Temperature	Degrees Nin	ºNn
Force	Din	Dn
Moment	Lyn-Din	LD
Currency	Zwig	!

Deltas come in red and blue versions and always measure *2 lyns* per side so 4 “quarter-deltas”, *QDs*. Each rhombus in the plane defines 2 QDs.



As building components, deltas have functional and aesthetic characteristics that are more complex than their simple form and even dimensions would suggest. Especially when assembled into a cluster, as you will be doing, they behave in interesting ways. Deltas conduct heat among them, radiate heat to outer space, melt if too hot, and grow if too cool.

All deltas are subject to DeltaP’s two-dimensional gravity (which is itself subject to axial shifts during DeltaP’s not-infrequent gravity waves). Three different kinds of cement are needed to join them together, and joint alignment with respect to gravity affects ease of production as well as structural integrity. Different colours and different quantities of deltas cost different amounts of money per delta, and can be assembled in clusters that are either exceedingly ugly or very attractive to the Deltans. Your task will be to create a design that meets prescribed goals for all of these characteristics that are controlled for one of the four existent roles in the game.

1.2 Design Team Roles & Responsibilities

Your design team is organized such that each of you will be responsible for a subset of the design goals. One of you will be PROJECT MANAGER. Your main concerns will be with cost and schedule, the interpretation and reconciliation of performance specifications, and negotiations with the contractor and client. You want to keep costs and time-to-build at a minimum, but not at the expense of quality. When your team submits its final design, the project manager must report the estimated cost (in zwigs) and the time (in wex) that it will take to build.

Another of you will be the STRUCTURAL ENGINEER. Your main concern will be to see that the design “holds together” as a physical structure under prescribed loading conditions. You must see to it that the two points at which your structure is tied to ground are appropriately chosen and that continuity of the structure is maintained. When your team submits its final design, the structural engineer must attest to its integrity by identifying the strongest and weakest joints, and estimating the average load on all joints expressed as a percentage of the failure load.

Another of you will be the THERMAL ENGINEER. You will want to insure that the design meets the “comfort-zone” conditions specified in terms of an average temperature. You must also ensure that the temperature of all individual deltas stays within certain bounds. When your team submits its final design, the thermal engineer must estimate internal temperature and identify the hottest deltas.

Finally, one of you will be the ARCHITECT. Your concern is with both the form of the design in and of itself and how it stands in its setting. You must see to it that the interior of the residence takes an appropriate form and that egress is convenient. You should also develop designs with character. When your team submits its final design, the architect should be prepared to present a sketch and discuss generally how and why the Deltans will find the residence attractive and functional. The architect will also be asked to estimate a few more quantitative measures of architectural performance.

Summary of roles concerns:

Roles	Objectives	Constraints	Evaluation Parameters
Project Manager	- Minimum cost and lead-time.	- Cost of single elements and assembling. - Building Times	- Total Cost - Total Time
Architect	- Aesthetic House form - Internal/external	- Colour distribution	- Internal Area - Blueness parameter - Blue dispersion - I/E Ratio
Structural Engineer	- Prevent the structure to collapse. - Define the anchor points.	- Gravity force and Delta assembly joints resistance	- Maximum load at anchor points - Maximum internal moment - Percentage of failing joints
Thermal Engineer	- Keep average temperature acceptable. - Avoid hot and cold points.	- Thermal laws of DeltaP world: conduction and radiation.	-Average internal temperature - Maximum Temperature

1.3 The Design Task

The following section describes the specifications that your design must meet to be accepted by your clients on DeltaP.

Your Deltan clients have cleared the space shown on the site map and come to your team with their need for the design of a new residential cluster. The cluster itself must meet the following specifications.

The client wants the cluster to provide a minimum interior area of 100 QDs (as said above each diamond on your girded site map defines an area of two QDs). The space must be connected, i.e. no interior walls can cut the space into completely separate spaces. There must be one and only one entrance/exit.

The client is known to be colour sensitive blue; too much blue brings on the blues, so to speak. No more than 60% blue ought to be allowed; certainly blue deltas are not to exceed 70% of the cluster.

The residence, as all clusters, must be anchored at two points and two points only. There is a limit to the amount of force each anchor can support, as well as to the amount of internal moment each joint can withstand. Exceeding either limit would cause catastrophic failure and send the unwary residents tumbling into the void.

The average interior temperature must be kept within the Deltan comfort zone, which lies between 55 and 65 $^{\circ}$Nin. The temperature of the elements themselves must be kept above the growth point of 20 $^{\circ}$Nn and below the melt-down point of 85 $^{\circ}$Nn. Delta temperatures outside of this range will result in catastrophic structural failure with little more warning than excessive load.

All of this --design, fabrication and construction --must be done under a fixed budget and within a given time period. At your team meeting you are to develop a conceptual design that meets or exceeds all design goals. When each team submits their design, individual members will be asked to report design performance on parameters for which they are responsible.

In the next table the specifications and the limit values are summarized.

Specification	Limit Value
Functional internal area	>100 Qd (Area)
Maximum Blue Delta's	[60,70] %
Average Internal Temperature	[55,65]º Nm (Temperature)
Indiv. Delta Temparature Range	[20,85]º Nm (Temperature)
Maximum load at the anchors	20 Dn (Force)
Maximum internal moment	40 LD (Distance x Force)
Total Budget	1400! x K (Currency)

Thermal Engineer Paper – Specific Paper

1.1Introduction

As thermal engineer, **you are responsible for the comfort and thermal stability of your team's design**. This primer will review some basics of heat transfer on DeltaP, then cover methods you may use to estimate the average temperature and extreme values for individual deltas. It assumes you have read the introduction to the exercise.

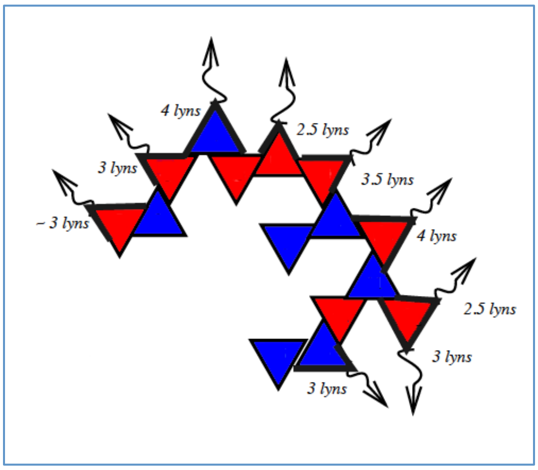
To insure the comfort of prospective residents, you want the average temperature of all deltas in the cluster, a good proxy for **interior temperature, to fall between 55 and 65 degrees Nn**. For stability, you want the **temperature of each delta to stay above 20º Nn and below 85ºNn** , as they melt at 85ºNn and begin to grow at 20ºNn . Either event would have catastrophic consequences, with your clients tumbling down the plane amidst the wreckage of their dwelling. When your team submits its final design, therefore, you will be asked to estimate internal temperature and the location and temperature of the hottest deltas.

1.2 Thermal Engineer Calculations

There are two things to keep in mind throughout your calculations. First, keep them as simple as possible. Work only in integers, always rounding up or down and estimating lengths to the nearest lyn*.*

Deltas, the building elements your team will use to design the residence, come in two colours: red and blue. Red deltas are heat sources, while blue deltas are passive, neither a source nor a sink.

The red sources produce heat continually over time, at a rate q_0 measure in Deltan Thermal Units per microwex (dtu/µwx). All deltas, red and blue, conduct heat to and from adjacent elements in the cluster. The amount of heat conducted per unit time is determined by three things: the temperature difference between the adjacent deltas, the length of the joint between the adjacent elements and a coefficient of conductivity, k_c. Those deltas that have an outward-pointing free node in the exterior Wall (See figure) can also radiate heat to the exterior space which value depends on the same factors than conduction but instead of being related with the coefficient k_c are related with the equivalent coefficient for radiation (k_r). In the delta world this parameters and the q_0 are constants thus the operational process to get the correct temperature results are simplified.



To figure out which is the higher temperature in the cluster and the average of all of them you will have to calculate first the temperature of the radiating deltas (T*) which are those ones that have a row in the last figure. After finding the temperature of the exterior elements of the cluster then you should identify and calculate the temperature of those red deltas that remain inside the cluster. These Deltas can just conduct their heat to the adjacent deltas and each one of them have a particular temperature (Ti). When all the deltas' temperatures are calculated you are able to determinate the Global Temperature (T).

1.2.1 Temperature radiating deltas (T*)

$$\mathrm{N_{red}} = \text{Number of red Deltas}$$
$$\mathrm{L_{out}} = \text{Total lenght on the outward pointing deltas}$$

$$\boldsymbol{T^{*}} = \frac{\boldsymbol{N_{red} \times 160}}{\boldsymbol{L_{out}}}$$

Realize that if you want to reduce the temperature of the radiating deltas you have two options, reduce the number of red deltas in the cluster or increase the length of the outward points.

1.2.2 Temperature Blue Interior Deltas

The temperature of **all the blue deltas** is going to be supposed the same as the temperature in the exterior façade of the building, so the same temperature of the radiating deltas.

$$\mathbf{T^{*} = T_{radiating\ deltas} = T_{Blue\ interior}}$$

1.2.3 Temperature Red Interior Deltas

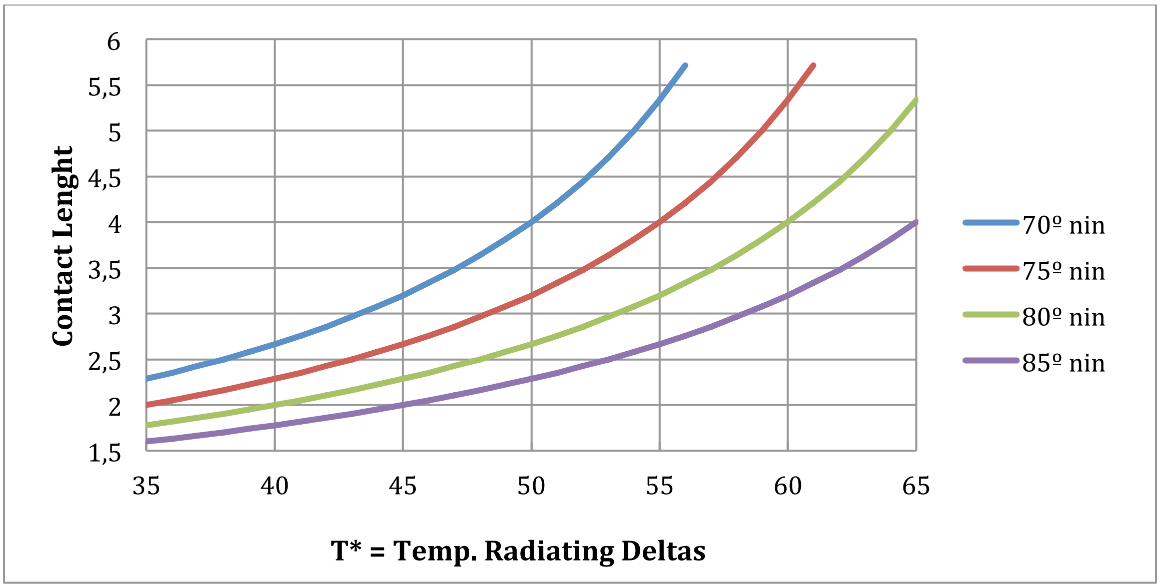
The temperature in red interior deltas is going to be the higher in the cluster but it depends on the contact length with the adjacent cooler deltas. Each red interior delta (i=1,2,3…) have a particular temperature if the contact length is different from the others.

$$L_{con} = Total\ Lenght\ contact\ with\ adjacent\ deltas$$

$$\boldsymbol{T_i} = \frac{\mathbf{80}}{\boldsymbol{L_{con}}} + \boldsymbol{T^{*}}$$

Realize that you have two options to reduce the temperature of the red interior deltas as well. First, you can try to reduce the temperature of the radiating deltas, and second and easier, you can try to increase the length contact with the adjacent deltas.

Developing this formula the next useful chart is plotted.



This chart helps you to define the contact length you need for the red interior deltas to bring them inside the temperature limits. For instance if the T* of the radiating deltas is 45º Nn and you want the temperature of the interior deltas at 85ª Nn the contact length with the adjacent deltas has to be of 2 lyns, if its more then the temperature will be lower thus inside the limits.

1.2.4 Global Temperature (T)

The global temperature in the cluster is the average of all deltas' temperatures. Having all deltas' temperatures you can find different expressions to find the average; the next expression is one of these options;

$$N_{rred} = Number\ of\ red\ radiating\ Deltas$$
$$N_b = Number\ of\ blue\ Deltas$$
$$N = Total\ number\ of\ Deltas$$

$$\boldsymbol{T} = \frac{\left(\boldsymbol{T}^{*}\boldsymbol{x}\ (\boldsymbol{Nrred} + \boldsymbol{Nb})\right) + (\boldsymbol{T}_{i1} + \boldsymbol{T}_{i2} \dots)}{\boldsymbol{N}}$$

1.3 Thumb rules and simple analysis

This section is really important. The next rules are going to be used during the design process and are going to be provided to the architect who is going to develop the first dwellings' alternatives. The exact temperature calculations are just going to be done for you so you are the responsible. Be fast and practical while calculating; if any doubt appears ask to the tutors. Be sure that the next rules are followed during the design process.

Thumb rules:

- Never 3 or more elements in a row in the same colour.
- Never 2 inward reds together.
- Inward reds need a large contact surface, minimum 1,5 lyn.

Structural Engineer – Specific Paper

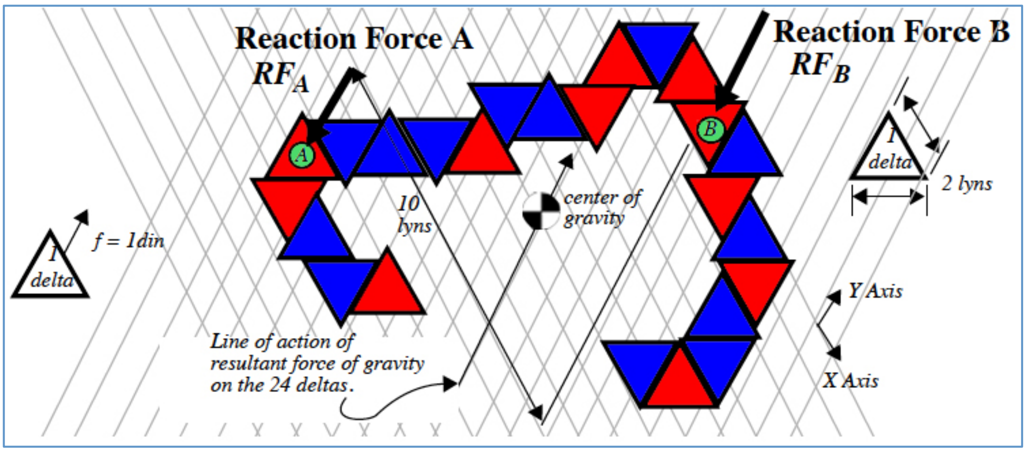
1.1. Introduction

As structural engineer, **you are responsible for the physical integrity and robustness of your team's design**. You must insure that the residence you propose will hold together under prescribed loading conditions. You should see to it that **the two points at which your structure is anchored (Anchors) to the plane are appropriately chosen**, that all **joints are sufficiently strong**, and that the overall shape of the cluster does not violate sound structural engineering practice.

When your team submits its final design, you will be asked to attest to its quality by explaining the location of the anchors, identifying the strongest and weakest joints, and estimating, as a measure of robustness, the average load on all joints expressed as a percentage of failure loads.

As a structural engineer the mathematics behind your role are quite complicated but a simplified way to make the calculations is developed in the next section. D**uring the first stages of design process your team will work with more than one alternative, while this process you will be able to use the approximations and the "Thumb rules" provided next instead of the precise methods which are going to be used just to assess your final design**.

1.2. Structural Engineer Calculations



In the DeltaP **each delta experiences a force of one din**. Thus for the cluster of 24 elements shown in the figure, we can say that it has a total weight of 24 dins, and that the resulting force due to Deltan gravity acts in the plane along a line parallel to the y axis and running through the cluster's center of gravity, as shown. The structure is kept stationary despite this force by offsetting reaction forces at the anchors, marked in the figure as points A and B. The distances in the delta world are defined in the same direction than the axis as well; thus, realize that the distance between the anchors A and B in the figure is 10 lyn.

The first step in structural analysis is to locate the cluster's center of gravity (CG). For our initial purposes, we actually only need the CG's "x" coordinate, which gives us the line of action of the gravity force shown on the previous page. We do not need to know the "y" coordinate until we consider DeltaP's recurrent gravity waves, which flip gravity between axes.

We could use the moment equilibrium technique to locate the CG of any subsection of a cluster so to **calculate the loads in the joints and the loads in the anchors** but it would be too heavy and non really useful for this game purpose. Thus, the CG and the internal moments of the joints are going to be defined following the next steps.

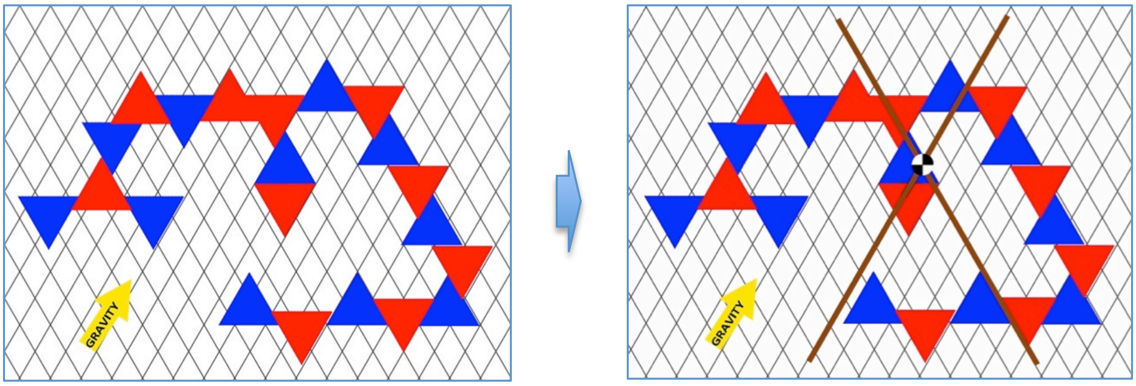
1.2.1. The Center of Gravity

There are two things to keep in mind throughout your calculations. First, keep them as simple as possible. Work only in integers, always rounding up or down and estimating distances, forces and moments to the nearest lyn, din, or lyn-din respectively.

For finding the centre of gravity of all the dwelling:

1.2.1.1. Approximated Method:

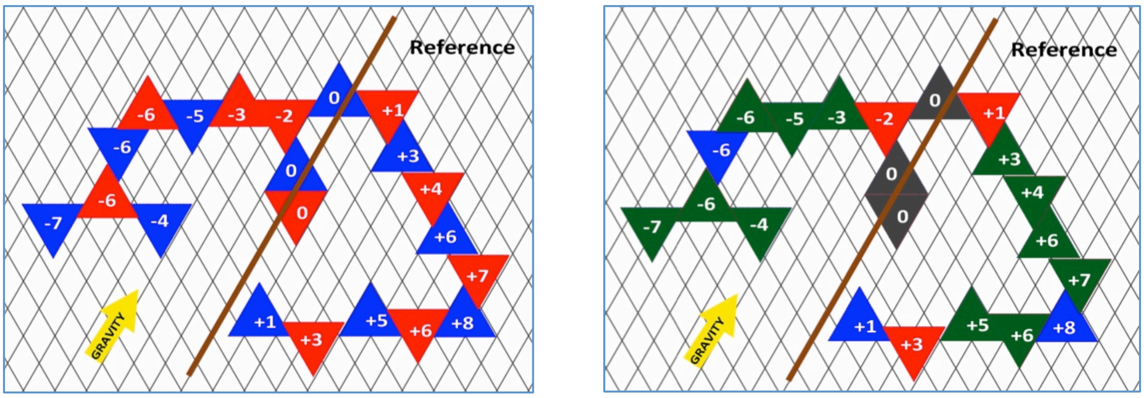
The center of gravity is the average (arithmetic mean) location of all the mass in a body or group of bodies. Place the CG using your expertise and criterion, first do it for one axis and then for the other. In that case the symmetries in the cluster can help.



1.2.1.2. Exact Method:

This method, as said above, is just going to be used in the final part of the game, when a final design has been chosen. Remember that the distances in the delta world are computed just taking care of the axis directions so it does not exist the concept of horizontal distance.

STEP 1 - Choose an approximately reference line near from the middle of your cluster (maybe you are lucky and you chose the line that crosses the CG as well). From that line to the right the distances are going to be"+", to the left are going to be "-".



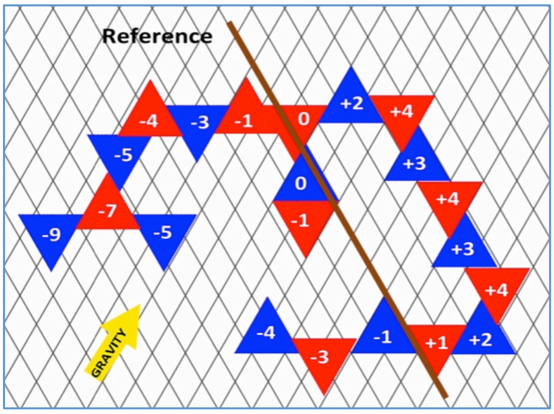
STEP 2 - Eliminate equidistant Deltas on both sides.

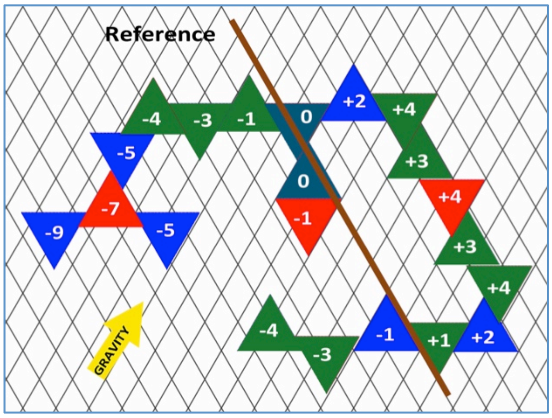
STEP 3 - Make the addition of the distances of the last remaining deltas and divide for the total number of Deltas of the cluster. Round off the result t the nearer whole number.

$$\frac{Addition}{Total\ Nº\ Deltas} = \frac{-6-2+1+1+3+8}{21} = 0{,}24\ lyn\ \approx 0\ lyn$$

STEP 4 - Define the CG. The number you found is the distance from your reference to the CG. In the example the reference line is at the same time the line of the CG.

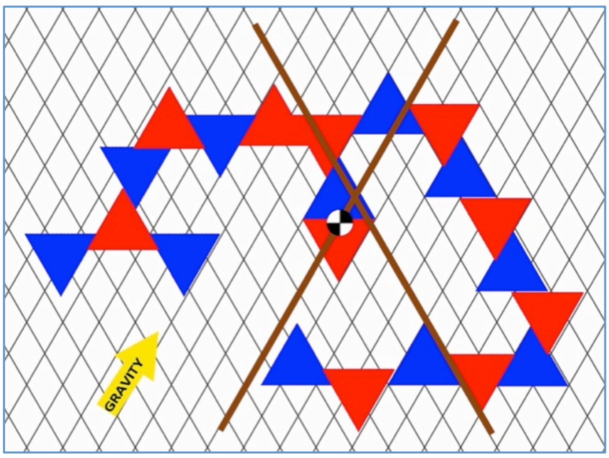
STEP5 - Repeat the process in the opposite axis.





$$\frac{Addition}{Total\ Nº\ Deltas} = \frac{-9-7-5-5-1-1+2+2+4}{21} = -\ 0{,}95\ lyn\ \approx -1\ lyn$$

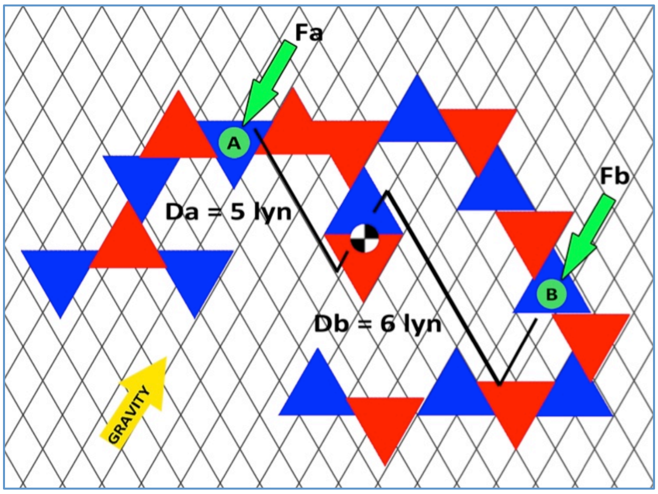
STEP 6 - Point the CG.



Obs: The difference between the approximated method and the exact method shouldn't differ more than 1 lyn in each axis.

1.2.2. The Anchor Support loads:

When you know approximately where is the CG is the moment to place the anchors. Each anchor can support as maximum 20 din of load so the biggest dwelling can be of 40 deltas. Use the next two equations to find the forces in the anchor A and in the anchor B. Realize that if the distance from the CG to the anchors is the same then the load is perfectly distributed.



$$Fa = Force\ in\ Anchor\ A \qquad Da = Distance\ from\ A\ to\ CG$$
$$Fb = Force\ in\ Anchor\ B \qquad Db = Distance\ from\ B\ to\ CG$$

$$\mathbf{Fa + Fb = Total\ N^{o}\ Deltas} \quad \rightarrow \quad \mathrm{Fa + Fb = 21\ din}$$

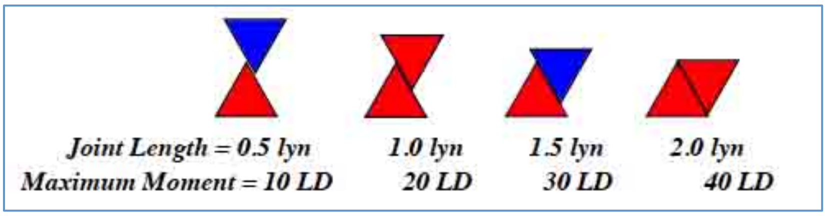
$$\mathbf{Fa = \frac{Db}{Da} \times Fb} \quad \rightarrow \quad \mathrm{Fa = \frac{6}{5}\ Fb}$$

For this example; Fa = 11,5 din Fb= 9,5 din

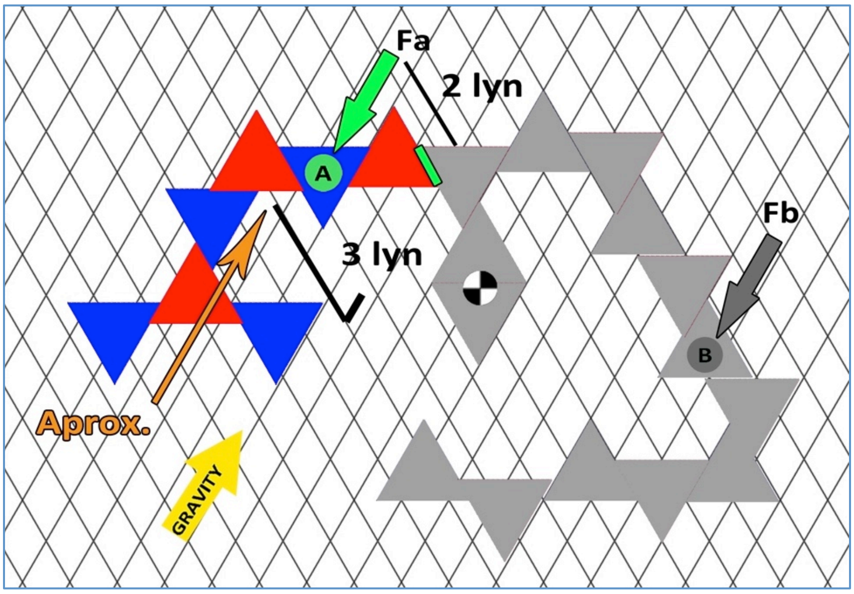
Realize that if a gravity wave occurs the distances are going to be in the opposite axis and the forces are going to change. **The best way to avoid the problems generate for the gravity changes is to place the anchors in the same distance from the CG in both directions** (If it is possible).

1.2.3. Internal Moments and Fastener Requirements.

Adjacent elements are held together by cement. The cement is necessary because otherwise the structure could not support the internal forces and moments, again due to gravitational loading. The internal moment is the most critical of these. Although the strength of the cement varies by supplier, your source has certified hers at **20 LD per lyn of contact**, resulting in the linear relationship between length and strength shown in the figure below.



To estimate the moment in the joint simply treat each joint as the boundary between two parts of the cluster. Choose the smallest one and calculate the momentum approximately following the next steps:



STEP 1 – Find approximately the line that could be the CG coordinate for the remaining deltas.

STEP 2 - Solve the next equation. (Take care because the anchor force factor has to appear only if the anchor is included in the remaining deltas set).

$$\textbf{Internal moment} = \textbf{Daprox.} \times \textbf{N}^{\underline{o}}\textbf{remaining Deltas} - \textbf{Fa} \times \textbf{Da}_{\textbf{joint}}$$

In the example;

$$\textbf{Internal moment} = \textbf{3 lyn} \times \textbf{7} - \textbf{11,5} \times \textbf{2 lyn} = -\textbf{2 lyn} * \textbf{din}$$

Realize that the joint studied in the example has an structural momentum really low, maybe during the design process we could suggest to use less cement there, the Project Manager would be grateful.

1.3. Thumb rules and simple analysis

With the next rules you are going to develop different solutions during the first stages of the design process. Remember, the exact calculations are just going to be done with the your team's final design. Be fast and practical; if any doubt appears ask to the tutors.

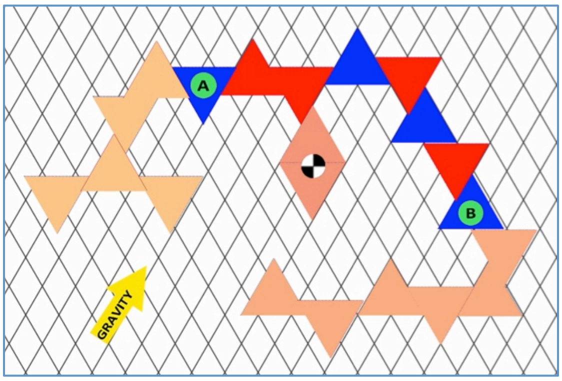
Preliminary Design Criteria:

- Place the CG using the approximate method.
- Place the anchors at the same distance of the centre of gravity in both directions if it is possible.
- The anchors have to divide the cluster in three similar parts.
- Suggest symmetries if it is possible.
- Rough evaluation of the critical joints.

Thumb rules:

This section is really important. The next rules are going to be used during the design process and are going to be provided to the architect who is going to develop the first dwellings' alternatives. The exact structure calculations are just going to be done for you so you are the responsible. Be fast and practical while calculating; if any doubt appears ask to the tutors. Be sure that the next rules are followed during the design process.

Free Branches → The free branches are those parts of the cluster that are not from the main skeleton (the main stream of Deltas between anchors). In the figure we can see three free branches.



Depending on the contact length in the branches we have a safety maximum of supported deltas in each branch. Placing more deltas than the safety number in a branch will imply the specific analysis of this one.

Contact Length	Load Capacity	Safety Supported Deltas
0,5 lyn	10 lyn*din	Max. 3 Deltas
1 lyn	20 lyn*din	Max. 5 Deltas
1,5 lyn	30 lyn*din	Max. 6 Deltas
2 lyn	40 lyn*din	Max. 7 Deltas

Project Manager – Specific Paper

1.1. Introduction

As project manager, **your main concerns are cost and schedule**, the interpretation and reconciliation of performance specifications, and negotiations with contractor and client. You want to keep costs and time-to-build at a minimum, but not at the expense of quality. When your team submits its final design, **you must report the cost and time that you estimate will be required to build it**. These estimates will be in zwigs (!) and wex, respectively.

As an experienced project manager, you know that all specifications are prone to slip during the conceptual design phase, and that budget and schedule, your specific responsibilities, are the most vulnerable. You have already realized that both are likely to be binding constraints, and further, that the Deltans are tight with a zwig and anxious to move in. Like clients everywhere, they desire a better residence then they can comfortably afford.

1.2. Project Manager Calculations

Your job of estimating project cost has been greatly simplified by finding a supplier-contractor that quotes material costs inclusive of delivery and most assembly charges. The cost schedules presented below for buying deltas and the cement needed to glue them together thus reflect near-final costs, with two important exceptions. One source of additional cost comes from the modular construction techniques used on DeltaP: material prices cover the labour cost to assemble deltas into modules, which is done at the factory, but not the on-site cost of positioning and joining these modules into the final structure. The second additional cost is overhead, which covers, among many other things, the cost of paying your design team.

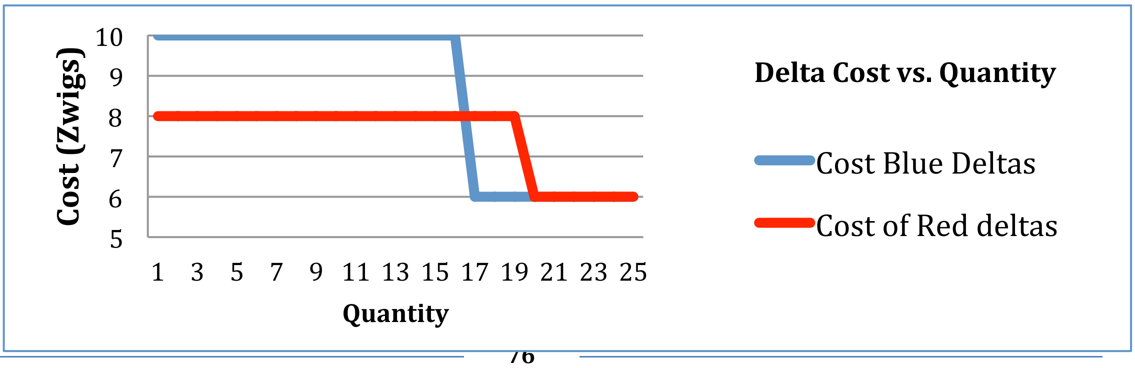
To estimate the cost of your team's design: figure the cost of the deltas used (Δcost), figure the cost of the cement needed to joint them (Ccost) and figure the number of modules and the cost to join them (Mcost), sum all these up and multiply by the overhead rate (K).

$$\boldsymbol{Total\ Cost = K\ x\ (\Delta cost + Ccost + Mcost)}$$

The overhead rate is a factor that can change during the game, it express the economic context in the DeltaP world, as it happens in the Earth the initial budged in one project is not always is realistic. As a starting point **take the K factor in 1,4**.

1.2.1. Deltas' Cost – Δcost

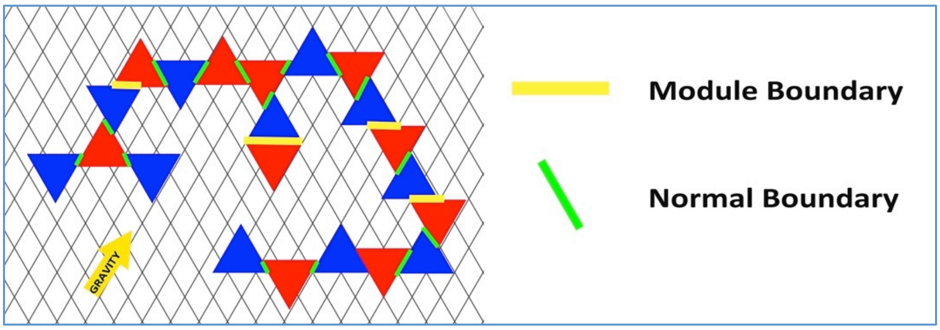
The cost of deltas varies by colour and quantity purchased. The price break for blue deltas is at 16 units: blues cost !10 apiece if fewer than 16 are purchased, !6 for 16 or more. The price break for red deltas is at 20 units: reds cost !8 each if fewer than 20 are purchased, !6 for 20 or more. These costs are shown in the next plot.



1.2.2. Cement Cost – Ccost & Module Cost - Mcost

You will need to purchase three different types of cement, at three different costs, to assemble deltas into your structure. Three types (RR,BB, and RB) are required because different types of joints require different types of cement. RR is the red-red binder needed to bond one red delta to another red delta. RB, the most expensive, is the red-blue binder that bonds a red delta to a blue delta. Finally, BB is the least expensive and bonds two blue deltas.

The construction of the dwelling will proceed in two stages. In the first stage, individual deltas are joined into modules. This takes place at the factory, where the supplier firm has developed jigs and fixtures that simplify the task, allowing them to accurately predict and therefore include the costs in the quoted prices for deltas. The individual modules into which a given structure will be decomposed and constructed at the factory are easy to identify, because the boundaries between them are defined by the orientation of the joints relative to gravity. To an earthly eye, any intersection of two deltas that runs left to right, across the page, is a module boundary. For example in the next figure we have a cluster with 5 modules; one of 4 deltas, 1 of 8, 1 of 1, 1 of 2 and 1 of 6 deltas.



When all modules are completed on the factory, they are transported to the site, joined together, and anchored to the plane. This on-site work is more difficult to cost out in advance, so the client will essentially have to pay whatever costs are incurred. Your experienced contractor, however, has told you that her rule of thumb for predicting them is to figure the cost of glue needed for the module-to-module joints and double it. The number of joints, their length and their orientation defines the costs of joining the cluster. Remember that the horizontal boundaries are the modules boundaries.

The following costs apply;

Cement Type	CCost (Zwigs/lyn)	Mcost (Zwig/lyn)
RB	20	40
RR	10	20
BB	5	10

1.2.3. Time to build

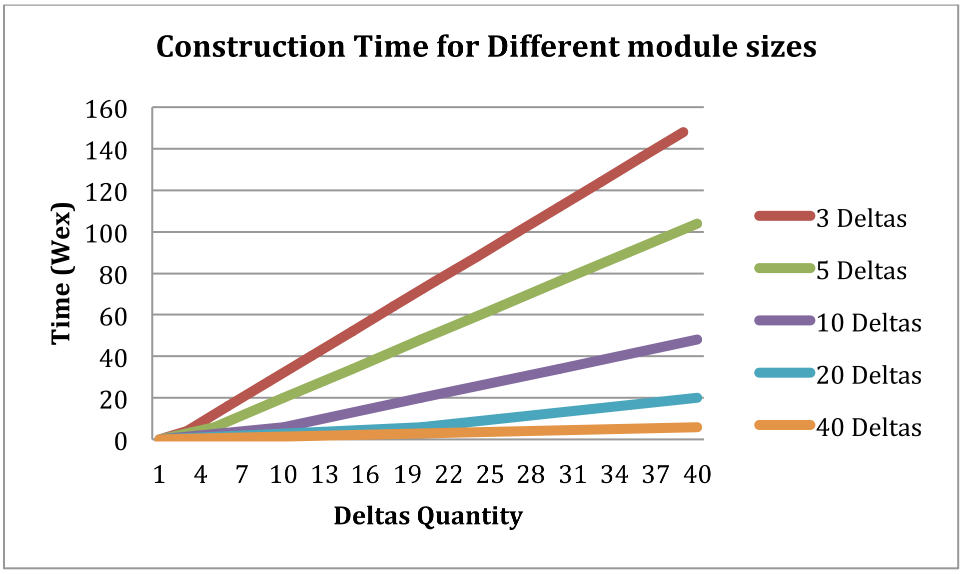
Estimating time-to-build is inexact, at best, but again your contractor has supplied some rules of thumb. Rough results are shown in the graph, but you will do better to figure them more precisely.

For each module consisting of three deltas or fewer, allow 2 wex;

For each module consisting of more than three deltas, allow 3 wex;

For each module-to-module joint, allow 4 wex;

Sum all of these up and double the result.



1.3. Thumb rules and simple analysis

The next rules are going to help you while developing different solutions during the first stages of the design process. Be fast and practical; if any doubt appears ask to the tutors.

Preliminary Design Criteria:

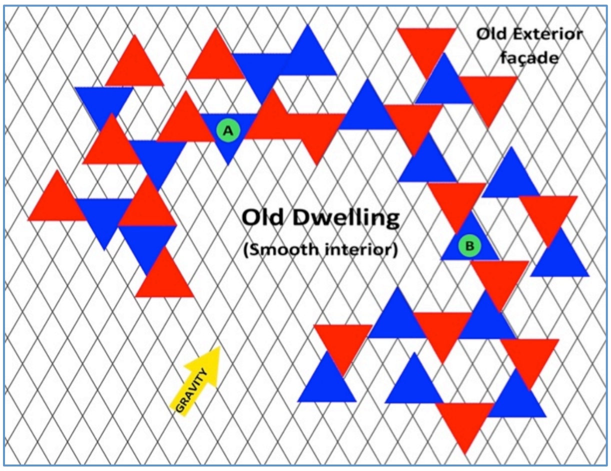
- Build modules as big as possible.
- Alternate BR joints with RR or BB
- Use more than 16 blue Deltas if possible.
- Use more than 20 red Deltas if possible.
- Make joints as short as possible.

Architect – Specific Paper

1.1 Introduction

As architect, your concern is with the intrinsic form and function of your team's design, as well as how it relates to the site. When your team submits its final design, you should be prepared to discuss how and why the Deltans will find the residence attractive and functional. You will also be asked to report some more quantitative architectural measures discussed below.

As simple as the fundamental building elements appear, quite complex, intricate and angular form can be composed out of deltas. As architect, it is your responsibility to create design that not only meets the clients' physical needs.



You imagine a form that, while rooted in tradition, suggests a reaching out toward the unknown. Tradition has valued the angular exterior facade. You want to experiment with the smooth exterior façade. In the figure an example of old design.

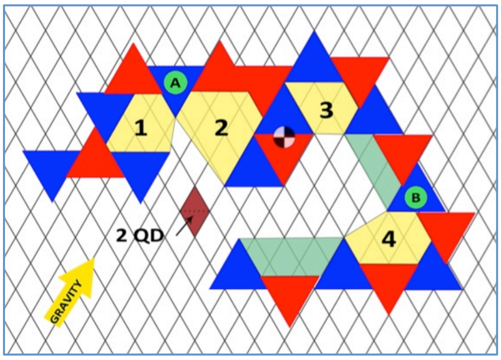
Coming more into vogue is the angular interior. There is some kind of reversal going on here. The interior traditionally has been made smooth, to maximize interaction and communication. Nowadays privacy has become a common word in architectural discourse. Actually your team challenge is to build a dwelling for six deltans. Thus, the house designed has to have;

- At least 3 small rooms suitable for an occupancy of two Deltans (>6 QD).

- At least 2 medium-sized spaces that all 6 Deltans can occupy at once (>10 QD).

- At least 1 large space to accommodate the Deltan family and guests (>16 QD).

In DeltaP the rooms are identified by the walls, a room has to have at least 4 walls. See in the next figure the rooms in yellow and in green spaces that can confuse but are not rooms.



While an argument can be made that the use of deltas to shape interior nooks and spaces is an inefficient use of this one resource, you think that this is an advanced point of view. Your clients want to go even further. They seem to want some kind of "fractal" interior not just one space with nooks but sub-spaces which themselves suggest nooks and crannies. This is all very fuzzy in your mind but you are keen to experiment and have started sketching. The desired rooms in the specifications can be a good starting point.

The single entrance/exit is conventionally aligned with the force field and "upstream" as viewed from outside; that is, one enters the cluster moving forward, in the direction of gravitational pull. This is so because Deltans are themselves subject to gravity. They have evolved over the many gigawex of their existence to the point where they now are able to manoeuvre in any direction without conscious attention to the force field. However, the entrance to most clusters is located so that the residents would fall into rather than out of the cluster if they were to lose this sense. This orientation is essential during passage of a gravity wave.

As noted in the description of the design task, your client is blue sensitive. While the allowable dosage of blue deltas in the environs is no set number, you conjecture that the blues ought not to constitute more than 60% of the elements. Dispersion of the blues is preferred as well, so that residents are not confronted with seemingly endless blue vistas when viewing the interior.

Although the Deltans will ultimately judge the quality of your work by stepping back and casting a critical eye at the overall design, they have also requested that you provide some simple measures of design quality. These measures, and the methods to use to figure them, are as follows:

Internal Area: Estimate the internal area (in QDs) by using the grid on the site map. Each diamond has an area of 2 QDs. (>100QD)

Blueness Ratio: Calculate the blueness of your design by figuring out how many of the deltas used are blue, expressed as a percentage of the total. [60,70]%

Blue Dispersion Ratio: Count the total number of joints between deltas where either or both are blue. Now count how many of these do not join two blues, and express the result as a percentage of the total. 100% would mean you had achieved perfect dispersion.

I/E Perimeter Ratio: Measure the interior and exterior wall lengths in lyns and divide the interior length by the exterior. Because a craggy wall will be longer than a smooth one, the higher this ratio is, the best you are doing. (>1)

1.2 Start Design

It is time to start with the design. You as architect are responsible for putting forward the initial configurations. Your role is the most creative so while the others are learning more about the technical specifications you have time to present different design alternatives. Try to find different options with different criteria; maybe you can play with symmetry in some designs and not in the others.

You know the constraints about the general design but your knowledge in the technical specifications is limited. To fill this gap below some "thumb rules" are exposed coming from the expertise of the other roles, follow them during the finding alternatives process, if you don't do it your work will be completely useless, probably then your dwellings will be too weak, to hot or too expensive.

Thumb Rules:

2. Never place 3 or more Deltas in a row in the same colour.

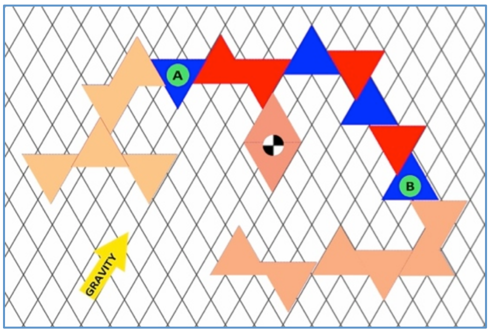
3. Never place 2 inward red deltas together.

4. Start with preliminary designs of around 25/30 Deltas.

    5. Free Branches:

    The free branches are those parts of the cluster that are not from the main skeleton (the main stream of Deltas between the green points, the anchors). In the figure we can see three free branches. Depending on the contact length in the branches we have a safety number of supported deltas in each branch. If you want you can place more deltas but then an specific analysis by the Structural engineer will have to be done.

Contact Length	Load Capacity	Safety Supported Deltas
0,5 lyn	10 lyn*din	Max. 3 Deltas
1 lyn	20 lyn*din	Max. 5 Deltas
1,5 lyn	30 lyn*din	Max. 6 Deltas
2 lyn	40 lyn*din	Max. 7 Deltas



APPENDIX B –Questionnaires Round 1 and Round 3

Delta Design Game Questionnaire – Round 1

Assessing Lean Product Development principle
of Set-Based Concurrent Engineering
Using a Design Game
Master Thesis

Group number:
Role:

Please rate the follow items on a scale of 0-9, with 9 being best.

Group Activity

The quality of your team's final Delta House Design.	0	1	2	3	4	5	6	7	8	9
Your performance as a design group.	0	1	2	3	4	5	6	7	8	9
The co-operation within the team.	0	1	2	3	4	5	6	7	8	9
Quantity of knowledge shared between members.	0	1	2	3	4	5	6	7	8	9
How well your team attempted to apply SBCE.	0	1	2	3	4	5	6	7	8	9
Late design changes.	0	1	2	3	4	5	6	7	8	9

Personal performance

Your performance as a team contributor.	0	1	2	3	4	5	6	7	8	9
House design quality just from the perspective of your role.	0	1	2	3	4	5	6	7	8	9
How easily you applied your knowledge during the game.	0	1	2	3	4	5	6	7	8	9
How well you shared your knowledge within the team.	0	1	2	3	4	5	6	7	8	9

Your knowledge of the four domains of expertise:

Architect	0	1	2	3	4	5	6	7	8	9
Thermal Engineering	0	1	2	3	4	5	6	7	8	9
Project Manager	0	1	2	3	4	5	6	7	8	9
Structural Engineer	0	1	2	3	4	5	6	7	8	9

Would you like to take another role in round two? Which one? ____________________

Delta Design Game

Activity explanation and clarity.	0	1	2	3	4	5	6	7	8	9
How much you learned during the game.	0	1	2	3	4	5	6	7	8	9
The ability to apply the tools and techniques of the course.	0	1	2	3	4	5	6	7	8	9

Use the back for comments. Thank you very much for your collaboration!

Delta Design Game Questionnaire – Round 3

Assessing Lean Product Development principle
of Set-Based Concurrent Engineering
Using a Design Game
Master Thesis

Group number:
Role:

Please rate the follow items on a scale of 0-9, with 9 being best.

Group Activity

The quality of your team's final Delta House Design.	0	1	2	3	4	5	6	7	8	9
Your performance as a design group.	0	1	2	3	4	5	6	7	8	9
The co-operation within the team.	0	1	2	3	4	5	6	7	8	9
Quantity and quality of knowledge shared between members.	0	1	2	3	4	5	6	7	8	9
How well your team attempted to apply SBCE.	0	1	2	3	4	5	6	7	8	9
Your response to the late design changes.	0	1	2	3	4	5	6	7	8	9

Personal performance

Your performance as a team contributor.	0	1	2	3	4	5	6	7	8	9
House design quality just from the perspective of your role.	0	1	2	3	4	5	6	7	8	9
How easily you applied your knowledge during the game.	0	1	2	3	4	5	6	7	8	9
Could you share your knowledge within the team?	0	1	2	3	4	5	6	7	8	9

Your knowledge of the four domains of expertise:

Architect	0	1	2	3	4	5	6	7	8	9
Thermal Engineering	0	1	2	3	4	5	6	7	8	9
Project Manager	0	1	2	3	4	5	6	7	8	9
Structural Engineer	0	1	2	3	4	5	6	7	8	9

Delta Design Game

Did you learn during the activity about the design process complexities?	0	1	2	3	4	5	6	7	8	9

Do you know something about Lean Product Development? ______________________

Rate the design process as a Lean Product Development process.	0	1	2	3	4	5	6	7	8	9

Materials Activity

The materials provided were correct	0 1 2 3 4 5 6 7 8 9
Did you feel lost during the game? Could you do your task?	0 1 2 3 4 5 6 7 8 9
Could you make fast iterations and analysis over the designs?	0 1 2 3 4 5 6 7 8 9
The game schedule was correct	0 1 2 3 4 5 6 7 8 9
If not, what would you change?	______________________
Rate the utility of:	
The PPT introduction	0 1 2 3 4 5 6 7 8 9
The written papers	0 1 2 3 4 5 6 7 8 9
The A3	0 1 2 3 4 5 6 7 8 9

Use the empty space below for comments. Thank you very much for your collaboration!

APPENDIX C – Questionnaires Results Table

	Session 1														Session 3											
	Group 1				Group 2				Group 3				Total S1		Group 1						Group 2					
	A	PM	SE	TE	A	PM	SE	TE	A	PM	SE	TE	S1	σ2 S1	A	PM	SE	TE	G1	σ2 S3G1	A	PM	SE	TE	G2	σ2 S3G2
Group Activity																										
The quality of your team's final Delta House Design.	8	8	7	5	4	6	7	5	8	-	-	3	6,10	1,79	7	7	7	8	7,25	0,50	7	-	7	6	6,67	0,58
Your performance as a design group.	8	8	6	7	3	7	6	7	2	-	-	1	5,50	2,55	6	7	7	6	6,50	0,58	9	-	7	7	7,67	1,15
The co-operation within the team.	5	7	6	8	3	8	7	8	2	-	-	4	5,80	2,20	6	7	6	7	6,50	0,58	9	-	7	6	7,33	1,53
Quantity and quality of knowledge shared between members.	3	5	5	6	4	5	4	3	2	-	-	2	3,90	1,37	6	7	5	7	6,25	0,96	9	-	5	6	6,67	2,08
How well your team attempted to apply SBCE.	0	5	2	1	2	3	1	1	0	-	-	0	1,50	1,58	7	3	5	5	5,00	1,63	6	-	3	5	4,67	1,53
Your response to the late design changes.	3	1	2	0	2	2	2	2	4	-	-	0	1,80	1,23	5	6	7	5	5,75	0,96	7	-	4	7	6,00	1,73
Personal performance																										
Your performance as a team contributor.	6	8	2	7	4	6	3	6	3	-	-	0	4,50	2,51	6	6	5	6	5,75	0,50	7	-	4	5	5,33	1,53
House design quality just from the perspective of your role.	8	9	1	5	6	4	7	6	6	-	-	2	5,40	2,50	6	6	5	7	6,00	0,82	9	-	5	7	7,00	2,00
How easily you applied your knowledge during the game.	8	8	1	7	3	6	7	5	8	-	-	0	5,30	2,98	5	6	4	7	5,50	1,29	8	-	1	5	4,67	3,51
Could you share your knowledge within the team?	6	8	1	7	4	5	2	2	2	-	-	0	3,70	2,71	7	7	6	7	6,75	0,50	8	-	6	6	6,67	1,15
Your knowledge of the four domains of expertise:																										
Architect	8	2	6	5	6	3	3	2	8	-	-	0	4,30	2,71	8	5	3	3	4,75	2,36	9	-	4	6	6,33	2,52
Thermal Engineering	5	1	6	9	2	2	2	5	1	-	-	3	3,60	2,59	4	2	3	6	3,75	1,71	8	-	4	8	6,67	2,31
Project Manager	3	9	8	4	3	8	2	2	2	-	-	0	4,10	3,11	6	8	3	4	5,25	2,22	8	-	4	5	5,67	2,08
Structural Engineer	2	1	1	4	1	2	8	2	1	-	-	0	2,20	2,30	5	2	6	4	4,25	1,71	7	-	7	5	6,33	1,15
Average of knowledge od other domains													2,58	1,93					3,67	1,23					5,67	1,66
Average of own domain													6,5	2,72					7	1,15					8	1,00
Delta Design Game																										
Activity explanation and clarity	6	7	3	4	6	6	7	3	7	-	-	5	5,40	1,58												
How much did you learn during the activity	5	4	7	3	4	4	3	4	7	-	-	0	4,10	2,02												
The ability to apply the tools and techniques of the course	4	2	3	3	3	3	7	2	7	-	-	5	3,90	1,85												
Did you learn during the activity about the design process complexities?															9	7	7	7	7,50	1,00	8	-	7	5	6,67	1,53
Do you know something about Lean Product Development?															yes	yes	yes	yes			yes	-	yes	yes		
Rate the design process as a Lean Product Development process.															5	3	5	4	4,25	0,96	6	-	5	5	5,33	0,58
Materials Activity																										
The materials provided were correct															7	8	6	7	7,00	0,82	8	-	7	5	6,67	1,53
Did you feel lost during the game? Could you do your task?															7	7	7	7	7,00	0,00	8	-	8	6	7,33	1,15
Could you make fast iterations and analysis over the designs?															5	4	3	7	4,75	1,71	9	-	1	5	5,00	4,00
The game schedule was correct															5	6	4	8	5,75	1,71	9	-	5	4	6,00	2,65
If not, what would you change?																										
Rate the utility of:																										
The PPT introduction															8	5	5	7	6,25	1,50	4	-	7	4	5,00	1,73
The written papers															8	7	7	8	7,50	0,58	9	-	7	6	7,33	1,53
The A3															5	1	7	6	4,75	2,63	7	-	7	6	6,67	0,58

	Session 3		Comparing	
	Tot S3	σ2 S3	S1 vs. S2	S3G1 vs. S3G2
Group Activity				
The quality of your team's final Delta House Design.	7,00	0,58	0,90	-0,58
Your performance as a design group.	7,00	1,00	1,50	1,17
The co-operation within the team.	6,86	1,07	1,06	0,83
Quantity and quality of knowledge shared between members.	6,43	1,40	2,53	0,42
How well your team attempted to apply SBCE.	4,86	1,46	3,36	-0,33
Your response to the late design changes.	5,86	1,21	4,06	0,25
Personal performance				
Your performance as a team contributor.	5,57	0,98	1,07	-0,42
House design quality just from the perspective of your role.	6,43	1,40	1,03	1,00
How easily you applied your knowledge during the game.	5,14	2,27	-0,16	-0,83
Could you share your knowledge within the team?	6,71	0,76	3,01	-0,08
Your knowledge of the four domains of expertise:				
Architect	5,43	2,37	1,13	1,58
Thermal Engineering	5,00	2,38	1,40	2,92
Project Manager	5,43	1,99	1,33	0,42
Structural Engineer	5,14	1,77	2,94	2,08
Average of knowledge od other domains	4,20	2,31	1,62	2,00
Average of own domain	7,42857143	1,13	0,93	1,00
Delta Design Game				
Activity explanation and clarity				
How much did you learn during the activity				
The ability to apply the tools and techniques of the course				
Did you learn during the activity about the design process complexities?	7,14	1,21		-0,83
Do you know something about Lean Product Development?				
Rate the design process as a Lean Product Development process.	4,71	0,95		1,08
Materials Activity				
The materials provided were correct	6,86	1,07		-0,33
Did you feel lost during the game? Could you do your task?	7,14	0,69		0,33
Could you make fast iterations and analysis over the designs?	4,86	2,61		0,25
The game schedule was correct	5,86	1,95		0,25
If not, what would you change?				
Rate the utility of:				
The PPT introduction	5,71	1,60		-1,25
The written papers	7,43	0,98		-0,17
The A3	5,57	2,15		1,92

APPENDIX D – Practical exercises Round 1 and Round 3

Exercises Round 1:

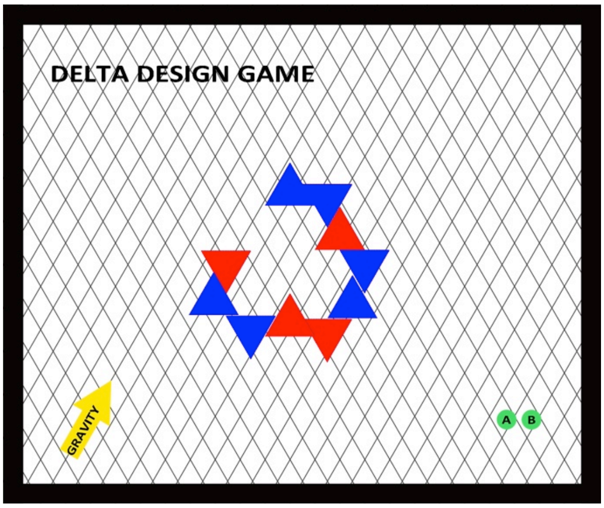
THERMAL ENGINEERS LEARNING EXERCICE:

Evaluate the next two structures following the thermal rules of Delta World.

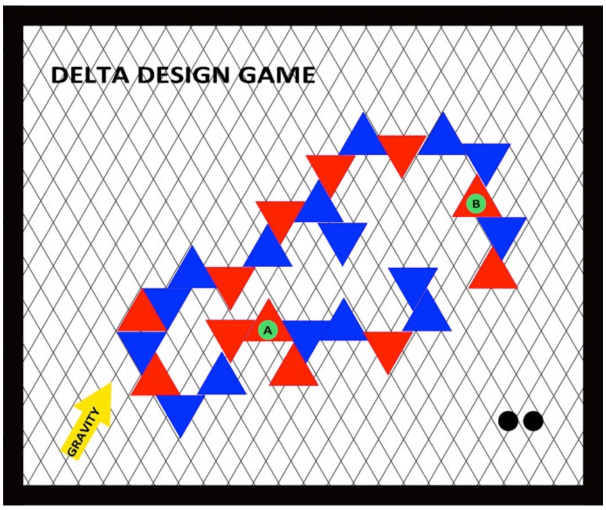
Find the average Temperature of the radiating deltas (T*), the temperature of the interior deltas and the average temperature of the entire cluster in the next two preliminary designs.

Are any of the designs not valid? Why?

Ex1)



Ex 2)



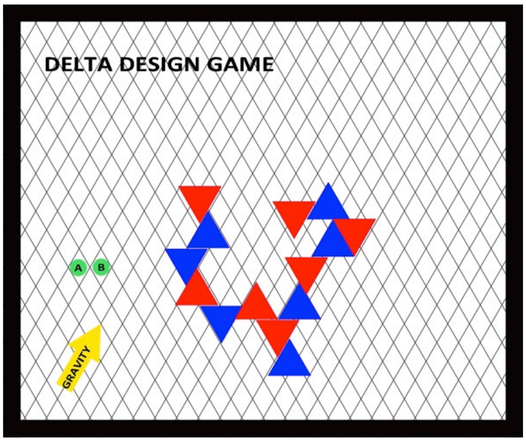
T*=43,6 OK

STRUCTURAL ENGINEERS LEARNING EXERCICE:

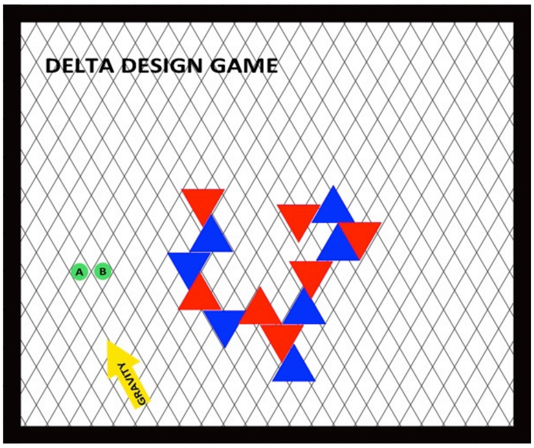
Evaluate the next two structures following the gravity rules of Delta World.

Identify the cluster load. Decide where to put the anchors (A and B) in each exercise and find the weaker points in the structures. The results of each exercise will change depending on your decisions so try to experiment and make questions if needed.

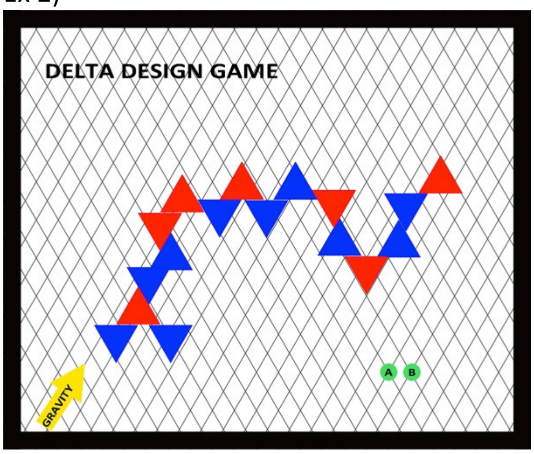
Ex 1.1)



Ex 1.2)

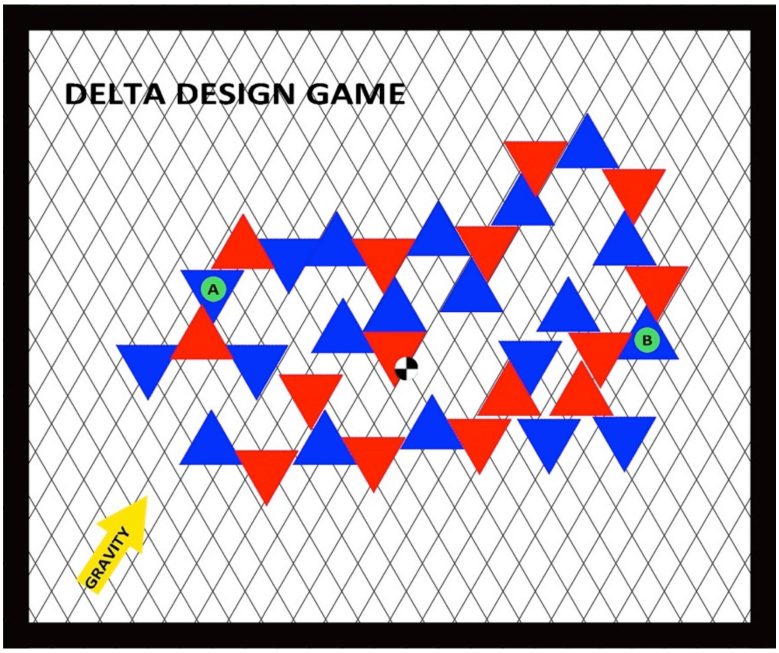


Ex 2)



PROJECT MANAGERS LEARNING EXERCICE:

Evaluate the total cost of the next structure with the Delta World rules.

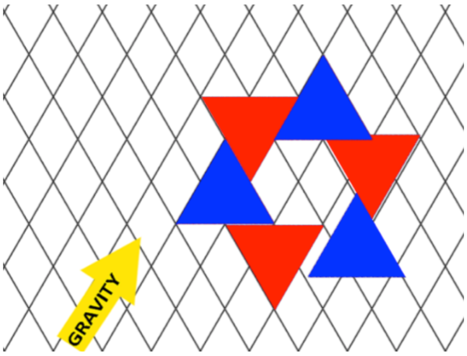


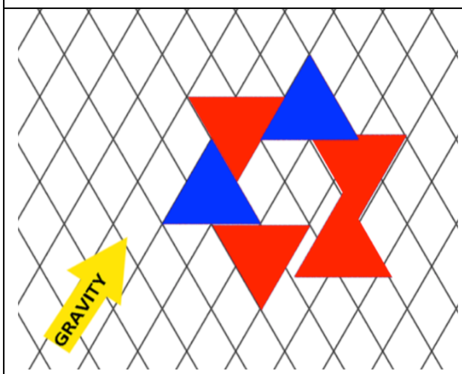
Exercises Round 3

THERMAL ENGINEERS LEARNING EXERCISES:

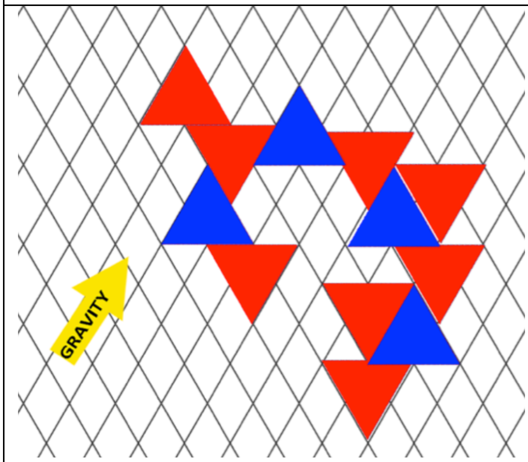
Evaluate the next structures following the thermal rules of Delta World.

Find the average Temperature of the radiating deltas (T*), the temperature of the interior deltas if needed, and the average temperature of the entire cluster. State if the clusters are well designed and if not suggest solutions.

Exercice 1	**Calculation:**	
		
	Results: **NOK**	Lout= 17 T*= 28,3 T = 28,36 Nn

Exercice 2:	**Calculation**	
		
	Results: **NOK**	Lout=17 T*= 37,6 Nn T= 37,6 Nn

Exercice 3

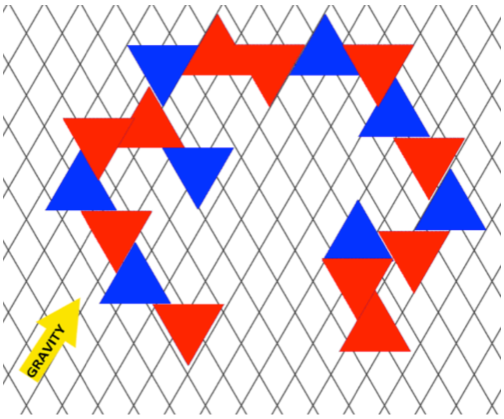


Calculation:

Results:
OK

Lout=29
T*= 44,1 Nn
Ti2=84,13 Nn Ti3=70 Nn
T= 50,2 Nn

Exercice 4:

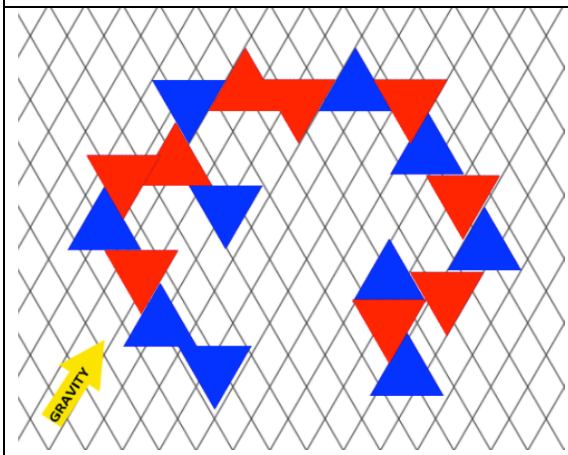


Calculation:

Results:
NOK

Lout=32
T*= 55
Ti1 = 95 Ti2=81,7 Nn
T = 62,7 Nn

Exercice 5: Removing 2 Red Deltas



Calculation:

Results:
OK

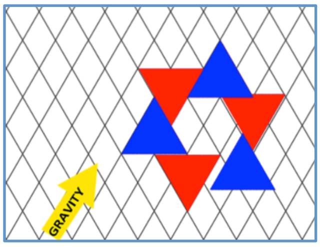
Lout=32
T*= 45
Ti1 = 85 Ti2=71,7 Nn
T = 52,7 Nn

STRUCTURAL ENGINEERS LEARNING EXERCICE:

Evaluate the next two structures following the gravity rules of Delta World.

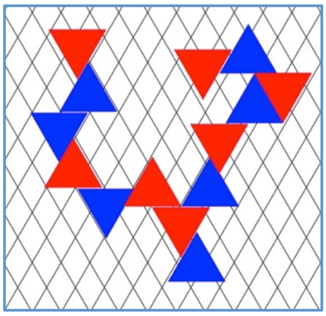
Exercise 1: Identify the cluster load. Place the anchors and identify their load**.**

Calculation:



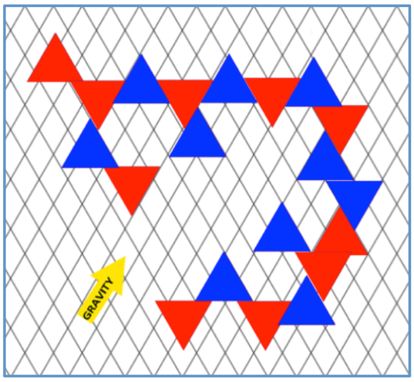
Exercise 2: Do the same as in the first exercise and the fast analysis of each joint starting on the left and clockwise.

Calculation:



Exercise 3: Same as in the second exercise.

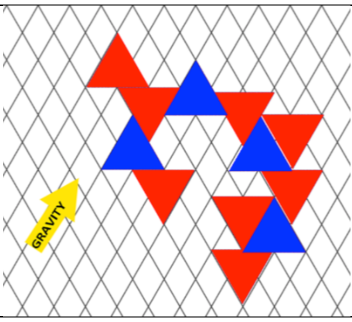
Calculation:



PROJECT MANAGERS LEARNING EXERCICE:

Evaluate the total cost and the lead time of the next structures with the Delta World rules.

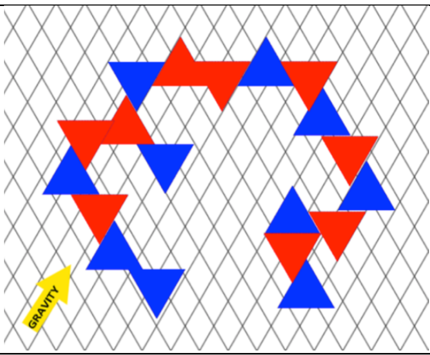
Exercice 1



Calculation:

Results: OK	Tcost= !579,6 Ttime= 54 wex

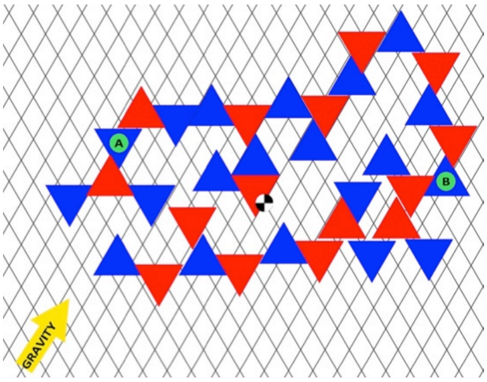
Exercice 2



Calculation:

Results: OK	Tcost=!814,8 Ttime=78wex

Exercice 2



Calculation:

Results: OK	Tcost=!1295 Ttime= 132 wex

APPENDIX E – Original "Rules of Thumb"

Structural Engineers:

1. Mirror design, symmetric for gravity.
2. Anchor on the same distance from centre of gravity.
3. Three equal parts for the anchors to supports

Thermal Engineers:

1. Never more than two elements in a row in the same colour.
2. Red inward-blue outward.
3. Inward reds needs a large contact surface.

Project Managers:

1. Very expensive if we have horizontal joints. ("Means new module").
2. Expensive to joint deltas with different colours.
3. Blues are very expensive when they are less than 16.
4. Red deltas are expensive when they are less than 20.
5. Try to build "modules" as big as possible. (No or few horizontal joints)
6. Joints as short as possible.

Architect:

1. Circular shape
2. Every second delta: blue/red.
3. Symmetry favourable
4. Large entrance favourable.

APPENDIX F – A3 Reports

A3 - Thermal Eng.

Thermal Concepts --- Temp. Radiating Deltas = T*
Temp. Interior deltas = Ti
Global Temp = T

Responsibilities:

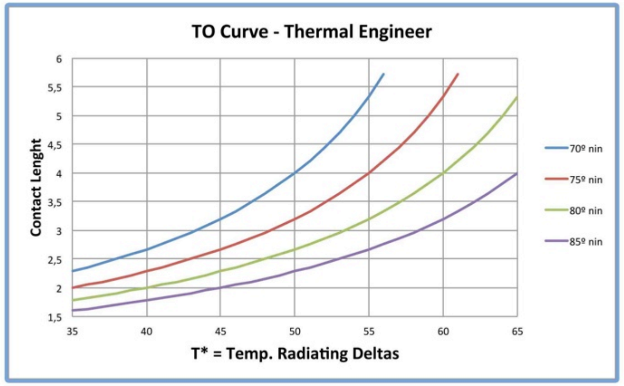
- Keep average temperature acceptable
- Avoid hot and cold points.

Evaluation Parameters:

- Average internal temperature
- Maximum Temparature

Thumb rules:

1. **Never 3 or more elements in a row in the same colour**
2. **Never 2 inward reds together**
3. **Inward reds need a large contact surface, minimum 1,5 lyn.**



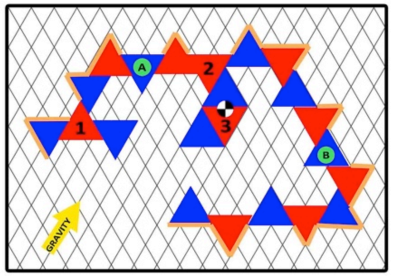
Calculations:

$$T^* = \frac{N_{red} \times 160}{L_{out}} \quad [20,85]º \text{ Nn}$$

$$T_i = \frac{80}{L_{con}} + T^* \quad [20,85]º \text{ Nn}$$

$$T = \frac{(T^* x\,(Nrred + Nb)) + (T_{i1} + T_{i2} \ldots)}{N} \quad [55,65]º \text{ Nn}$$

Example:



$$T^* = \frac{10 \times 160}{31} = 51,61 \qquad T_1 = \frac{80}{2,5} + 51.6 = 83,6º\,Nn$$

$$T_2 = \frac{80}{3} + 51,6 = 78,3º\,Nn \qquad T_3 = \frac{80}{4} + 51,6 = 71,6º Nn$$

$$T = \frac{(51,6\,x\,(7+12)) + (83,6 + 78,3 + 71,6)}{22} = 55,2º Nn$$

A3 - Architect & Proj.Manager

Structural Concepts --- Center of Gravity - CG
Anchor - A & B
Momentum - lin*din

Responsibilities:

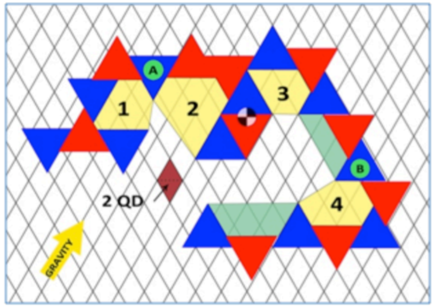
- House form Aesthetic
- First Designs

Evaluation Parameters:

- Internal Area (>100QD)
- Blueness parameter [60,70]%
- Blue dispersion
- I/E Ratio (>1)

Thumb rules:

1. **Alternate Red Deltas with Blue Deltas if possible**
2. **Internal area >100QD**
3. **One big entrance.**
4. **Dwelling for 6 inhabitants.**
    a. **At least 3 small rooms for two Deltans. (>6 QD)**
    b. **At least 2 medium-sized spaces (>10QD)**
    c. **At least 1 large space to accommodate guests. (>16QD)**

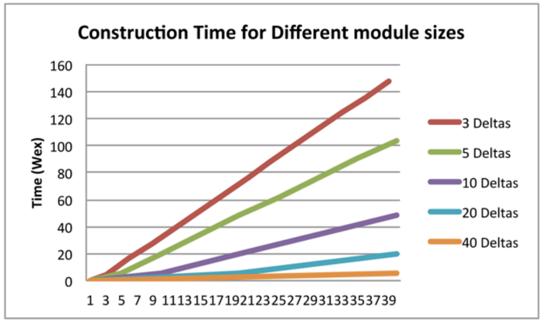


Responsibilities:

- Minimum Cost
- Minimum lead time

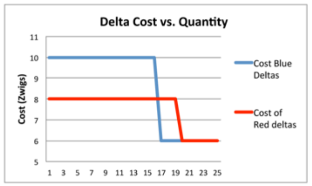
Thumb rules:

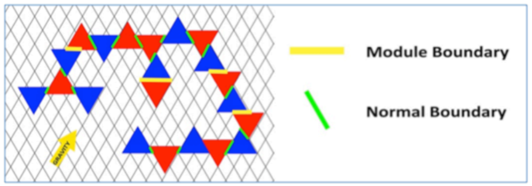
1. **Build modules as big as possible.**
2. **Alternate BR joints with RR or BB**
3. **Use more than 16 blue Deltas if possible.**
4. **Use more than 20 red Deltas if possible.**
5. **Make joints as short as possible.**



Evaluation Parameters:

$$\text{Total COST} = \text{K x } (\Delta\text{'s Cost} + \text{Cement Cost} + \text{Module Cement Cos})$$





Cement Type	CCost (Zwigs/lyn)	Mcost (Zwig/lyn)
RB	20	40
RR	10	20
BB	5	10

A3 - Structural Eng.

Structural Concepts --- Center of Gravity - CG
Anchor - A & B
Momentum - lyn*din

Responsibilities:

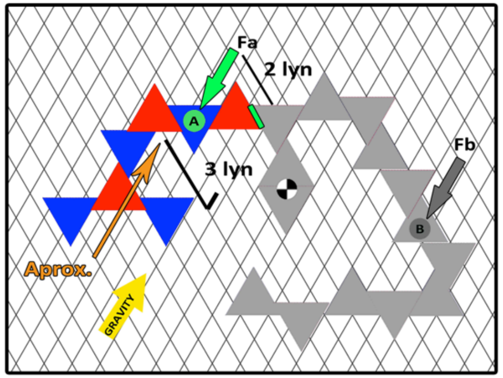
- Prevent the structure to collapse.
- Define the anchor points

Evaluation Parameters:

- Maximum load at anchor points
- Maximum internal moment for all the joints
- % of failing joints

Rough calculations:

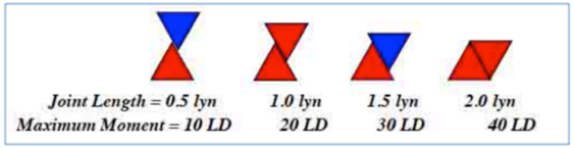
$$IM = Daprox. \times Nºremaining\ Deltas - Fa \times Da\_joint$$
$$IM = 3\ lyn \times 7 - 11{,}5 \times 2\ lyn = -2\ lyn * din$$

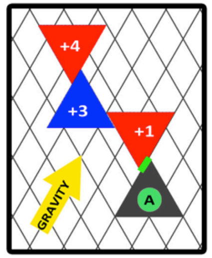


Thumb rules:

1. Anchors at the same distance of the center of gravity
2. Three equal parts for the anchors to support.
3. Make the cluster as more simetric as possible.
4. Strong joints
5. Free Branches:

Contact Length	Load Capacity	Safety Supported Deltas
0,5 lyn	10 lyn*din	Max. 3 Deltas
1 lyn	20 lyn*din	Max. 5 Deltas
1,5 lyn	30 lyn*din	Max. 6 Deltas
2 lyn	40 lyn*din	Max. 7 Deltas





Internal momentum analysis:

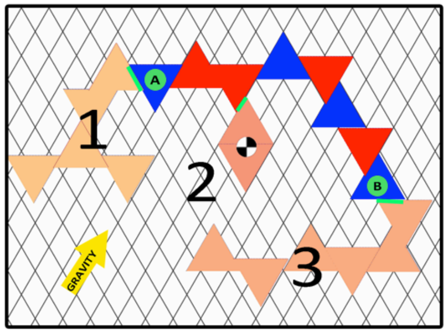
+8 lyn*din < 10 lyn*din

OK!

Aprox. Momentum Joint 1 = 5 lyn*din

Arpox. Momentum Joint 2 = 2 lyn*din

Aprox. Momentum Joint 3 = 18 lyn*din



A3 - Roles' Conflicts

The next table summarizes and contrast your team's roles interests. It has to be useful to solve conflicts and to know how your particular interests can affect to the general design, so to the final success.

		Conflicts			
Role	Role Interests – "Rules of Thumb"	Structural Engineer	Project Manager	Architect	Thermal Engineer
Structural Engineer	Strong Joints		Increase Cost	Constraint Design	Better Conduction
	Free Branches Control		Optimize Cost		
	Symmetrical Cluster Concept			Constraint Design	
Project Manager	Modules As Big as Possible	Higher momentum		Constraint Design	
	Blue-Blue and Red-Red Joints			Blue dispersion ratio	Never more than two in a row
	Use more than 16 Blue Deltas			Blueness ratio	Low Temperature
	Use more than 20 Red Deltas				High Temperature
	Short Joints	Colapse possibility			Bad Conduction
Architect	Alternate Red with Blue Deltas		Increase Cost		Reduce Hot Spots
	Internal area >100 QD	More branches More Analysis			
	Big Entrance	More branches More Analysis			
	Dwelling Spaces	More branches More Analysis			Control Inward Deltas
Thermal Engineer	Never 3 in a row same colour		Increase Cost	Ok. Alternate colours	
	Never two red inward together		Increase Cost	Ok. Alternate colours	
	Large Contact for red inwards	Better joints	Increase Cost	Constraint Design	