Aproximación Metaheurística a la Optimización de Estructuras de Acero. Beijing National Aquatics Center, el WaterCube.

Metaheuristic Approach to Steel Structures Optimization. Beijing National Aquatics Center, the WaterCube.

Aproximació Heurística a l'Optimització d'Estructures d'Acer. Beijing National Aquatics Center, el WaterCube.

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SUPERVISOR: AGUSTIN PEREZ GARCIA (UPV);

MASTER'S DISSERTATION SUBMITTED IN ORDER TO OBTAIN THE ACADEMIC DEGREE OF MASTER OF SCIENCE IN DE INDUSTRIËLE WETENSCHAPPEN: BOUWKUNDE

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Metaheuristische Benadering van de Optimalisatie van een Staalconstructie. Beijing National water centrum, de WaterCube.

Michael Goethals

Supervisor: Agustin Perez Garcia (UPV); Anthony Tetaert (UGent);
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Preface

In front of you lays my Thesis " Metaheuristic Approach to Steel Structures Optimization. Beijing National Aquatics Center, the WaterCube.". This paper was written as part of my studies as Construction Engineer at the University of Ghent. I had the opportunity of making my final project abroad. For me, this was a great chance to learn more about the education system in another country and to find myself in another culture.

Together with my supervisor, Agustin Perez Garcia, we created the main goal of this thesis. After doing the required research and making different drawings and calculations, I was able to complete the main task of my subject. During this time my supervisor, Agustin Perez Garcia and my professors from my home university, Anthony Tetaert and Kathleen Gekiere, always there for me. They answered all my questions with a solid and clear answer, so I could continue with the progress of my project. I also want to thank the whole UPV community for giving me this opportunity.

By this I want to thank my coaches and all the companies that I contacted for their fine guidance and support during the process of my thesis. Without their support I would not have been able to complete this project.

Also, my friends and family who gave me wise counsel. In specific, Carmina Henzler Carrascal, for her help and aid during the writing and correcting of my thesis.

I hope you enjoy reading.

Goethals Michael

Belgium, May 31, 2019

Abstract

Español;

Los algoritmos metaheurísticos se han aplicado durante décadas para optimizar muchos aspectos de las estructuras de ingeniería de edificios. Estos procedimientos de búsqueda frecuentemente involucran la simulación de procesos naturales para diseñar la estructura tan eficientemente como lo hace la Naturaleza. La técnica de optimización evolutiva más conocida y utilizada con más frecuencia, los algoritmos genéticos (AG), se inspiró en los principios de Darwin sobre selección natural, genética y evolución, y simula el comportamiento de reproducción observado en las poblaciones biológicas. La optimización de enjambre de partículas (PSO) es otro método de optimización estocástica motivado por el comportamiento social de la bandada de aves y la escolarización de peces. La optimización de colonias de hormigas (ACO) es una técnica de búsqueda cooperativa que imita el comportamiento de forrajeo de las colonias de hormigas de la vida real para establecer rápidamente la ruta más corta de una fuente de alimento a su nido y viceversa. El método de búsqueda de sistema cargado (CSS) utiliza las leyes vigentes de la física y la mecánica. Las leyes de electrostática y las leyes de mecánica newtoniana impulsan el proceso de búsqueda de la configuración óptima del sistema. Sin embargo, a veces la analogía se deriva de comportamientos o fenómenos humanos o sociales. El algoritmo de competencia imperialista (ACI) es un procedimiento motivado sociopolíticamente que se aplica con frecuencia para resolver problemas de optimización estructural. El mapeo aéreo de vastos territorios (VTAM, por sus siglas en inglés) es un algoritmo inspirado en el levantamiento aéreo del paisaje con fines de caracterización orográfica.

La tesis de máster se dedicará a la introducción de los enfoques metaheurísticos mencionados anteriormente y se aplicará para resolver casos prácticos relacionados con la optimización estructural de ingeniería de edificios. Cada estudio de caso se definirá específicamente para cada estudiante de máster, siendo el algoritmo VTAM (implementado en el grupo de cómputo de la Universitat Politècnica de València) la principal herramienta de investigación. En este caso, el edificio estudiado será el Beijing National Aquatics Center, conocido como el Water Cube.

optimización; estructuras; acero; heurística

English:

Metaheuristic algorithms have been applied for decades to optimize many aspects of building engineering structures. These searching procedures frequently involve the simulation of natural processes to design the structure as efficiently as the nature does. The most well-known and frequently used evolutionary optimization technique, genetic algorithms (GAs), was inspired from Darwin's principles about natural selection, genetics and evolution, and mimics the reproduction behavior observed in biological populations. Particle swarm optimization (PSO) is another stochastic optimization method motivated from the social behavior of bird flocking and fish schooling. Ant colony optimization (ACO) is a cooperative search technique that mimics the foraging behavior of real-life ant colonies to rapidly establish the shortest route from a food source to their nest and vice versa. Charged system search (CSS) method utilizes the governing laws of physics and mechanics. Electrostatics laws and Newtonian mechanics laws drive the searching process of the optimum configuration of the system. However, sometimes the analogy derives from human or social behaviors or phenomena. The imperialist competitive algorithm (ICA) is a socio-politically motivated procedure frequently applied to solve structural optimization problems. Vast territories aerial mapping (VTAM) is an algorithm inspired by the aerial survey of the landscape for orographic characterization purposes.

The Master Thesis will be devoted to introducing the abovementioned metaheuristic approaches and will be applied to solve practical cases related to building engineering structural optimization. Each case study will be defined specifically for each master student, being the VTAM algorithm (implemented in the computation cluster of the Universitat Politècnica de València) the main research tool. In this case the building to be analyzed will be the Beijing National Aquatics Center, el Water Cube.

optimisation; structures; steel; heuristic

Nederlands:

Metaheuristische algoritmen en processen worden al eeuwen toegepast om vele aspecten van bouwkundige constructies te optimaliseren. Deze optimalisatieprocedures zullen vaak een simulatie zijn van natuurlijke processen om zo de structuur net zo efficiënt te ontwerpen als de natuur ontworpen is. De meest bekende en vaakst gebruikte optimalisatietechniek zijn; genetische algoritmen (GA's), GA’s zijn geïnspireerd op de principes van Darwin, meer specifiek over de natuurlijke selectie, genetica en evolutie. Alsook zal de groei in het reproductiegedrag in biologische populaties worden waargenomen. Particle Swarm Optimization (PSO) is een stochastische optimalisatiemethode die gebaseerd is op het sociale gedrag van vogel groepen en visscholen. Ant-Colony Optimization (ACO) is een zoektechnologie die het foerageergedrag van mierkolonies in het echte leven nabootst om snel de kortste route van een voedselbron naar hun nest te bepalen en omgekeerd. Charged system search (CSS) maakt gebruik van de geldende wetten van de natuurkunde en mechanica. Elektrostaticawetten en Newtoniaanse Mechanica wetten zijn de basis van het zoekproces voor de optimale configuratie van het systeem. Hoe dan ook, soms komt de analogie voort uit menselijk gedrag of sociaal gedrag en fenomenen. De imperialist competitive algorithm (ICA) is een sociaal-politiek gemotiveerde procedure die vaak wordt toegepast om structurele optimalisatieproblemen op te lossen. Vast territories aerial mapping (VTAM) is een algoritme dat is geïnspireerd op het luchtfoto-onderzoek van het landschap voor doeleinden met betrekking tot orografische karakterisering.

De Master Thesis zal gewijd zijn aan het introduceren van de bovengenoemde metaheuristische benaderingen en zal worden toegepast om praktische gevallen op te lossen met betrekking tot optimalisatie van de structuur van gebouwen gebaseerd op staal. Elke case study zal specifiek worden gedefinieerd voor elke masterstudent, zijnde het VTAM-algoritme (geïmplementeerd in het rekencluster van de Universiteit Politècnica de València), de belangrijkste onderzoekstool. In dit geval zal het te analyseren gebouw het Beijing National Aquatics Centre, el Water Cube, zijn.

optimalisatie; structuren; staal; heuristisch

List of symbols

K_m	Material cost of steel	Euro/kg
ρ	Density of steel	Kg/m3
V_{el}	Volume of the elements	m3
$C_{welding}$	Consumption welding	
$C_{weld,manufact}$	Consumption manufacturing	
$C_{weld,material}$	Consumption welding material	
$C_{assembly}$	Consumption assembly	
k_{weld}	Cost factor of the weld	Euro/h
f_{weld}	Welding factor (increases welding arc time)	
a_w	Size of the weld	cm
L_w	Lenght of fillet welds	m
$M_{weld,i}$	Material consumption welding (electrode, wire)	Kg
$C_{cutting}$	Consumption of cutting	
$C_{cut,manufact}$	Consumption of manufacturing during cutting	
$C_{cut,material}$	Consumption of material during cutting	
$C_{plate\ \text{handling}}$	Consumption plate handling during cutting	
$C_{painting}$	Consumption painting	
A_{pl}	Area that needs to be painted	m2
k_{paint}	Cost factor of the paint	euro/h
T_{paint}	Time consumption laying in the paint	Min/m^2
$k_{m.paint,i}$	Price per square meter paint	Euro/m^2
$M_{paint,i}$	Paint consumption	Kg
A_p	Area of elements	m2
$C_{transportation}$	Consumption transportation	
K_{transp}	Price for transportation manner	Euro
V_{struct}	Volume of the structure	m3
W(k)	Characteristic value of wind loads	Kn/m2
$\beta(z)$	Dynamic response factor at the height of z or wind vibration coefficient	
$\mu(s)$	Shape factor	
$\mu(z)$	Exposure factor or Variation coefficient of wind pressure altitude	
W(o)	Basic wind pressure	kN/m2
ρ	Air density	T/m3
V(o)	Basic wind speed	m/s
$V(z)$	Boundary layer wind speed at the level of z	m/s
α	Exponential factor due to terrain roughness	
ξ	Gust amplitude factor	
ν	Wind turbulence and correlation factor	
Φ_z	Mode shape factor	
$S(k)$	Characteristic value of the snow load	kN/m2
$\mu(r)$	Coefficient of snow distribution over the roof	
S (0)	Reference snow pressure	kN/m2

List of abbreviations

RHS	Rectangular hollow profiles
CHS	Circular hollow profiles
ETFE	Ethylene Tetrafluroethylene
AutoCAD	Computer-aided drafting software program used to create blueprints for buildings and other things.
SI	Swarm intelligence
GA	Genetic Algorithm
SA	Simulated annealing
ACO	Ant colony Optimization
PSO	Particle swarm optimization
FA	Firefly Algorithm
CSS	Charged system search
VTAM	Vast territories areal mapping
Tetrakaidekahedron	Polyhedron with 14 faces
Dodecahedron	Polyhedron with 12 faces
.AVEX	Extension for file made in Architrave
.AVE	Extension for file made through VTAM
.AVER	Extension for file with user defined sections
SLS	Serviceability limit state
ULS	Ultimate limit state
.txt	Extension for arguments file

1 List of Content

2 Introduction

One of the more impressive buildings in the Olympic Park in Beijing is the Olympic Swimming Pool, also known as the WaterCube (Chinese: 水 立方 / Shuǐlìfāng) where all the swimming events of the Olympic Games were held, such as swimming and synchronized swimming. [1] Originally, the water polo competitions were also planned here, but these were moved to the Yingdong Natatorium or National Olympic Sports Center. After the Games, the capacity of the sports complex was reduced to a more suitable number of spots according to the use of the building. The structure is built as a square to compensate for the round shapes of the National Stadium that is located on the opposite side. Also, the WaterCube associates water in a structural and thematical way with the square, the primitive form of the houses in Chinese tradition and mythology. A square is not an uncommon object in the Chinese culture. To position themselves in the universe, China choose the square as the prime geometry for their cities, palaces, and houses. The Olympic Swimming Pool is the result of collaboration between a Chinese and an Australian design agency and has won several awards for architecture. To attract more visitors to the Olympic Park, the building was converted in 2010 to a subtropical swimming pool, with slides and different activities.

In most methods used these days, architectural designs normally adapt to the structural limits that accompany it, in other words, the structural load capacity dominates over the shape of the building, especially in the design of skyscrapers or large buildings. The design of the WaterCube structure is approached in such a way that the structure is part of the architectural design. The structure of the building is so strong that it can be supported on its edges and still maintain its original shape. It is a well-known concept that the construction of conventional structures consists out of vines, columns and slabs. For this reason, the WaterCube is an exceptional design, since the building itself is also the structure. The structure of the WaterCube is a spatial structure with the dimensions 177.7m x 177.7m x 31m.

During the design of the structure the designers did not only focus on the building itself but also on the landscape surrounding the building. The landscape is inspired by the concept of a cube being dropped into a body of water. The result is a splashing effect which scatters water drops all over the area next to the building. These drops will form ponds which recycle rainwater and drain water from the pools inside. These ponds are connected underground to a sewerage which runs around the perimeter of the building. This sewerage collects the rainwater that comes from the structure and the water that comes from the water wall that surrounds the base. This water wall stretches over the full height of the entrances of the building, giving the people the sensation of passing into a watery environment. The design of the building is inspired by cells and soap bubbles and is based on a common natural pattern that comes from organic cells and the natural formation of soap bubbles. The structural engineers of Arup realized that a structure based on a unique geometry would be repetitive and because of the repetition it is possible to realize this structure, but the look would appear random and organic. It is one of the most efficient ways to subdivide a three-dimensional space with cells of the same size.

3 Watercube

3.1 The building

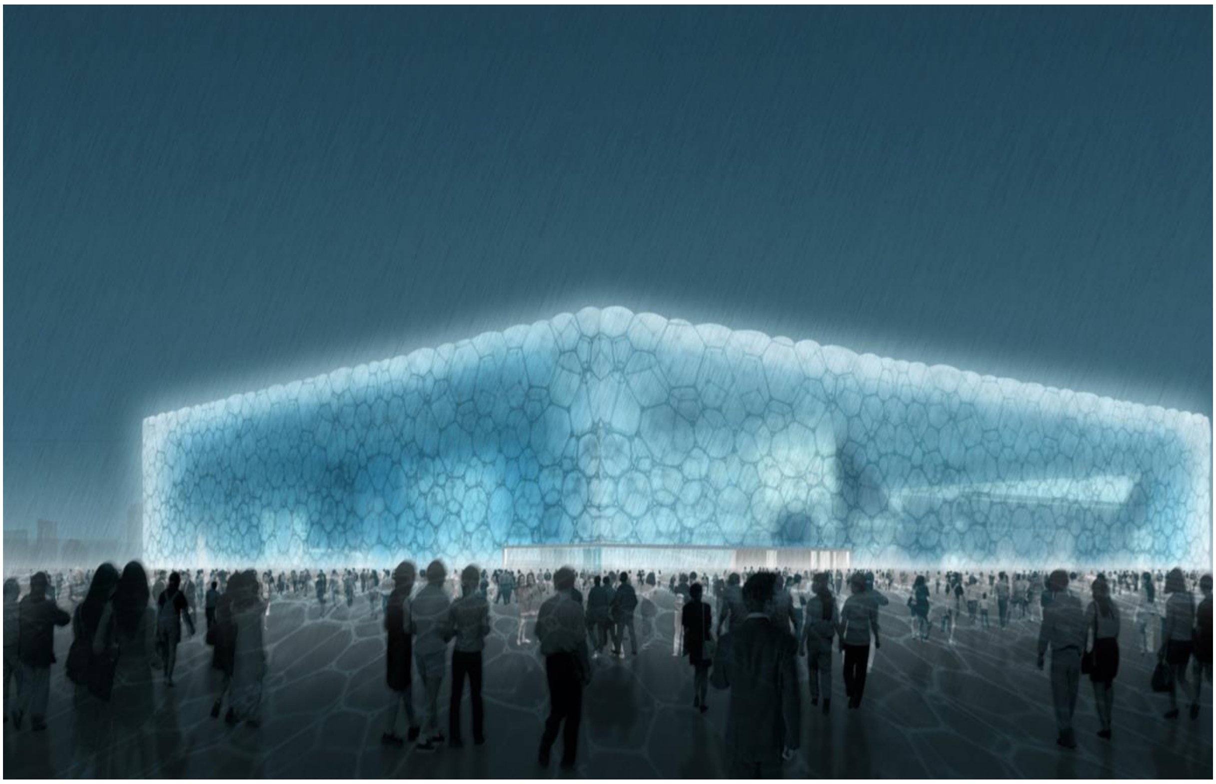


Figure 1:WaterCube The Building. Through led lights installed in the façade the building could have every possible color. [1]

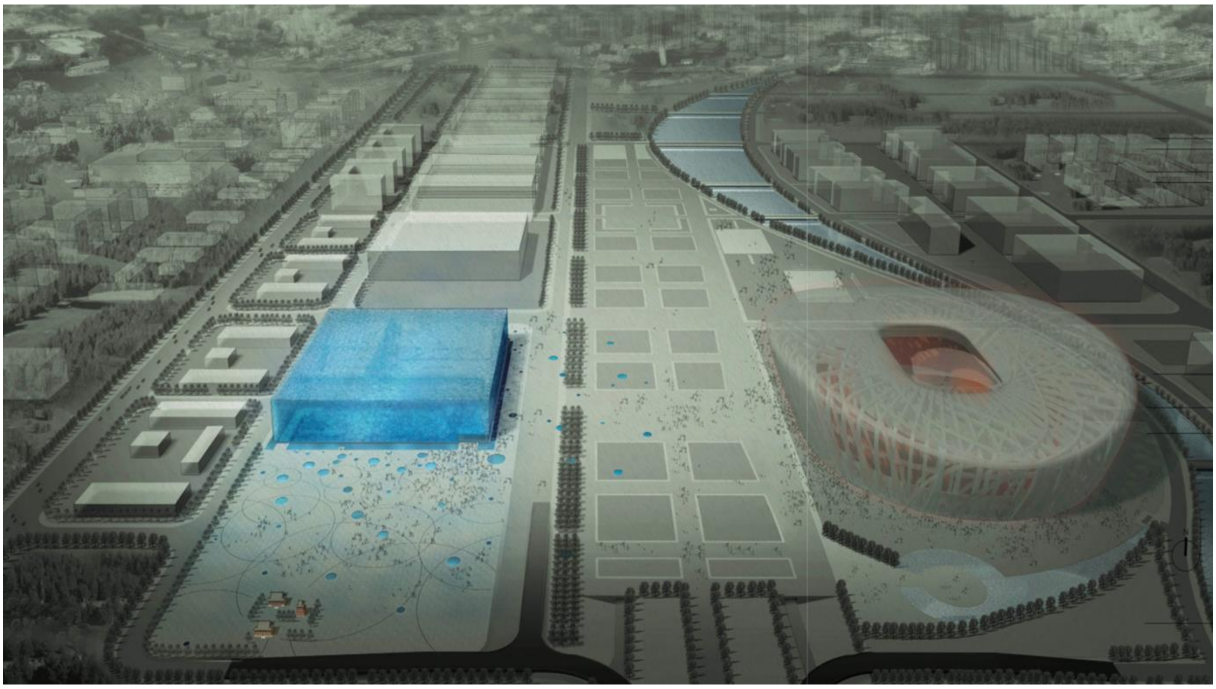


Figure 2: Watercube Landscape [1]

3.2 Structure

The structure of the WaterCube is inspired by the cells of soap bubbles, the most effective division of three-dimensional space. Finding the shape of soap bubbles with a minimum of partitions in a continuous area of bubbles is a mathematical problem studied since the end of the 19th century. The innerweb of the structure is based on the Weaire-Phelan principle. Considered that soap bubbles can be divided into a 3-dimensional repeatable system without leaving empty spaces. However, despite their apparent randomness, the bubbles must always be contact with each other with a regular geometry and this is the fact that makes the design feasible. Despite having different forms, these cells have identical volumes. This highly efficient structure is the base for the placement of the 22,000 steel beams and the 12,000 nodes of the National Swimming Center. [1]

The structure is divided into three different types of structural elements each with their own shape steel beams:

- Group one is formed by the elements of the external and internal surfaces, except for the edge elements. In this group, Rectangular Hollow Profiles (RHS) with a cross section of 450 x 300mm at 180 x 300mm were used with 13 different cross sections, including geometric changes and changes in steel thickness.
- Group two is used by the edge elements of group one. Its cross section is architecturally governed by sections of 300 x 300 RHS. Only the wall thicknesses of those members change, with a total of eight options in the cross section.
- The last group consists of the internal members that make up the "internal network". This group consists of 16 cross sections CHS ranging from 219mm in diameter to 610mm in diameter.

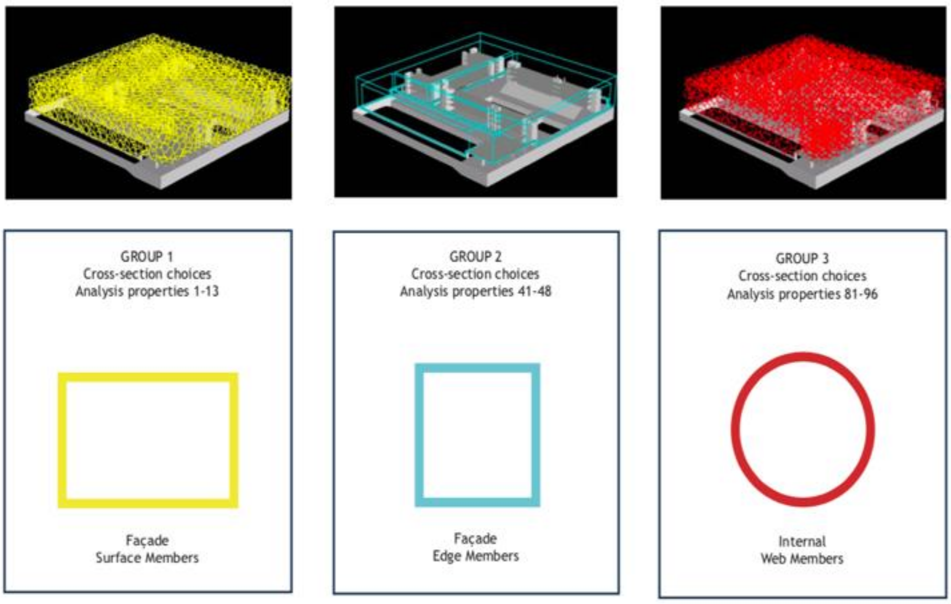


Figure 3: Three different groups of steel shapes each with their own dimension. [1]

The thickness of the steel used in any part of the design is in between the range of 4mm to 40mm. All the steel has been specified as grade Q345, which is equivalent to a steel grade of S355.
The external and internal groups are built of rectangular hollow frames in different dimensions. The perimeter frames provide the perfect prismatic shape of the structure and can be considered as the cutting planes of a foam structure.

There are around 4,000 bubbles throughout the structure and the approximate width for each bubble is about 7.5 meters each. The internal structure consists of Circular Hollow Profiles in various dimensions. Each profile is welded to spherical nodes. Therefore, all connections of the internal structure are rigid.

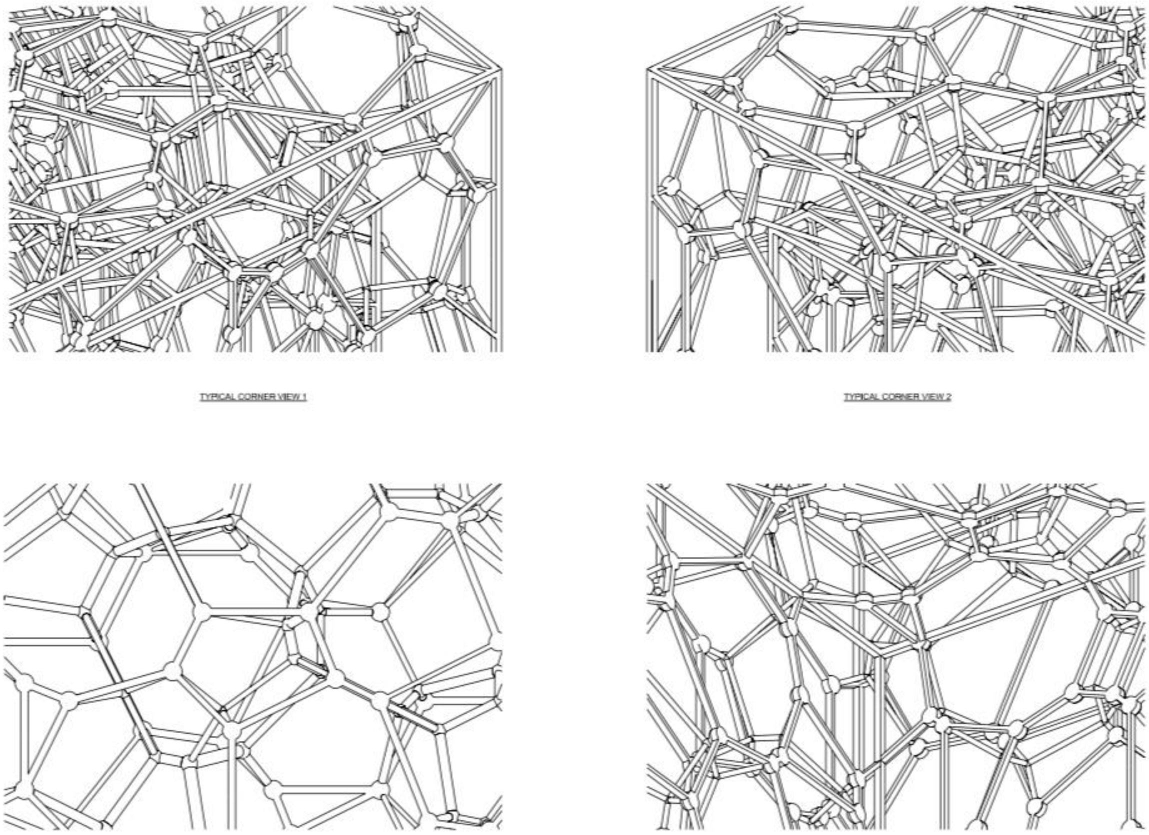


Figure 4: Connection of the three different groups through nodes [1]

The skin of the WaterCube is build out of Ethylene Tetrafluoroethylene **(**ETFE). This material has many advantages that benefit the construction of big facilities such as sport facilities. The reason for this is that ETFE, in comparison with glass, only has 1% of the weight of glass, it allows a wider spectrum of light to pass through, easy to keep clean and is very strong. It can carry up to 400 times its own weight. Also, because the structure is a public building the fire safety is a big issue. ETFE has a resistant to temperatures up to 150°C and has a self-extinguishing capability. Meaning that the ETFE film will not drip when it is burning and the possibility to expand the fire even faster is prevented.

3.3 Original Design Process

The production process of the WaterCube was totally automated. One program generates the complete geometry based on the Weaire-Phelan model and on the shape and size of the building. With this process of structural optimization, all steel members and their connections were designed. After the generation of the geometry a script converts the structural analysis of the wire model into an accurate three-dimensional model of CAD. At the end of the design phase, it took less than a week to generate a new set of constructive documents after making a major change in size or shape. [1]

The optimization process determined the size of the members for the 22,000 beams that must meet 13 stress equations at 5 points per beam for 190 load combinations according to the China Steel Code. There are 22,000 design variables and 22,000x13x5x190 = 271.7 million design limitations.

A specific optimization software had been developed to determine the minimum set of members of different sizes for the 22,000 Beams. A series of methods were adopted to define the three types of metal profiles with which the entire project was resolved. The methods used to evaluate them were steel annealing, plastic vs. elastic design and structural analysis. The optimization code was written in Visual Basic 6.0. The VB software controlled the entire process. The structural analysis has been simulated using the Strand7 Finite Element Software and its set of procedures and functions (API).

4 Algorithms

4.1 What is it

Finding an optimal solution for certain optimization problems can be an incredibly difficult task, often practically impossible. This is, when a problem gets sufficiently large, there are enormous numbers of possible solutions to consider and each one must be evaluated. Even with modern computing power there are still often too many possible solutions to consider. In this case it is unrealistic to find the optimal one within a sensible amount of time and the algorithm will settle for the closed value to the optimal solution. [2]

A metaheuristic is defined as an approach which guides particles for exploring and exploiting a certain amount of space. They are mainly inspired by observing the phenomena occurring in nature. Metaheuristic optimization algorithms have demonstrated their efficiency in finding near-optimal solutions where exact and analytical approaches may not be able to produce superior solutions within reasonable computational time. Metaheuristic algorithms form an important part of global optimization algorithms, computational intelligence and soft computing. These algorithms are usually nature-inspired with multiple interacting agents. A subset of metaheuristics is often referred to as swarm intelligence (SI) based algorithms, and these SI-based algorithms have been developed by mimicking the so-called swarm intelligence characteristics of biological agents such as birds, fish, humans and others. In the last two decades, more than a dozen new algorithms such as particle swarm optimization, differential evolution, bat algorithm and firefly algorithm have appeared, and they have shown great potential in solving tough engineering optimization problems.

Some of the characteristics of the heuristic methods are:

- There is no guarantee that a solution to the problem will be found, although this one does exist
- In case of finding a solution, it cannot be guaranteed that this is the best of the existing
- In certain situations, a heuristic search will find a solution

4.2 Different types

4.2.1 Genetic Algorithm

Genetic Algorithm (GA) is based on Charles Darwin's theory and is one of the oldest algorithms. [3] GA is a class of computational models that mimics the process of natural evolution and adaptation to the environment. This application has been used in the structural engineering since 1986 for the optimization of a 10-bar truss system.
The procedure of GA can be summarized in the following five steps:

Step 1: Encoding.
Step 2: Initialization of the population.
Step 3: Reproduction.
Step 4: Selection
Step 5: Termination Criteria

Until now, GA and its variants have been successfully employed in optimization of structural engineering problems. The benefits of using the genetic algorithms is that the concept is easy to understand and there is always an answer also the answer gets better with time. The biggest issue for GA practitioners is that the solution is only as good as the evaluation function.

Recent applications are structural system identification, design of long-span bridges, topology optimization of steel space-frame roof structures, truss topology optimization, and many others.

4.2.2 Simulated Annealing

The annealing process is where a metal is heated so that its structure can rearrange during the cooling time to increase the ductility and strength of the metal. [4] Simulated annealing uses a certain temperature variable to imitate this heating process. The temperature is initially set high and will slowly cool down as the algorithm runs. While this temperature variable is high the algorithm will accept solutions that are worse with more frequency. This gives the algorithm the ability to dismiss any local optimums it finds itself in. The acceptation of worse solutions is reduced as the reference temperature is dropped. Therefore, allowing the algorithm to focus on an area close to the optimum solution. SA has been used to solve many optimization problems in civil engineering and for recent applications.

4.2.3 Ant colony optimization

Ants live in a colony and the population of their colony is between 2 and 25 million. They are practically blind but still find their way to the food. They lay a scent pheromone to communicate with each other. This way of communication is called stigmergic. Each individual ant follows a pheromone trail and when exploring the surroundings, more pheromone will be laid from/to the food source. In this way they establish the shortest route/path from their colony to the feeding sources and back. The probability of ants following a certain route is in function of the pheromone intensity, visibility and evaporation. [5]

Ant colony optimization (ACO) has also been applied for several structural engineering problems.

4.2.4 Particle Swarm Optimization

Particle swarm optimization (PSO) imitates the behavior of social swarms and was inspired by birds, fishes, etc. [6] PSO is a population-based metaheuristic algorithm and applies the concept of social interaction for problem solving. The algorithm uses a set of particles flying over a search space to locate a global best solution. The initial parameters are the swarm size, position of particles, velocity of particles and maximum number of iterations.

In a swarm, particles are randomly generated, and new solutions are updated in an iterative manner. A particle encodes a candidate solution to a problem at hand. The solution particles tend to move toward the current best location, while they move to new locations. Since all particles tend to be the current best solution, each particle updates his position according to its previous experience and the experience of its neighbors.

The basic concept of PSO is that each particle moves towards the best-found own position and the global best-found position by any other particle with a certain random acceleration at each step.

Most recent applications are the design of tall buildings, size optimization of trusses, slope stability analyzing, and water distribution systems.

4.2.5 Firefly Algorithm

The flashing characteristic of fireflies have inspired a new metaheuristic algorithm. All fireflies are unisex. Thus, any individual firefly will be attracted to other fireflies. The brightness is related to attractiveness. In that case, the less bright firefly will be attracted by the brighter one. Attractiveness and brightness will decrease when the distance increases. If there is no brighter one, the firefly will move randomly. The landscape of the optimization objective affects and determines the brightness of individuals. [7]

FA has two major advantages; automatically subdivision and the ability of dealing with multi-modality. First, FA is based on attraction and attractiveness decreases with distance. This leads to the fact that the whole population can automatically subdivide into subgroups, and each group can swarm around each mode or local optimum. Among all these modes, the best global solution can be found. Second, this subdivision allows the fireflies to be able to find all optima simultaneously if the population size is sufficiently higher than the number of modes.

FA has been employed in structural engineering designs such as tower structures, continuously cost steel slabs, and truss structures.

4.2.6 Charged System Search

In 2010, Kaveh and Talatahai introduced the Charged System Search (CSS), a metaheuristic algorithm inspired from electrostatic- and Newtonian mechanic laws. The charged system search is based on a population research. There will be agents, each will be considered as sphere who is charged with a certain radius. The charge has a volume density that allows the insert of an electric force to other agents. The magnitude of the forces depends on the separation distance between the CP’s, and for a charged agent who is located outside the sphere it is inversely proportional to the square of the separation distance between particles. [8]

The procedure of the CSS will happen through the following steps.

- Initialization, random positions will be determined inside a search space and the velocities of charged particles are assumed to be zero. Best CP’s will be saved in the charged memory with Xbest, worst with fitworst.
- Forces determination
- Updating process
- Terminating criterion control

Recently, CSS has been applied for civil engineering problems such as damage detection in skeletal structures, cost optimization of castellated beams, optimum design of engineering structures.

4.2.7 Vast Territories Areal Mapping

Vast Territories Aerial Mapping (VTAM) is a metaheuristic optimization algorithm that exploits the analogy of searching the best location for human settlements across large territories based on the topography and local conditions of each location. Terrains are expressed the best in a three-dimensional map to see the differences in the altitudes of the hills and valleys present on a terrain. The VTAM will use this terrain to map out a cost related solution of the problem according to the altitude of the hills and valleys. Also, there are two factors that the algorithm considers. The first one is the cost of the total structure and the second one is to check if the structure applies to all the pre-assigned factors or in other words the stability of the structure. To take this into account in the algorithm a sea level will be introduced into the space/terrain. Every location underneath the sea level means that the structure will fail due to stability, strength or excess of deformation issues but everything to far above the sea level means that the total cost of the structure will be too high. The optimal solution would be to find a point by the seashore or by any interior lakeshore were the stability and the cost are equally balanced.

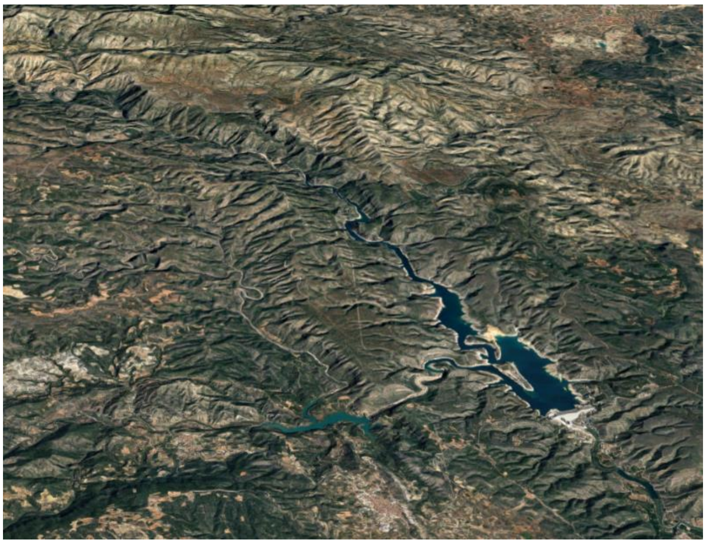


Figure 5: Origin of the idea of implementing VTAM. An area that crosses a large territory

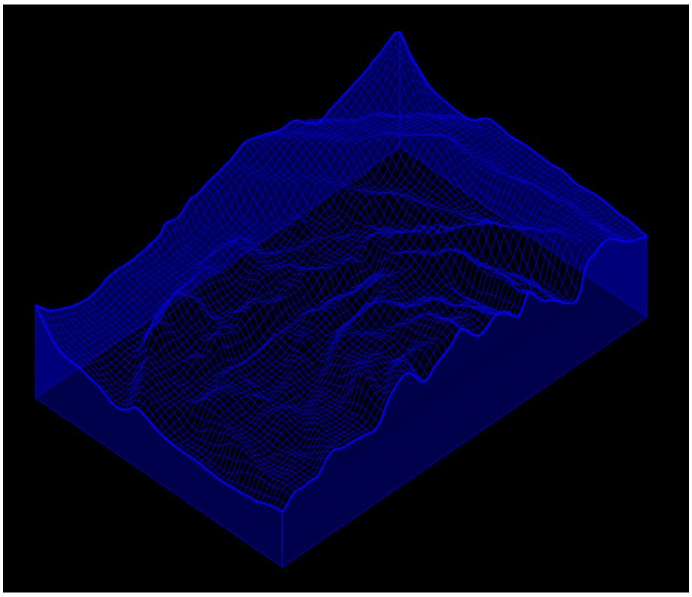


Figure 6: Topographical example of space devided in different altitudes

The optimal or best solution is a vague concept when using a metaheuristic algorithm. The best solution would mean that the algorithm has controlled all the possible possibilities in a certain space and checked them with each other which is unlikely to happen. This is one of the drawbacks of using a metaheuristic algorithm. The reason for this inconvenience is, when the algorithm finds a local best solution it will use this solution to search around this point to find more and even better solutions. As this happens the algorithm gets “stuck” in this area and will not explore the rest of the space of configurations looking for better local solutions which could be closer to the real global solution. Explained through the VTAM algorithm this would mean that the algorithm has found a local solution which can be compared to a valley in the terrain and would explore this valley without searching other valleys that could offer even better opportunities.

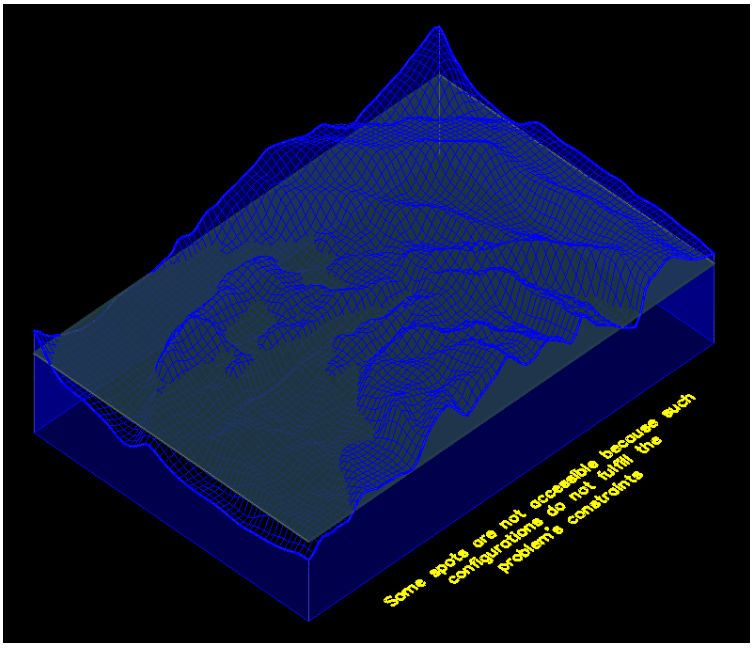


Figure 7: Water level applied in the topographical area to divide the area in a constructional stable side and a minimum cost price

To solve the problem of this issue the collaboration of man and machine is advisable. To be sure that the algorithm does not get stuck in a local optimum the optimization problem should be run parallel through the algorithm a few times to enrich the diversity of the heuristic search. The user then must analyze the outcome of the results of the algorithm manually and see what kind of proposal the algorithm has given. According to this, the user can change the construction by changing dimensions or shapes of the steel bars and re-optimize the newly adjusted structure. This procedure increases the chance of finding the best cost related solution. Also, knowing that the algorithm chooses a certain amount of randomly chosen configurations for the structure (randomly assigned cross-sections for each steel bars group), subsequent optimization processes will help to find configurations that are as closest as possible to the global best configuration.

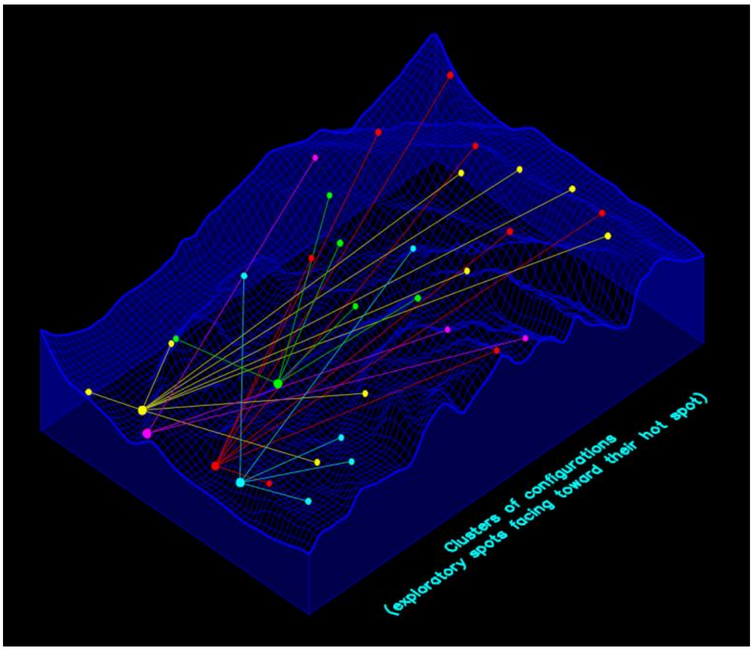


Figure 8: Hotspots sending out explores to explore the surroundings

The VTAM will use these randomly assigned combinations and spread them all over the terrain. Each one of these will have their own altitude according to the terrain and cost function related to it. Now, each of these points, which is called "head family member" will send out "explorers" to discover how the terrain or, in other words, how locations around this point look like. Each one of them has the same amount of family members to discover the surroundings. After the explorers explore new positions, the lowest point, in our case the best solution, will be the most valuable location and will be called "the flagship of the family". Once all the head family members collected the values of their flagships, the highest or the less profitable solution will be discarded, and these explorers will go in a straight line to the best location of their family group to help find an even better location. During the translation movement the points get translated randomly on this straight line which means they could end up on the other side of the of the flagship. In this way they can reach points on the other side of the valley or in neighbor valleys.

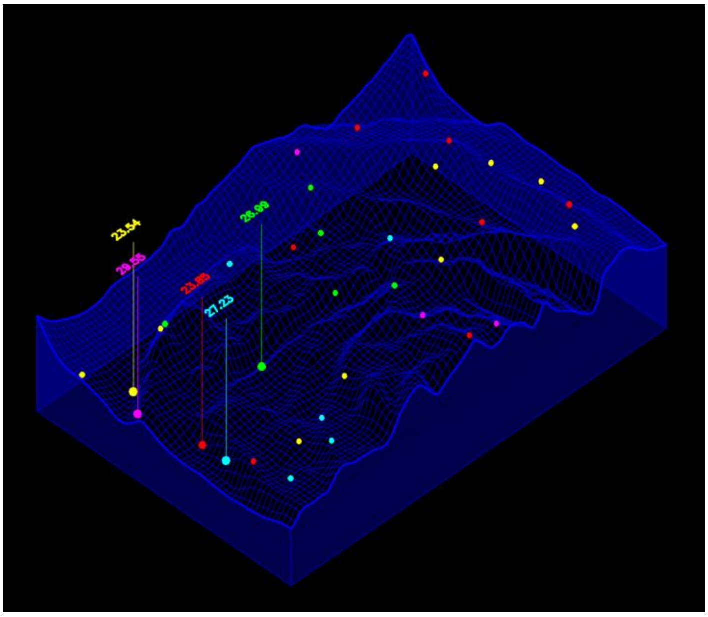


Figure 9: Flagships of the head family members with the lowest values found in the search area

The only requirement for this is that these points should always be inside the topographical area of the searched territory. After the translation, the elevation of each point is compared to the flagship of that group and, if one point is now lower than the flagship, that point becomes the new flagship. Now again, the group with the highest flagship gets discarded and these points are assigned to the family with the best flagship. This iteration goes on until all the points are in only one group and even then, the iteration of translating the points in the direction of the straight line towards the flagship can be continued indefinitely. Usually the iteration process is stopped if the last iteration only improved the result by a certain percentage, for example 0,5%.

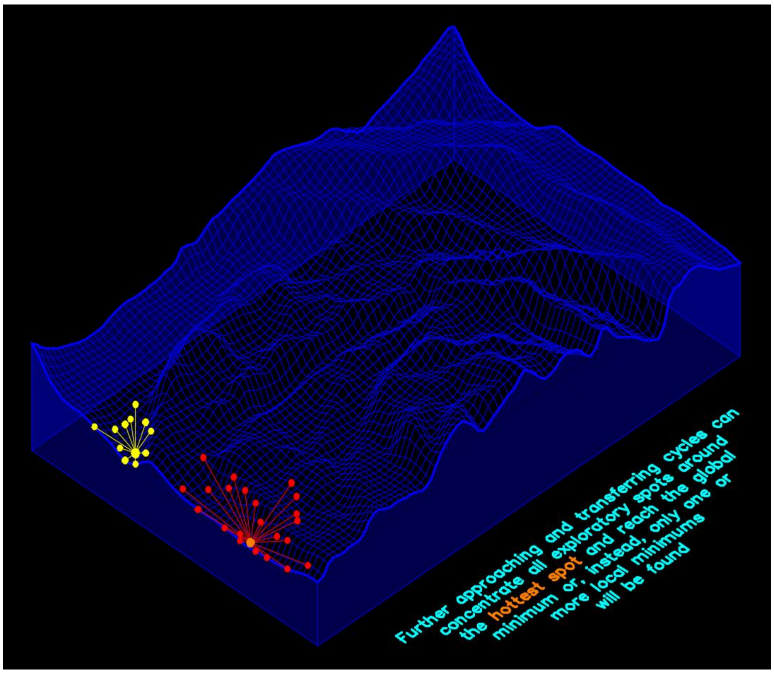


Figure 10: Concentrating of the research around the lowest found possibilities.

The main logic behind the algorithm is that when a local best solution is found an even better solution could be found around this location. Of course, there is a chance that the lowest flagship point is in a local low point which would not render the absolute optimal result. However, by translating the points in the other randomly formed groups, there is a very good chance that the other groups will detect a lower point and thus shifting the lowest group from the local low point to the absolute low point. VTAM web is based on a cluster of computers which computational resources are made available progressively expanding according the users demand. The basic cluster is formed by five computers. Having everyone two processors, the cluster for the VTAM algorithm can run 10 parallel optimization processes to efficiently map the large spaces of configuration that characterizes many structural optimization problems.

Figure 11: Basic of 5 computers used for the optimization process

To explain in detail on what the VTAM internally is based, there will be referred to L. Pavlovcic, A. Krajnc and D. Beg [9] and the up following information;

While the weight of a steel structure is a major component of the total cost, the minimization of the cost should be the final objective for optimum use of available resources. The total cost of a steel structure includes; the material cost of structural members such as beams, columns, and bracings, the fabrication cost including the material costs of connection elements, bolts, and electrodes and the labor cost, the cost of transporting the fabricated pieces to the construction field and the erection cost including the material costs of connection elements, bolts, and electrodes and the labor cost.

The cost of a total steel structure is based on all the different subjects as stated above. These factors will then be divided in subgroups, each with their own cost related activities. The general cost or developing cost function can be described as following:

In general, the steel consumption cost will be depended of the mass of the elements. This statement means that the end cost price will be related to the mass of steel of which grade steel will be used. If these words would been put in a formula is would be as following:

$$C_{\text{steel-elem}} = k_m \rho V_{el} \quad (1)$$

K_m =Material cost for steel

ρ =Density of steel

V_{el} =Volume of the elements

In the upcoming formulas and information will give the different subfactors of the main cost calculation. This to give a better idea on what must considered while calculating the total cost price of certain structure.

Welding of the elements

To construct a steel structure welding is required to connect different pieces of steel together. To creation of one welding will require the implementation of the manufacturing time, manhours, the cost of the material and the assembly.

$$C_{welding} = C_{weld,manufact} + C_{weld,material} + C_{assembly} \tag{2}$$

The manufacturing cost of welding show in equation 3 is mainly based on the labor, equipment, etc... Also, the time needed to perform this a certain weld will be included and will depend on the length of the weld.

$$C_{weld.manufact.} = k_{weld} \left[f_{weld} \, T_{weld} \, (a_w) L_w + T_{weld,extra} \right] \tag{3}$$

The material cost of the weld, equation 4, will be based on the length of the weld. This is a valid statement, because the greater the length of the weld the more material will be needed to complete the task.

$$C_{weld.material} = [\sum k_{m.weld,i} M_{weld,i}(a_w)] L_w \tag{4}$$

In general, the consumption of material needed for one weld is based on the size of the weld.

$$T_{weld} = 2{,}62 * a_w^{\,2} + 1{,}37 * a_w + 0{,}09 \; [min/m] \tag{5}$$

Cutting costs for elements

To create a steel structure, cutting of elements will be essential. Every structure is different and will require different dimensions and shapes. The equation of the cost for cutting (6) is analogous to the equation of welding (3). The manufacturing, material and handling of material will have the main influence on the cost of this matter. The only big difference between welding cost and cutting cost is that length of cutting will depend on the shape of the element.

$$C_{cutting} = C_{cut,manufact} + C_{cut,material} + C_{plate\ handling} \tag{6}$$

$$C_{cut.manufact.} = k_{cut} \left[f_{cut} \, T_{cut} \, (t_{pl}) L_c + T_{cut,extra} \right] \tag{7}$$

$$C_{cut.material} = [\sum k_{m.cut,i} M_{cut,i}(t_{pl})] L_c \tag{8}$$

$$C_{handling} = k_{handling,pl} \, T_{handling,pl} \, (\rho V_{el}) \tag{9}$$

Painting of the elements

The cost of painting elements is mainly based on manufacturing and materials. The greater the volume of the elements, the more paint and time will be needed to complete the task. Also, situation requiring a greater effort will make the cost increase, because of the use of different equipment or methods to complete the task. The location where the steel elements will be implemented also has influence on the cost. When used in more humid areas or in bad condition the paint will need more layers or a different composition which will make the cost go up. All these factors are combined in equation (10).

$$C_{painting} = [k_{paint}\, T_{paint} + \Sigma(k_{m.paint,i}\, M_{paint,i})] * 2A_{pl} \quad (10)$$

k_{paint} = Cost factor of the paint
T_{paint} = Time consumption
$k_{m.paint,i}$ = Price per square meter
$M_{paint,i}$ = Paint consumption
A_p = Area of elements

Transportation of the elements

To transport the elements to the location where they will be developed to a structure can be a difficult and exhausting task. This work can be very time consuming. It is difficult to make a perfect analyze for the cost of this transportation factor because it depends on the length, the shape and the weight of the material that must be transported. Also, some places are difficult to reached with normal transport and other ways for transportation must be found. To create a general calculation of this factor the weight of the steel will be in relation with the type of transport.

$$C_{transportation} = k_{transp} \rho V_{struct} \quad (11)$$

5 Loads

5.1 Wind Calculation

According to some traditional reasons, building designs and bridge designs in China follow their own individual specifications. The current wind loads used in building design is a part of China National Standard – Load Code for the Design of Building Structures (GB50009-2001)1, which has been valid since March of 2002. This load code was created in 1954, and has five updated versions, including Temporal Code of Loading (1-54) and (1-58), Loading Code for Industrial and Civil Building Structures (TJ9-74), Load Code for the Design of Building Structures (GBJ9-87) and (GB50009-2001) 1. [10]

The wind load that acts in a normal way on the surface of buildings is defined as wind force over unit area and will be calculated with as represented in equation (12) :

5.1.1 Wind load

$$W(k) = \beta(z).\mu(s).\mu(z).W(0) \tag{12}$$

W(k) = characteristic value of wind loads, kN/m2.
$\beta(z)$ = dynamic response factor at the height of z or wind vibration coefficient.
$\mu(s)$ = shape factor, the values for some common buildings and structures are tabulated in the code, and wind tunnel test is encouraged for unusual shapes;
$\mu(z)$ = exposure factor or Variation coefficient of wind pressure altitude
W(o) = basic wind pressure, kN/m2.

Based on Load Code for the Design of Building Structures (GB50009-2001)1, the basic wind speed V(o) is defined as the 10-minute average wind speed over a flat and open terrain at an elevation of 10m with a mean return period of 50 years.

5.1.2 Basic wind pressure

The basic wind pressure is calculated through the basic wind speed and the air density in the same conditions:

$$W(0) = \frac{1}{2}.\rho.V(0)^2 \tag{13}$$

V(o) = basic wind speed, m/s;
ρ = air density, t/m^3, the normal value is 1.225×10^{-3} t/m^3, and this value can be modified with the elevation z (m)

Table 1: Wind pressure and Snow pressure according to altitude [10]

Name of cities/provinces	City name	Elevation (m)	Wind pressure (kN/m2)			Snow pressure(kN/m2)			Snow load quasi-permanent value coefficient zoning
			n=10	n=50	n=100	n=10	n=50	n=100	
Beijing		54.0	0.30	0.45	0.50	0.25	0.40	0.45	II
Tianjin	Tianjin City	3.3	0.30	0.50	0.60	0.25	0.40	0.45	II
	Tanggu	3.2	0.40	0.55	0.60	0.20	0.35	0.40	II
Shanghai		2.8	0.40	0.55	0.60	0.10	0.20	0.25	III
Chongqing		259.1	0.25	0.40	0.45				
Hebei	shijiazhuang	80.5	0.25	0.35	0.40	0.20	0.30	0.35	II
	Wei County	909.5	0.20	0.30	0.35	0.20	0.30	0.35	II
	Xingtai City	76.8	0.20	0.30	0.35	0.25	0.35	0.40	II
	Fengning	659.7	0.30	0.40	0.45	0.15	0.25	0.30	II
	Weichang	842.8	0.35	0.45	0.50	0.20	0.30	0.35	II
	Zhangjiakou	724.2	0.35	0.55	0.60	0.15	0.25	0.30	II
	Huailai	536.8	0.25	0.35	0.40	0.15	0.20	0.25	II
	Chengde	377.2	0.30	0.40	0.45	0.20	0.30	0.35	II
	Zunhua	54.9	0.30	0.40	0.45	0.25	0.40	0.50	II
	Qinglong	227.2	0.25	0.30	0.35	0.25	0.40	0.45	II
	Qinhuangdao	2.1	0.35	0.45	0.50	0.15	0.25	0.30	II

Therefore, knowing that the wind pressure only dependents on the basic wind speed and the basic air pressure and these two factors are according to the actual elevation of the building there are some general values calculated as shown in Table 1. Knowing these values, the actual wind pressure, with a certain height, can be calculated through the interpolation method.

5.1.3 Wind profile model

According to China National Standard Load Calculations [10] there are three kinds of models describing the boundary layer wind profile, that is, Power Law Profile Model, Logarithmic Profile Model and the combination of these two models. Power Law Profile Model is currently the only model of boundary layer wind profile and is calculated through equation (14).

$$V(z) = V(0)\left(\frac{Z}{Z(0)}\right)^{\alpha} \tag{14}$$

V(z) = boundary layer wind speed at the level of z, m/s;
V(o) = basic wind speed at the level of zo, m/s;
α = exponential factor due to terrain roughness.

As stated in the Power law profile Model V(z) = $\mu(z)$. The variation of coefficient of wind pressure altitude shall be decided according to Table 1 and is based on the roughness of the terrain.

There are four different categories of terrain roughness in China, which can be described as the following:
Class A: sea, sea shores, islands, lake and deserts;
Class B: open fields, villages, forests, hills, sparsely-built town and the suburb of cities.
Class C: urban area of densely-populated cities.
Class D: center of large city with closely spaced tall buildings.

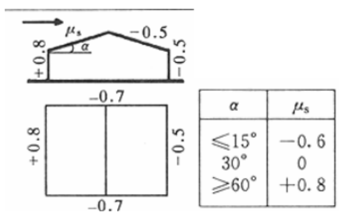
Table 2: Wind profile mode [10]

Height away from the ground or sea surface	Types of ground roughness			
(m)	A	B	C	D
5	1.17	1.00	0.74	0.62
10	1.38	1.00	0.74	0.62
15	1.52	1.14	0.74	0.62
20	1.63	1.25	0.84	0.62
30	1.80	1.42	1.00	0.62
40	1.92	1.56	1.13	0.73
50	2.03	1.67	1.25	0.84
60	2.12	1.77	1.35	0.93
70	2.20	1.86	1.45	1.02
80	2.27	1.95	1.54	1.11
90	2.34	2.02	1.62	1.19
100	2.40	2.09	1.70	1.27
150	2.64	2.38	2.03	1.61
200	2.83	2.61	2.30	1.92
250	2.99	2.80	2.54	2.19
300	3.12	2.97	2.75	2.45
350	3.12	3.12	2.94	2.68
400	3.12	3.12	3.12	2.91
≥450	3.12	3.12	3.12	3.12

5.1.4 Wind load coefficient

The wind load coefficient depends on the shape of the building. The WaterCube is a Square building with a flat roof. The applied coefficients can be diverted from Table 3.

Table 3: Wind load coefficient [10]

2	Close-type gable roof	 The median is calculated by interpolation method

5.1.5 Wind vibration coefficient.

For buildings with a height greater than 30m it is necessary to consider the impact of downwind vibration to the structure caused by the wind pressure pulse.

$$\beta(z) = 1 + \frac{\xi . v . \varphi(z)}{\mu(z)} \tag{15}$$

ξ = gust amplitude factor, augmenting of the ripple;
ν = wind turbulence and correlation factor, Influence coefficient of the ripple;
φ_z = mode shape factor of a structure.
$\mu(z)$ = Variation coefficient of the wind pressure height

The factors represented in equation (15) will be calculated as following;

- Augmenting factor is determent by the basic wind and the vibration of the structure. Also, the type of structure will have an influence on this factor and this value will be diverted from Table 4.

Table 4: Augmenting Factor [10]

$\omega_0 T^2_1 (kNs^2/m^2)$	0.01	0.02	0.04	0.06	0.08	0.10	0.20	0.40	0.60
Steel structure	1.47	1.57	1.69	1.77	1.83	1.88	2.04	2.24	2.36
Steel structure of building with filler wall	1.26	1.32	1.39	1.44	1.47	1.50	1.61	1.73	1.81
Concrete and masonry structure	1.11	1.14	1.17	1.19	1.21	1.23	1.28	1.34	1.38
$\omega_0 T^2_1 (kNs^2/m^2)$	0.80	1.00	2.00	4.00	6.00	8.00	10.00	20.00	30.00
Steel structure	2.46	2.53	2.80	3.09	3.28	3.42	3.54	3.91	4.14
Steel structure of building with filler wall	1.88	1.93	2.10	2.30	2.43	2.52	2.60	2.85	3.01
Concrete and masonry structure	1.42	1.44	1.54	1.65	1.72	1.7	1.82	1.96	2.06

- Mode factor shall be calculated according to the structural dynamics. In most typical cases, only the impact of the first vibration type will be considered. As the WaterCube is a building with larger width at the windward the modus factor will be chosen according to Table 5.

Table 5: Mode factor [10]

Relative height	Modus SN			
z/H	1	2	3	4
0.1	0.02	-0.09	0.23	-0.39
0.2	0.06	-0.30	0.61	-0.75
0.3	0.14	-0.53	0.76	-0.43
0.4	0.23	-0.68	0.53	0.32
0.5	0.34	-0.71	0.02	0.71
0.6	0.46	-0.59	-0.48	0.33
0.7	0.59	-0.32	-0.66	-0.40
0.8	0.79	0.07	-0.40	-0.64
0.9	0.86	0.52	0.23	-0.05
1.0	1.00	1.00	1.00	1.00

- Influences coefficient of the ripple will be determined by the dimensions of the structure. Because the structure has a width who is larger than the height this factor shall be calculated through the ratio between the total height H and its windward width B and will be determined by Table 6.

Table 6: Influence of the ripple [10]

H/B	Types of ground roughness	Total height H(m)							
		≤30	50	100	150	200	250	300	350
≤0.5	A	0.44	0.42	0.33	0.27	0.24	0.21	0.19	0.17
	B	0.42	0.41	0.33	0.28	0.25	0.22	0.20	0.18
	C	0.40	0.40	0.34	0.29	0.27	0.23	0.22	0.20
	D	0.36	0.37	0.34	0.30	0.27	0.25	0.24	0.22
1.0	A	0.48	0.47	0.41	0.35	0.31	0.27	0.26	0.24
	B	0.46	0.46	0.42	0.36	0.36	0.29	0.27	0.26
	C	0.43	0.44	0.42	0.37	0.34	0.31	0.29	0.28
	D	0.39	0.42	0.42	0.38	0.36	0.33	0.32	0，31
2.0	A	0.50	0.51	0.46	0.42	0.38	0.35	0.33	0.31
	B	0.48	0.50	0.47	0.42	0.40	0.36	0.35	0.33
	C	0.45	0.49	0.48	0.44	0.42	0.38	0.38	0.36
	D	0.41	0.46	0.48	0.46	0.46	0.44	0.42	0.39
3.0	A	0.53	0.51	0.49	0.42	0.41	0.38	0.38	0.36
	B	0.51	0.50	0.49	0.46	0.43	0.40	0.40	0.38
	C	0.48	0.49	0.49	0.48	0.46	0.43	0.43	0.41
	D	0.43	0.46	0.49	0.49	0.48	0.47	0.46	0.45
5.0	A	0.52	0.53	0.51	0.49	0.46	0.44	0.42	0.39
	B	0.50	0.53	0.52	0.50	0.48	0.45	0.44	0.42
	C	0.47	0.50	0.52	0.52	0.50	0.48	0.47	0.45
	D	0.43	0.48	0.52	0.53	0.53	0.52	0.51	0.50
8.0	A	0.53	0.54	0.53	0.51	0.48	0.46	0.43	0.42
	B	0.51	0.53	0.54	0.52	0.50	0.49	0.6	0.44
	C	0.48	0.51	0.54	0.53	0.52	0.52	0.50	0.48
	D	0.43	0.48	0.54	0.53	0.55	0.55	0.54	0.53

5.2 Wind calculation for the structure

Before the calculation of the wind loads for the structure is accomplished some basic information must be established. The structure is built in Beijing and this city is located with an elevation of 54m. As told in previous chapters, the structure is shaped as square with dimensions of 177,7m x 177,7m x 31m. Because the building is built in the Olympic park of Beijing, terrain category B will be accurate here. The reasoning behind this is that there are not many buildings surrounding it and it is located in the suburbs of the city.

The method of interpolation will happen through the following formula:

$$y_2 = \frac{(x_2 - x_1)(y_3 - y_1)}{(x_3 - x_1)} + y_1 \tag{16}$$

The basic wind pressure is based on the location and the height of the building. Collected from Table 1, with the interpolation method, the basic wind pressure is 0.3075kN/m2.

The wind profile mode is based on the height of the building and the terrain category. Collected from Table 2, with the interpolation method, the wind profile model is 1.71.

The wind load coefficient collected from Table 3 depends on the direction of the wind. As the wind blows there must be considered that there will be wind pressure and wind suction. The pressure values will be positive and the suction values negative. The values for the calculation of the front side will be 0.8, for the sides -0.7 and for the backside -0.5.

The wind vibration coefficient depends of four factors:

1) The augmenting factor depends on the type of structure and the wind speed in relation with the vibration time. Knowing that this structure is a steel structure, the augmenting factor will be 1.88.

$$\xi = w(0).T^2 = 0.101 \tag{17}$$

2) The coefficient of the ripple depends on the relation between the height and the width of the structure. The relation between these two factors is 0.175 which is smaller than 0.5. Knowing that the total height of the structure is 31m, the coefficient of the ripple will be 0.4205.

3) The mode factor depends on the relative height of the building which in this case is 0.3. Knowing that, using the general factor one is enough for the calculation this factor will be 0.34

$$\beta(z) = 1 + \frac{\xi.v.\varphi(z)}{\mu(z)} = 1 + \frac{1,88x0,4205x0,34}{1.71} = 1,15 \tag{18}$$

Based on eqs. 17-18 and previous collected values the wind pressure will be calculated in the four different directions of the structure:

1) The front side of the building (pressure)

$$W(k) = \beta(z).\mu(s).\mu(z).W(0) = 1.15\ x\ 0.8\ x\ 1.71\ x\ 0.3075 = 0{,}484 kN/m^2 \quad (19)$$

2) The left and the right side of the building (suction)

$$W(k) = \beta(z).\mu(s).\mu(z).W(0) = 1.15\ x - 0{,}7\ x\ 1.71\ x\ 0.3075 = -0{,}423 kN/m^2 \quad (20)$$

3) The back side of the building (suction)

$$\mathrm{W(k)} = \beta(\mathrm{z}).\mu(\mathrm{s}).\mu(\mathrm{z}).\mathrm{W(0)} = 1.15\ \mathrm{x} - 0.5\ \mathrm{x}\ 1.71\ \mathrm{x}\ 0.3075 = -0{,}302 \mathrm{kN/m^2} \quad (21)$$

5.3 Snow

The value of snow on the horizontal projection surface of the roof shall be calculated according to equation 22: [10]

$$S(k) = \mu(r).S(0) \quad (22)$$

S(k)=characteristic value of the snow load, kN/m^2
$\mu(r)$=Coefficient of snow distribution over the roof
S(0)=reference snow pressure, kN/m^2

The angle of the roof is smaller than 25°, so the coefficient of snow, according to Table 1 is 1.

6 Creation of the building

6.1 General

The essence of bringing this research to positive outcome is understanding how the original building is created. As mentioned before, the structure is built out of three main groups. The outside façade, inside façade and the innerweb of the building. The innerweb is made from the well know Weaire-Phelan concept and the two other groups will connect this concept to diverge the forces to the ground and can be considered as the “cutting” lines of the inner structure. .

Figure 12 shows a visual representation of how this concept works. The Weaire-Phelan concept is structurally created using two kinds of different cells, both with an equal overall volume. One is an irregular dodecahedron and the second is a tetrakaidekahedron. The pentagons, in both types of cells, are slightly curved to allow a perfect occupation of space.

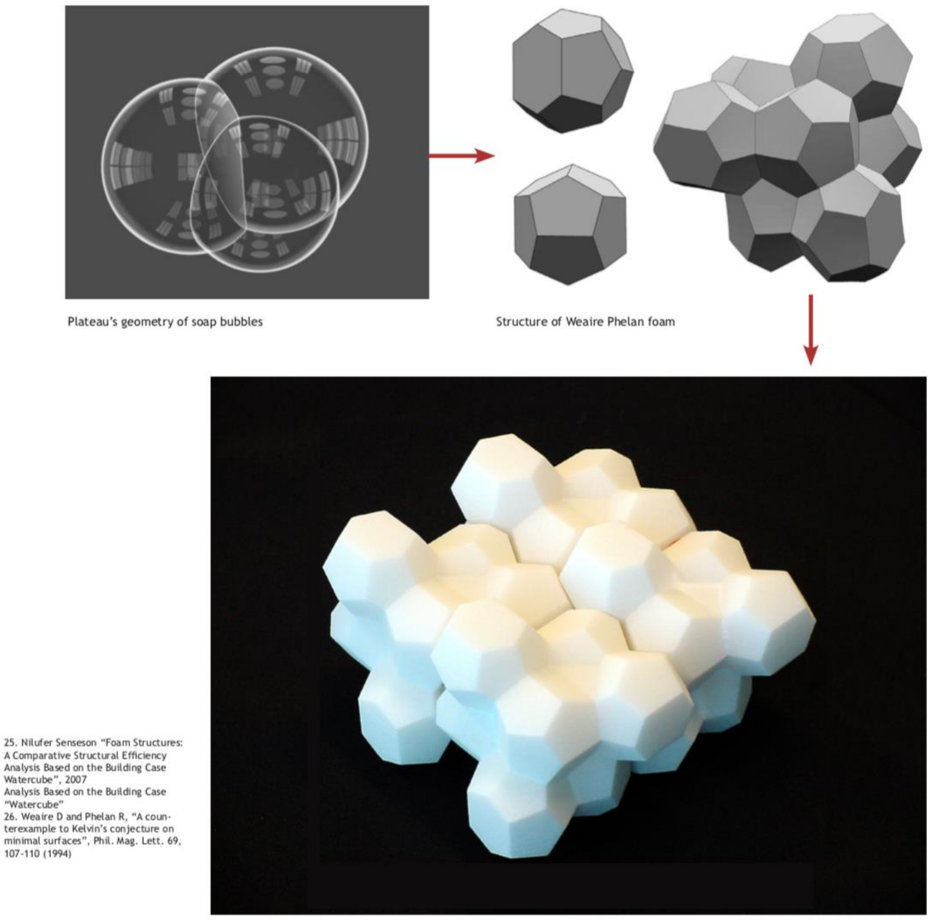


Figure 12: Composition of soap bubbles diverted to structural components [1]

The following step was to convert this concept into an AutoCAD drawing and create a construction with an identical geometry equal to the original structure. The tetrakaidekahedron was created through an algorithm that was assigned with a base of basic coordinates to automatically create the shape in AutoCAD. Afterwards this shape could be scaled with right dimensions and orientated in the correct location. In this case there is no need to create the dodecahedron. The reasoning behind this is that the only purpose of the dodecahedron is to fill the space in between a connection of two groups of six tetrakaidekahedrons. If the dodecahedron would be used in between two groups, it would result in a longer computing time because the number of overlapping bars would be significant larger.

After the creation of one single tetrakaidekahedron, it was rotated in the right position and connected to other tetrakaidekahedrons to create one group of six tetrakaidekahedron. This group would then serve as the basis of the structure and could then be copied and placed next to, up or down the other group and would fit perfectly. This perfect connection is the whole reasoning why the Weaire phenom model is used. Because of the repetition in between the groups of six tetrakaidekahedrons this structure is stable and applicable for structural designs. This action is then repeated until a block of different groups arises with a certain dimension, as show in Figure 13.

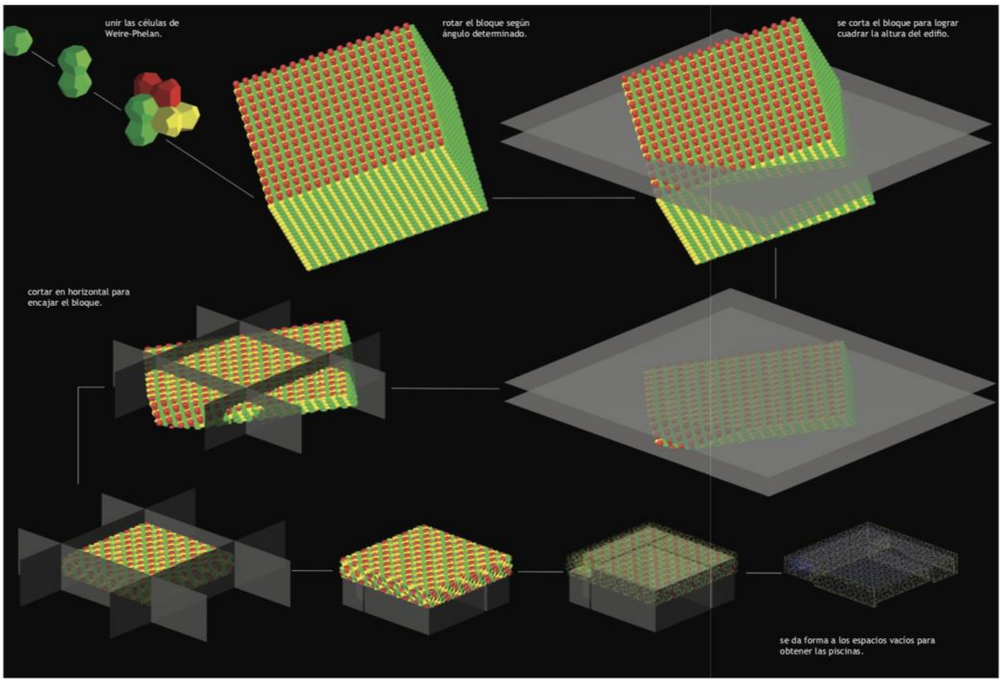


Figure 13: Cutting process Structure [1]

During the creation of the building they used a unique program specially made for designing this geometry. Because there was no access to this program, other ways to create an identical building had to be found. The first step in this process was to find the easiest and most efficient way to create a structure out of the Weaire Phenom model without spending a lot of time trimming and cutting every single line in AutoCAD individually. The easiest way to cut a building in 3D is through a certain amount of commands and using the slice command in AutoCAD. The method used to cut 3D objects is shown in Figure 14.

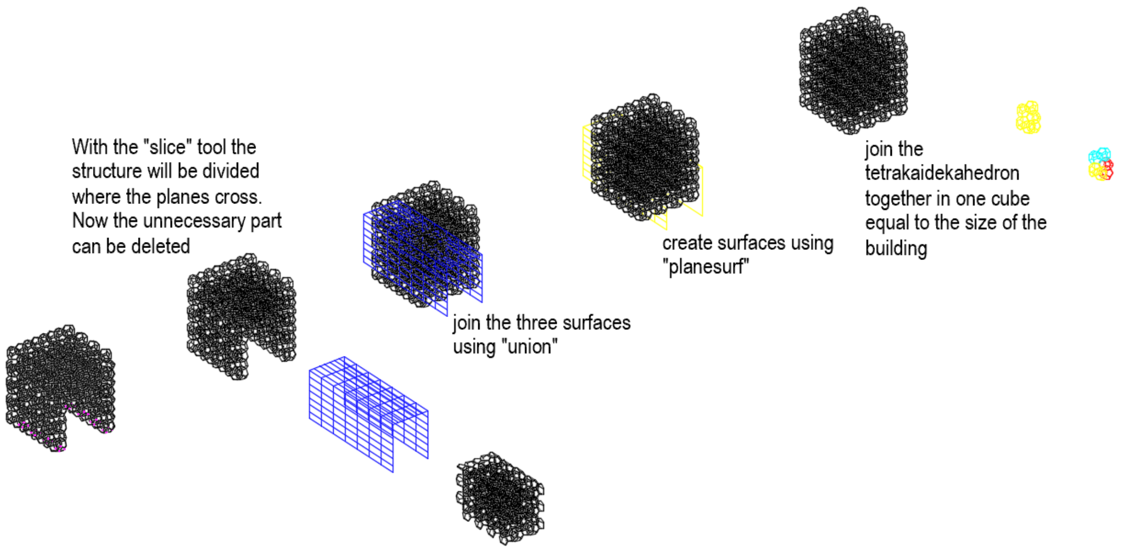


Figure 14: Method of cutting objects in 3D

Once this method was established, the first testing model was created in AutoCAD. This first model was a single cube, equal to the real structure but with only one room and the over span was smaller, Figure 15. Also, in this model no user defined materials were used to get a better understanding on how the structure and the VTAM works. For the first testing phase the construction was divided in three groups. The outer façade, the inner façade and inner web based on the Weaire Phenom design.

The correct dimensions of the cube could be diverted from the different plans available through the book that is written about the WaterCube. The following drawings, as shown in Figure 16, will give a perspective on how the elevation and inside of the cube looks like in reality.

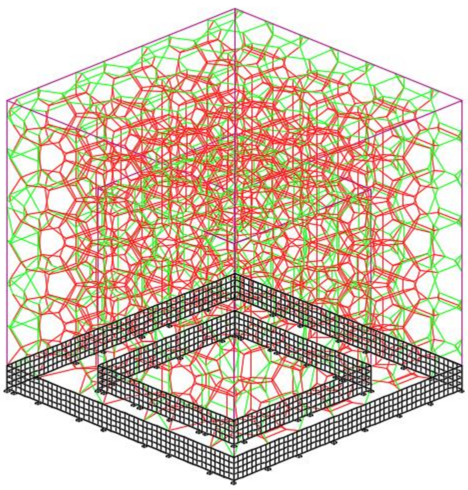


Figure 15: First testing model made through the cutting method

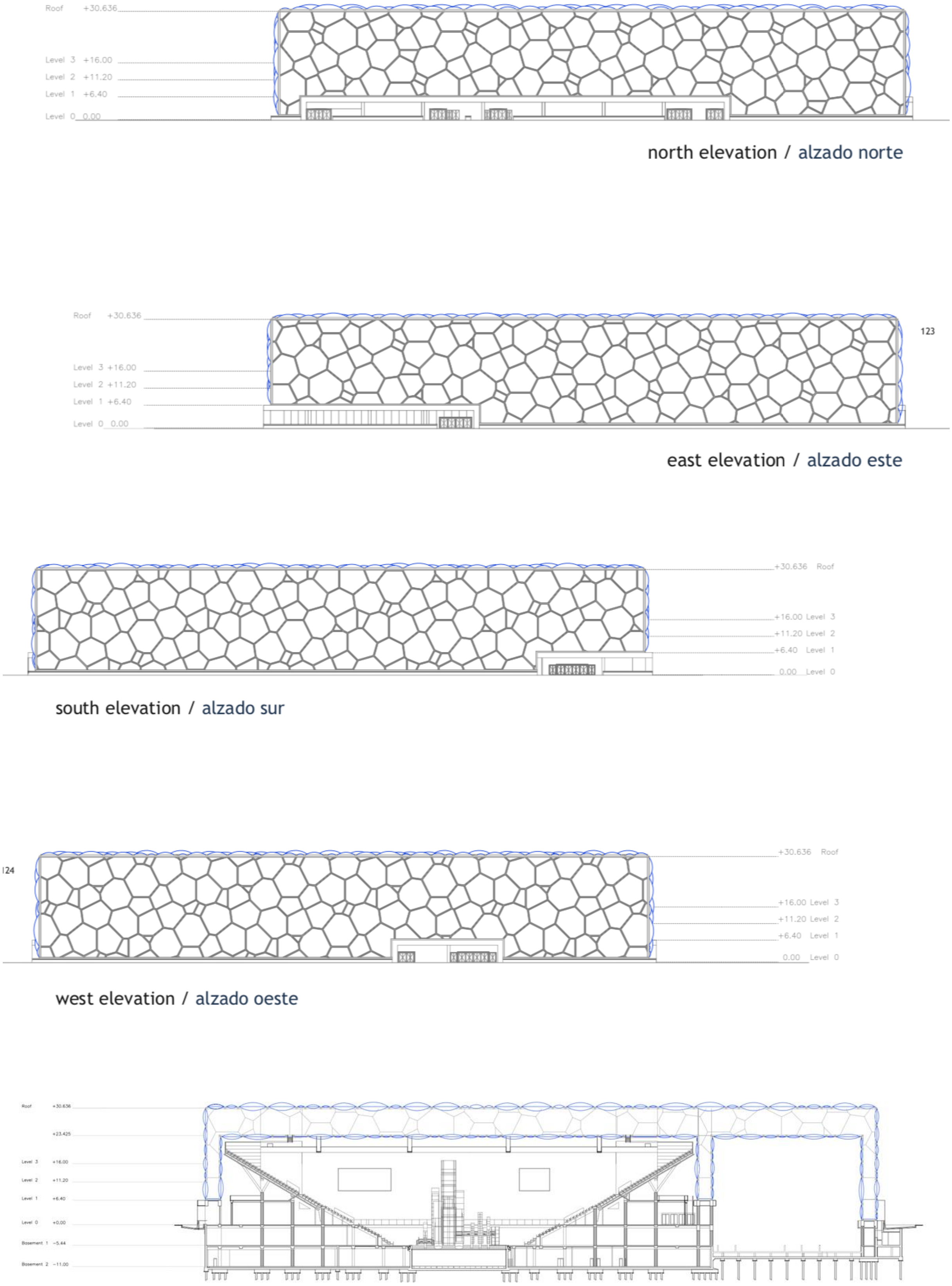


Figure 16: Elevation of the building and the inside structure [1]

7 Architrave

Architrave is a program that works in collaboration with the VTAM and exists out of two main parts. The actual program, where the structure will be evaluated and the Architrave Plug-in. [11]

7.1 Architrave plug-in

The Architrave plug-in works in collaboration with AutoCAD. The plug-in has many different capabilities and lay-out that is efficient to work with. Because of the variety of different function, the plug-in has only the most important to complete this thesis will be explained. When the Architrave program is installed on the computer the plugin will be available in the program files of the program. To be able to work with the plugin a specific layout, made for Architrave, has to be used in AutoCAD.

The layout of the plug-in is a basic table and is divided in different sections. Figure 17 gives a visual representation on how the plug-in looks like.

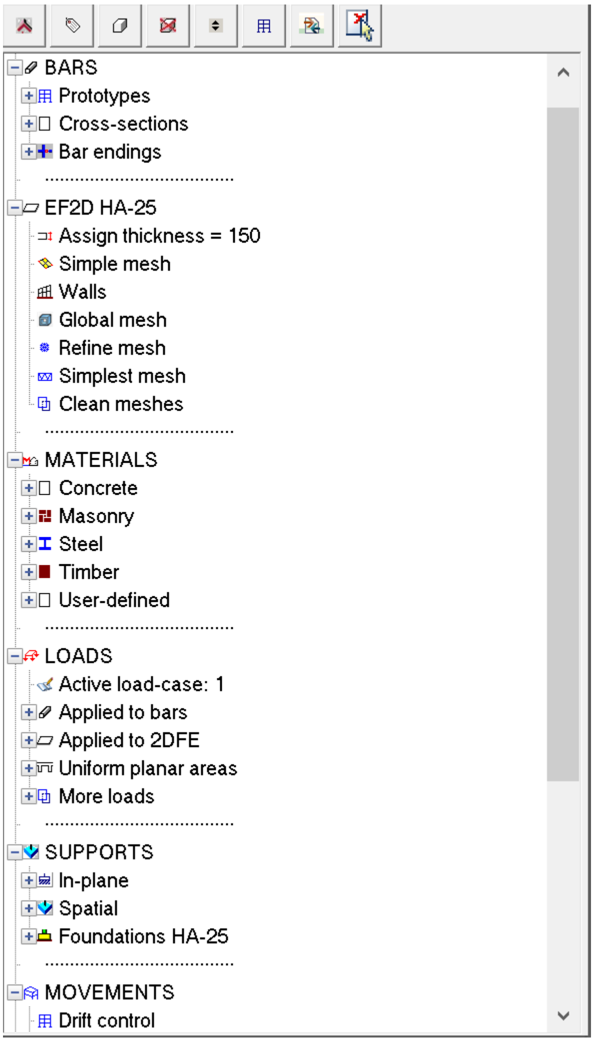


Figure 17: Architrave Plug-in

The first section of the plug-in, called “bars”, is focused on creating standard prototype trusses and the assignment of different cross sections to the designed structure in AutoCAD. The plugin provides a standard database with the most common used geometries each with their own variety of different dimensions. These standard dimensions and geometries will be used during the first testing phase to give an indication of where problems will occur and what sizes of dimensions can be expected. In some cases, for example in this project, some geometries and plate thicknesses will be needed that are not seen as standard. In that case, the plug-in offers a different approach to extent the original database with user defined geometries and dimensions. These geometries will automatically be saved in an .aver file and be needed when uploading the structure to the architrave program and the VTAM algorithm.

The creation of the user defined geometries will happen as following; the geometries and shape will be drawn through polylines in AutoCAD. The names of the sections can be chosen freely but to have an overview of what sections will be used it is advised to assign the actual dimensions of the sections to the names. The dimensions of these polylines should be drawn according to the 1cm=1drawing unit rule. When creating an open section there is asked for one polyline to design the shape and for a closed/hollow section two polylines will be needed. To create a closed section like a Circular Hollow Shape, first the outer polyline needs to be selected, followed by the inner polyline. This procedure must be followed in this order otherwise the plugin will be not accepted as a new section. The plug-in will automatically calculate the areas and inertias of the newly made user defined sections. An example of this calculation is given in Figure 18. This is a repetitive process and must be done for all the different geometries separately. The most convenient way to make a database is to first make different geometries with a wide range between the dimensions and after the optimization process make more geometries close to the ideal solution.

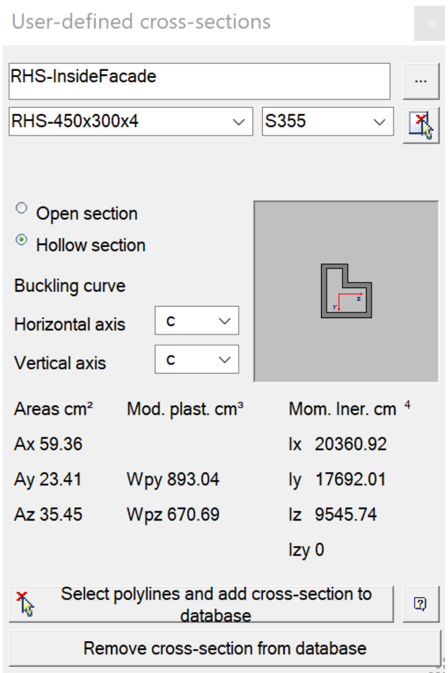


Figure 18: User defined cross section

The second important section of the plug-in is creating meshes. Meshes are the skin of the building. In this case, ETFE is used as the skin of the building. The practical use of these skins/meshes are obvious, they serve mainly to transfer the loads such as wind loads and snow loads to the load baring parts of the structure. Because the geometry of the façade is extraordinary and different on every side, meshes will be used to transfer these loads. These meshes will be applied as followed:

First, through a global mesh, the boundaries of the mesh will be chosen. Because the façade is made from many different shapes it is advised to use a small mesh that will only be connected in the corners of the different shapes of the facade. This to minimize the calculation time when using the VTAM algorithm. This option will be enforced by using the option "only in joints" available in the plug-in. When the mesh is created, the loads can be placed on the boundaries of the mesh. With the mesh applied on the structure, the loads with a certain forces per square meter, will be transferred over the complete façade. Because the skin of the building is made of ETFE, there is a need for an indication the program that this mesh is made of this material. To apply this, a new material will be made in the material section. In this section there are already different materials suggested; wood, concrete and steel, each with their own strength factor. A new material can be made in the user defined section with the same specifications of the material that will be used, in this case ETFE.

There are different options to apply loads on the structure using the Architrave Plug-in but because this building has a standard shape the wind loads will be placed on the structure as a perpendicular load and the snow loads as a horizontal load. Different loads can be assigned to different groups in the plug-in. Thus, the architrave program knows what kind of loads they are and what kind of factors will be applied during the calculation of the forces. In Figure 19 the different load cases are given. These can be deleted or adjusted according to what loads are applied on the structure.

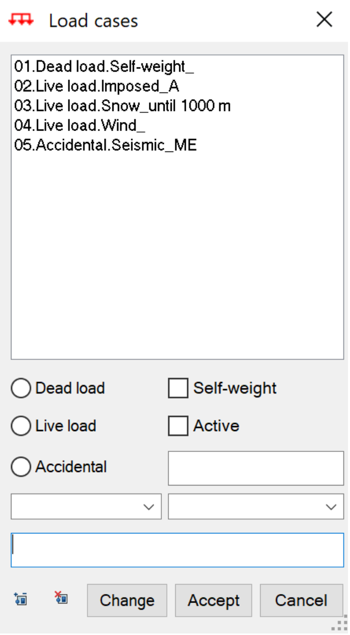


Figure 19: Different load cases

During the making of the drawing special attention is given to the assignment of different layers to different groups. When the AVEX file is imported to the algorithm it will need a reference to the used groups. This will be done through assigning layers. These layers should be assigned in AutoCAD during the design process. All the bars that are assigned to one group will have the same shape, meaning that the geometry and dimensions of section will be the same for the full group/layer. So, it is important to carefully assign bars to the right groups. Some bars will be more affected by strength and others more by deflection depending on the way they are placed in the structure. To create a collaboration between the group of bars in the argument file and the layers there is a certain way of naming the layers in AutoCAD. The name of the groups should consist of the type X.$G**. Here the X can be freely chosen, and the asterisks should be two numbers. The numbers of the groups should start at 00 and go up. It is also important that before exporting the model as an AVEX file, all the bars that are going to be optimized, are placed in consecutive groups. For instance, if group C.$G02 has no element, but group C.$G03 is not empty, the algorithm will not work, even though in Architrave, the model will load and be calculated properly without any effects.

7.2 Architrave program

Once the drawing is completed with the right setup and specifics through the architrave plug-in in AutoCAD it can be converted to an .AVEX file. The generation of this DWG file to an AVEX will happen through an action in the plug-in of architrave. With this action it is also possible to import a certain AVE/AVEX file into AutoCAD to adjust manually the results collected from the algorithm.

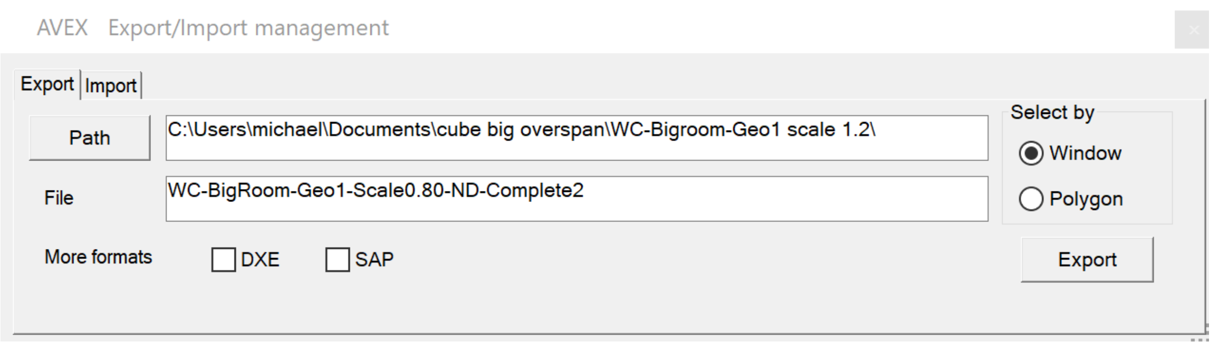


Figure 20: Import and Export files between AutoCAD and Architrave

After converting the AutoCAD drawing to an AVEX file, the program will read all the settings and context applied to the structure through the plug-in. The program has different functions, but the main function is to analyze if the structure has the right specifics to comply with the standard regulations of the Eurocode.

When the file is uploaded, the structure will be shown in the program. First, the program will show the errors that occur during the implementation in the program as show in Figure 22. Depending on these errors, the AutoCAD drawing will or will not be adjusted. To create a better image on how the structure looks like the program offers an option to create the structure in 3D. Once this function is activated the user will see the different shapes and geometry of the structure. As seen in Figure 21 the different shapes and dimensions used in the different layers of the building are clear and give a better impression on how the building will look like.

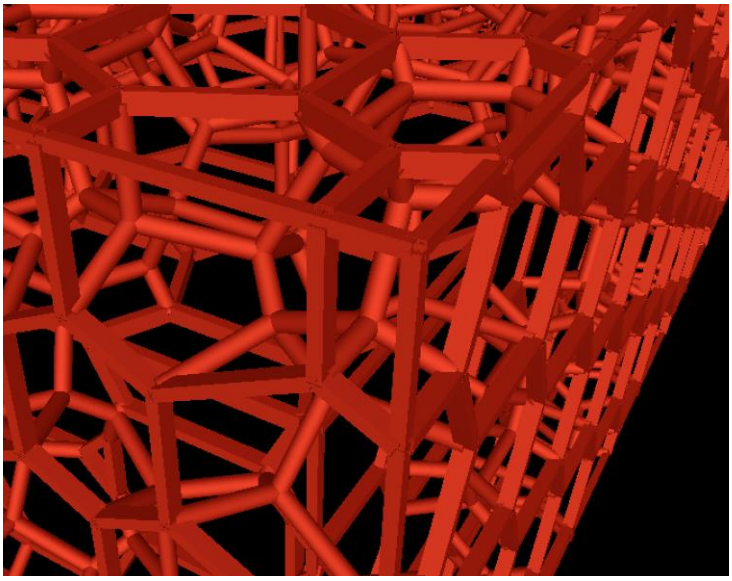


Figure 21: piece of 3D modeling with different layers

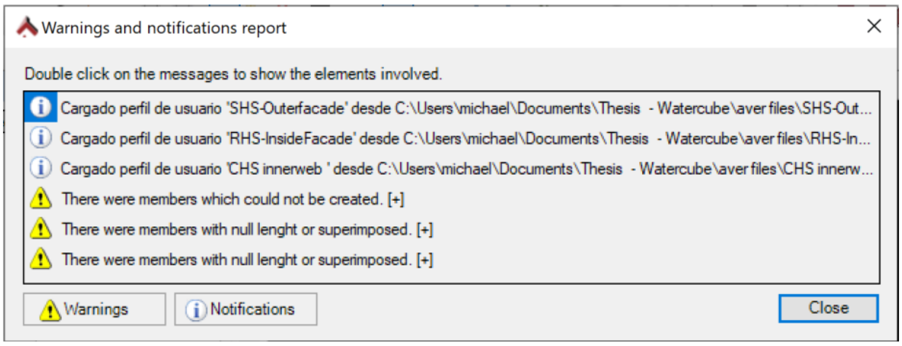


Figure 22: List of errors Architrave

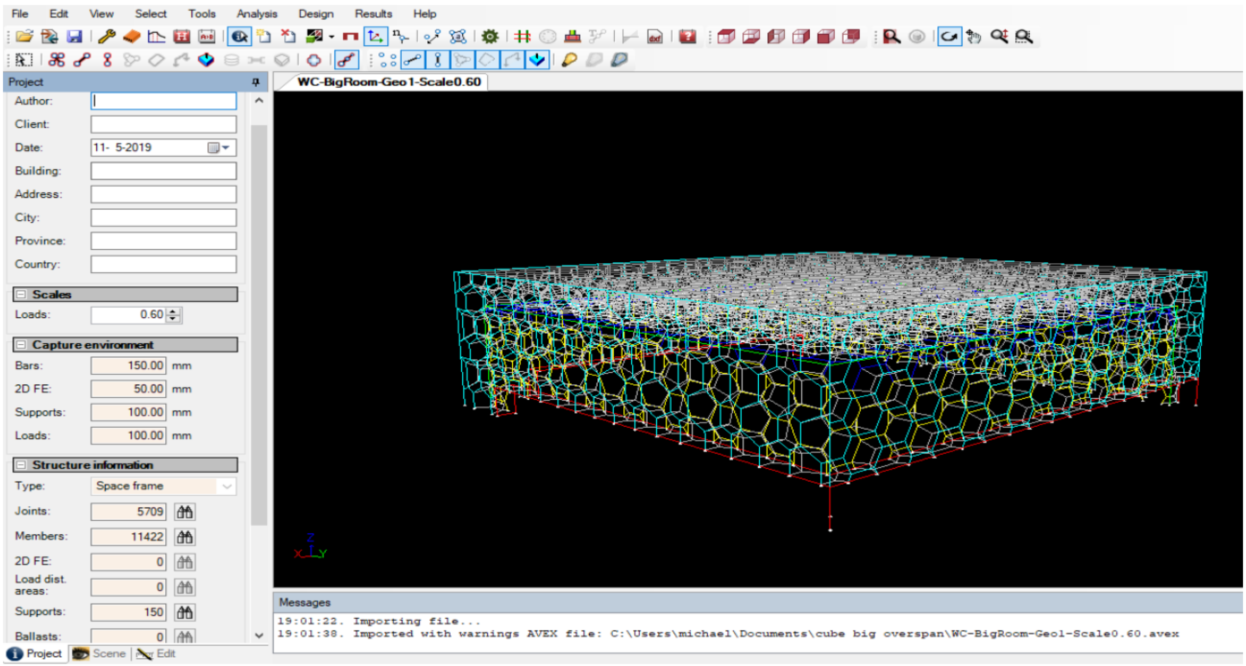


Figure 23: Architrave model and basic information

Basic information about the building is given in the column on the left side of the program. The number of joints and beams used is shown. It is also possible to give the project basic information such as; the location, information about the client and the building, etc. When more specific information is requested about a certain singular beam, hovering over this beam will give information about; the weight, the position of the beams, the length of the beams and to what group they belong to. To get a better and easier over view on the structure it is possible to dim out different parts/layers of the structures this can be done in the scene section in the column on the left as shown in Figure 23.

To continue the analyzation of the structure the function “simulate structure” needs to be activated. This function will calculate, according to the own weight and applied loads on structure what the actual forces are that are acting on every individual beam. As explained in 7.2 the load factor will be implemented according to the load groups they belong to. Forces such as; the longitudinal axial- and torsion forces, shear forces in the y and z directions will be calculated. Also, in a different tab the bending moments will be available. Because the loads are different for every structure and the values can have a big difference they can be scaled. This will make the visualization of the forces easier to understand. Also, for a more visual interpretation about the forces there is the possibility to create an animation. This animation will move in the direction of the forces from a low value to a high value. Giving the user an appealing view on how the structure will reacted to the different forces and combination of them.

When more information about a certain beam is required, the loads and strengths on a singular beam can be requested. This pop-up window will give all the information, in each part of the beam, for the axial and deflection forces.

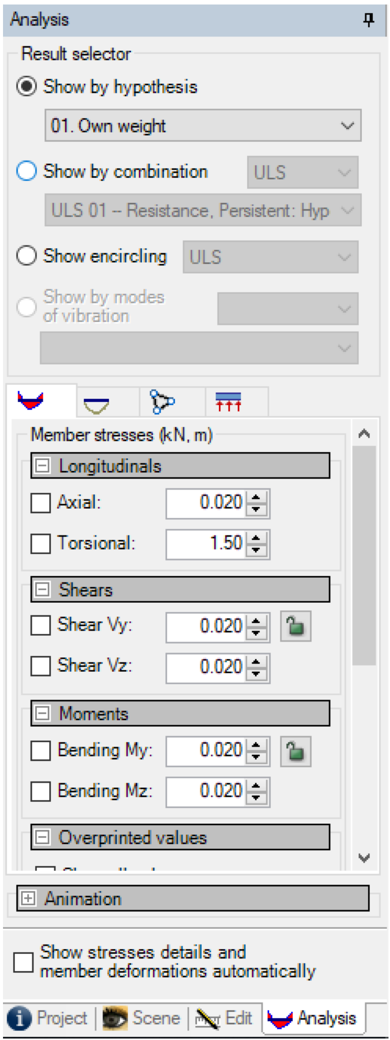


Figure 24: Analyze of the structure according to the loads

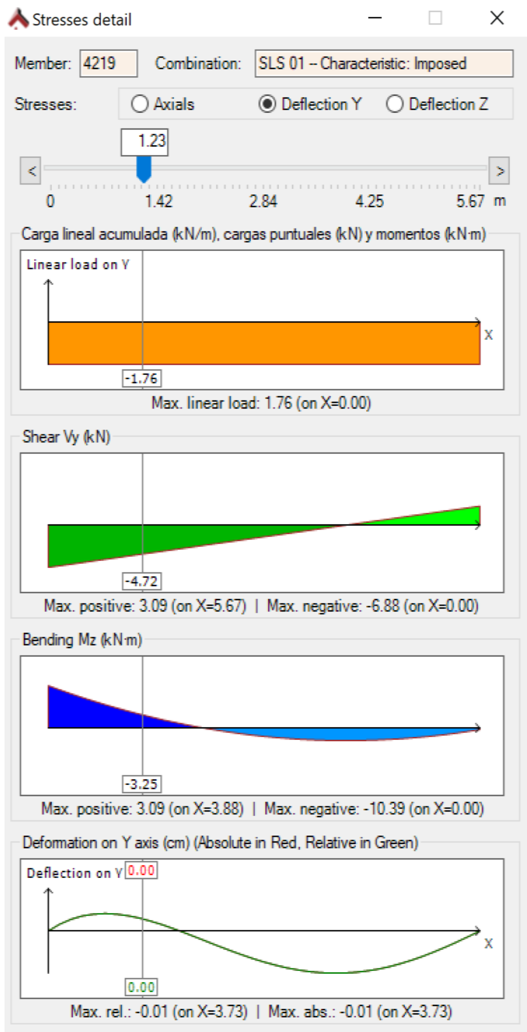


Figure 25: Detail of the stresses for each bar individual

After the analyzation of the structure is completed the “design” function will calculate the forces that will be applied on the beams and will check if these values are under the maximum values of the limited design values. These limited design values are according to the Euro-code.

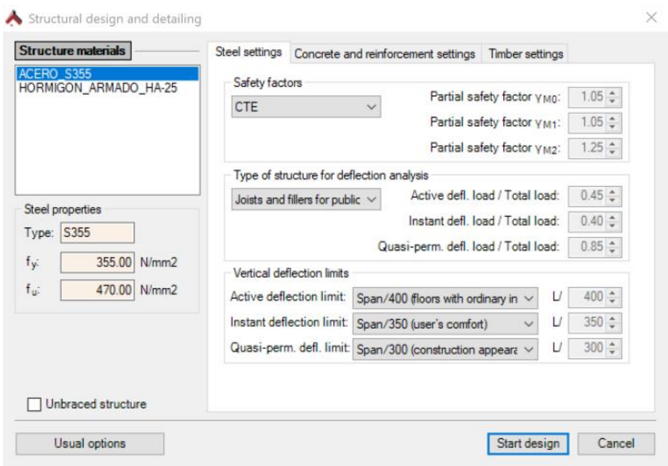


Figure 26: Design settings according to structure

The analyze will be divided in three different controlling factors. The first one is resistance, the second one is buckling and the third one is deflection. When there are certain individual beams that not comply to the standard limited state factors, they will pop up as an error in one or more of these three groups. To have the possibility to check how much these values exceed the safety factor the program offers more detailed information where all the information about the beams is given in the three different checking factors. As example, Figure 27 gives detailed information about a singular beam in specific. From this example and the information given can be diverted that the beam will fail due through deflection. In this case, when a certain beam has a failure due to one of these checking factors the program offers the option to search for beams that would comply with the factors submitted by the Eurocode. It is not recommended to use this function for all the beams. As the beams are changed, the weight will become higher which will influence the total structure. It is better to use this as an informative way to get more knowledge on what should be changed in the drawings to comply with the Eurocode. Figure 27 shows the layout of how this looks like and what the factors are based on. Once met with all the standard regulations and factors the structure is stable. The meaning of a stable structure does not necessarily mean that the used dimensions and geometry of the bars are the most sustainable solution. For this reason, a more specific and optimal solution is wanted, and this is where the metaheuristic approach through an algorithm is needed.

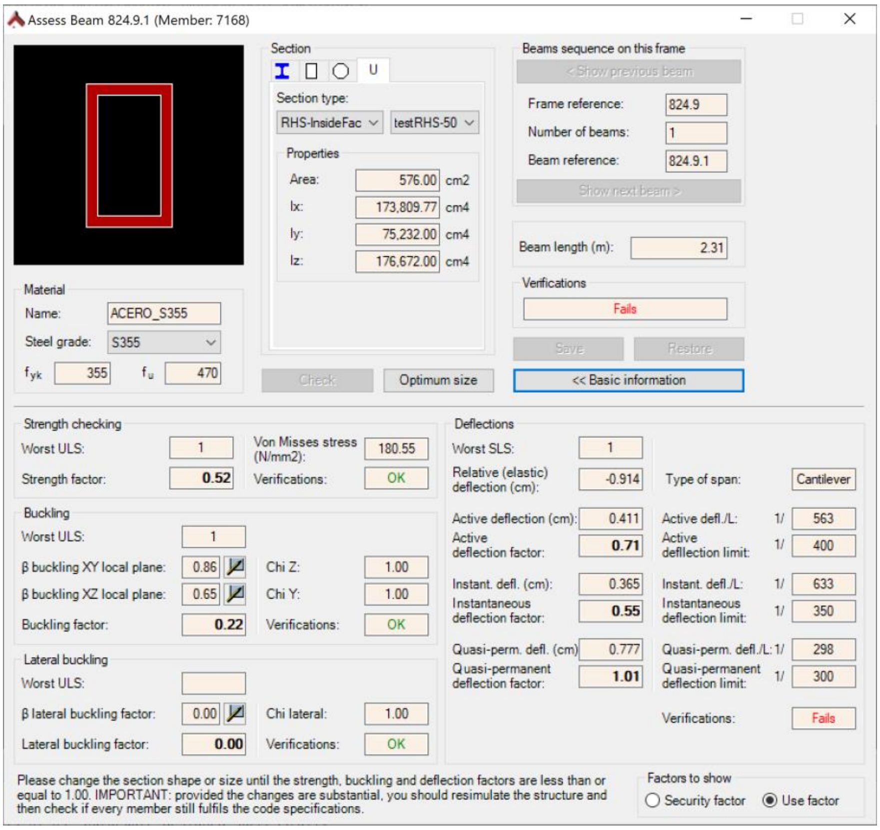


Figure 27: Basic information of the analyses

8 VTAM

As explained in 4.2.7, the VTAM is an algorithm based on the topography of a certain area. To implement these factors into coding the user needs to create a certain relation between the idea of the mapping of an area and the calculation process behind the algorithm.

There are two ways to use the VTAM algorithm. The first one is in local mode. This will reduce the time of the optimization process with a lot of time but is not available for all the users because the algorithm must be accessed in local mode. The easiest and most simple way to access the VTAM is through the website. At this moment the website is only available through the UPV internet, but this will change as the algorithm gets more optimized. This website will allow to upload the generated file in AVEX/AVE. The relation between the mapping and the calculation process will be given by an arguments file. The AVEX file will be generated through architrave as explained in 7.1. The Arguments file is a text file made in notepad on the computer and has an .txt origin. [12], [13]

The argument file will contain all the necessary information about the optimization procedure, and it exists out of two main parts. The first one contains all the mandatory parts and the second one all the user defined parts, in this part will be defined what the actual calculation is based on. The mandatory part will contain the basic information and gives the program more information on what exactly will happen and in what steps the optimization will be executed. Such as; what kind of structure it is, the format of the drawing and the type of research engine the algorithm will use. As explained previously, the algorithm is based on hotspots and the exploration around these hotspots. In this file, the assignment of the number of hotspots and explorations the algorithms need to carry out will be possible. To create a more visual image of where the hotspots are, the algorithm gives the option to create a 2D map. It is also possible to let the algorithm only search for valid configurations, nevertheless this option will slow down the progress because it takes longer before the program encounters one valid option. After the progress, the algorithm will create two lists, one ok list and one taboo list. This can also be deactivated if wanted. One of the more important parts, because this process is heuristic, is the possible to add a certain configuration that individually will be checked. When a configuration has been executed and the user wants to re-check one certain option, then the algorithm will only check this option.

The second part gives the user the freedom to let the algorithm investigate more user specified options and different restraining's to get a more detailed and specific solution. There are many different options but the most important ones that were used for this project were; checking of all the different states such as Serviceability limit state (SLS) and Ultimate Limit State (ULS), applying a maximum steel strength, assigning a maximum allowed movement in the X,Y and Z direction, the evaluation criteria in which the cost will be given and the optimization fields that gives the algorithm more information about what exactly needs to be optimized.

The website offers the option to add an ok-list or taboo-list of previous executed researches. This will make the process go faster if the user wants to re-evaluate a structure. On the website there are two crucial parts added on the website as well that will increase or decrease the amount of time needed to investigate a certain problem. The first one is the number of slots; this will be the number of processors the program will use to solve the problem. In other words, the number of computers that will be used in the cluster. The second one is the amount retries without any significant improvement. The layout of the website is given in Figure 28..

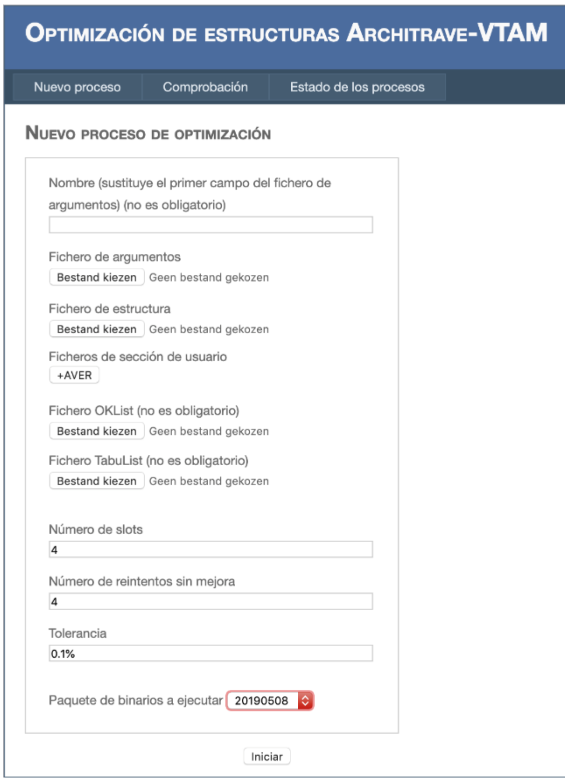


Figure 28: Layout VTAM

9 Models

As stated previously, the buildup of the actual model is based on the Weaire Phenom model. Out of this as the actual building a few test models were made to analyze the outcome of the worst situation in the building.

9.1 Actual Model

A replica of the actual model was created through the above-mentioned method and with similar dimensions and shapes of the beams. The actual model exists out of three rooms with each their own dimensions. The three rooms will each have their own swimming pool and the biggest room with has an over span of 100m and a capacity of 15000people.

To create an optimal solution for a structure a metaheuristic approach is needed. Not only through an algorithm but also the user will need to provide information and knowledge to the program to minimize the calculation process. The first step is to divide the structure into the correct groups. These groups will each have their own dimensions in one of the three different shapes as mentioned above and will be chosen according to the type of forces the beam will have to resist. For example, beams in a vertical position will have a different force impact then beams in a horizontal position.

The different layers and dimensions are given in Table 7.

Table 7: Different layers and dimensions used

Description	Group	Dimensions	Color of layer
ENTRANCE PUBLIC	.$G00	SHS 300x300x20	Red
INNERWEBROOF1	.$G01	CHS 269x28	Grey
INNERWEBROOF2	.$G02	CHS 369x20	Grey
INNERWEBROOF3	.$G03	CHS 469x40	Grey
INNERWEBROOF4	.$G04	CHS 469x40	Grey
INNERWEBROOF5	.$G05	CHS 610x40	Grey
INNERWALLS	.$G06	CHS 469x40	Grey
INSIDEFACADE	.$G07	SHS 300x300x20	Cyan
INSIDEROOF	.$G08	RHS 500x300x40	Dark Grey
INSIDEWALL	.$G09	RHS 450x300x30	White
CORNERINSIDEWALLBUCKLING	.$G10	RHS 500x300x40	Blue
CORNERINSIDEWALLRESISTANCE	.$G11	RHS 500x300x40	Blue
OUTSIDEFACADE	.$G12	SHS 300x300x20	Green
OUTSIDEROOF	.$G13	RHS 50x300x40	Purple
OUTSIDEWALL	.$G14	RHS 450x300x30	Black

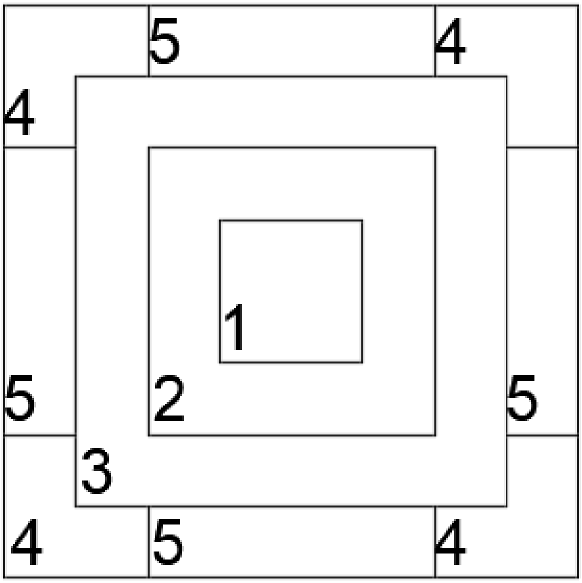


Figure 29: division of the roof for the different layers

The roof structure is divided in 5 different groups, each according to the location of the beams in the roof. These groups were made from the assumption that the beams in center of the roof will not need the same dimensions as the beams used on the side of the structure.

The Dimensions given in Table 7 are chosen by the user and gave the best outcome with the minimum errors in architrave. In total there are two actual models created. Both with the same scale but with a different geometry. The reason for this is to see the difference of how the forces would be transferred to the ground and if the same problems or weak points of the structure would occur at the same places.

Model one:

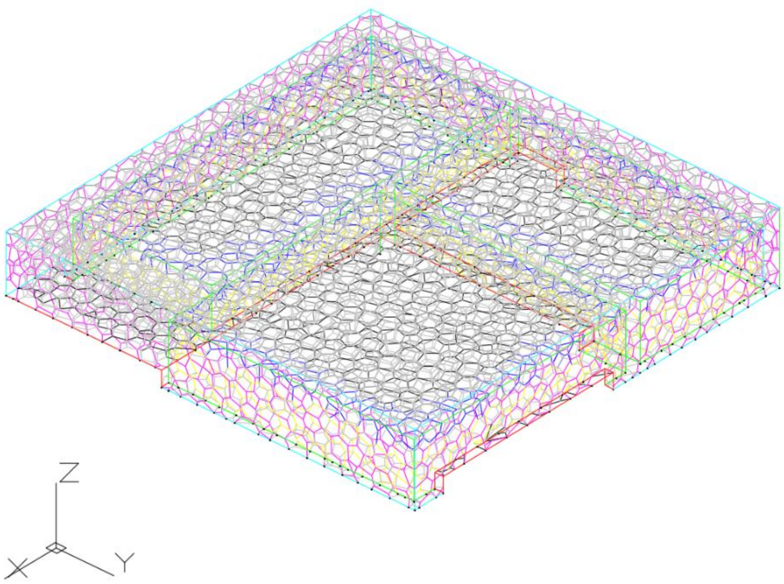


Figure 30: Actual structure model 1

Model two:

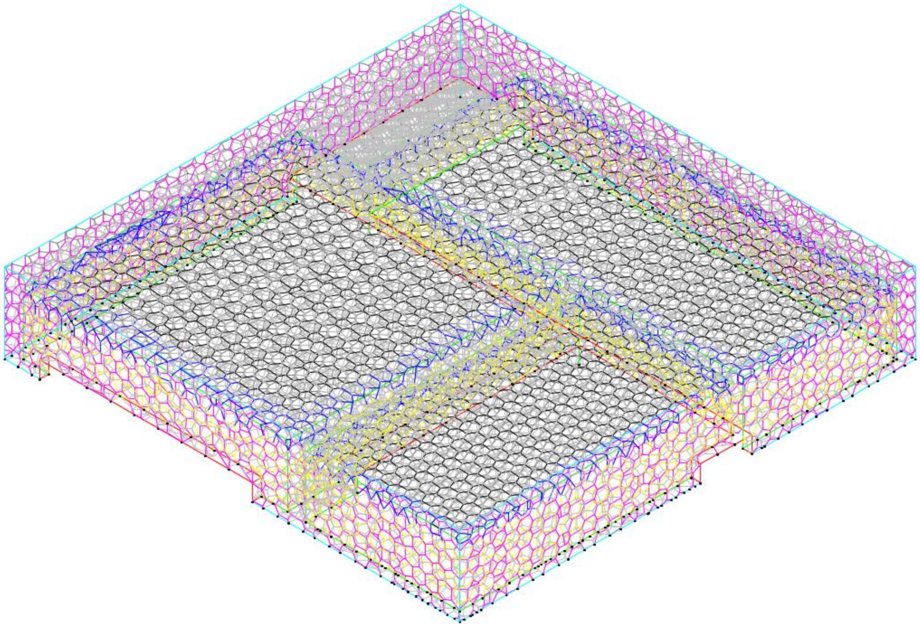


Figure 31: Actual structure model 2

9.2 Testing Model

After analyzing the actual model in architrave some assumptions could be made. The biggest span of the building (100m) creates the worse situation in the structure. According to this information test models could be simulated with the same influences as the real building. In total four different test models were made. Thus, to make a comparison with each other. The different test models were made from two different geometries each with two different scales which comes to a total of four different models. The dimensions and shapes of beams assigned to the different groups are the same in all the files. So, the change of errors due to resistance, buckling and deflection comes from the change in the scale or the rotation of the structure.

The reason why there is chosen for these four different models is: first, the geometries can individually be compared with each other to see what happens when the dimensions of the structure change. Secondly, the two geometries can be compared with each other to see what happens if the Weaire-phenom model is rotated in a different angle.

The first model:

The first model is named “WC-BigRoom-Geo1-Scale1”. The geometry of this model is based on the geometry of the real building. Also, the dimensions of the used beams, with other words the width of the water bubbles and the number of beams used is almost equal to the real building. In total there are 11422 steel beams present in this model and 5709 joints. The structure weights 10.723Ton.

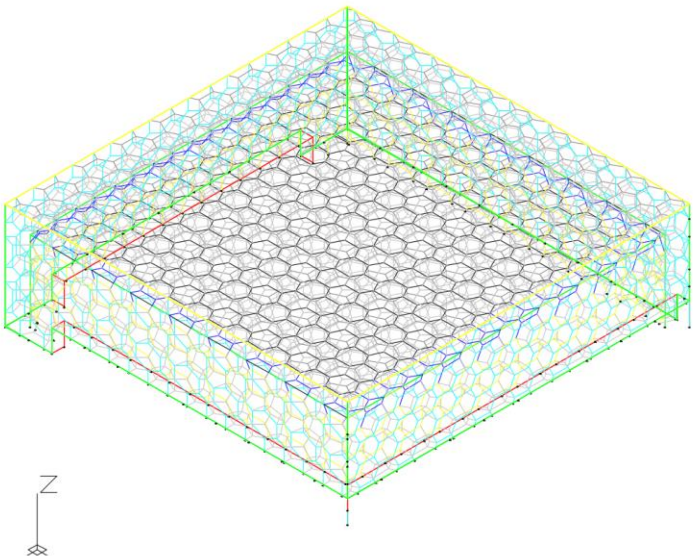


Figure 32:WC-BigRoom-Geo1-Scale1

The second model:

The second model is named “WC-BigRoom-Geo1-Scale1,2”. The geometry of this model is also equal to the geometry used in the real building. The only difference here is that dimensions of the beams will be larger because the Weaire phenom model has been scaled with 1.2 what leads a bigger width of the water bubbles and less beams and connections. In total there are 5247 steel beams present in this model and 2656 joints. The structure weights 7.148Ton.

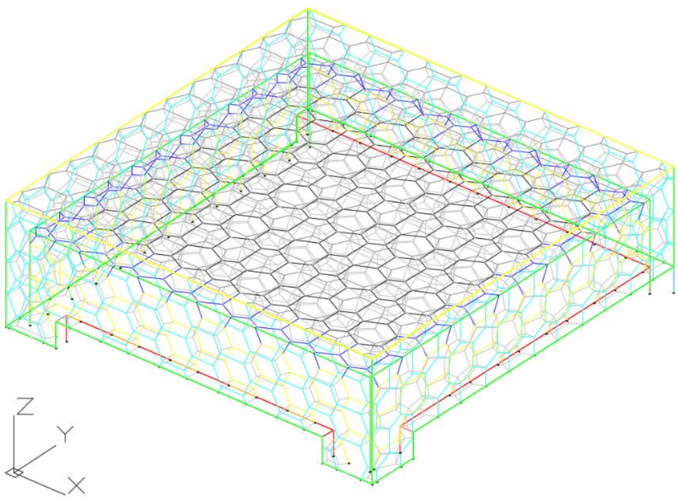


Figure 33: WC-BigRoom-Geo1-Scale1,2

The third model:

The third model is named “WC-Bigroom-Geo2-Scale1”. The geometry of this model is turned is such a way that it is turned 30° on the x-axes and 30° on the y-axes. The dimensions of the used beams and the width of the water bubbles will be like the real building. In total there are 9715 steel beams present in this model and 4852 joints. The structure weights 10.560Ton.

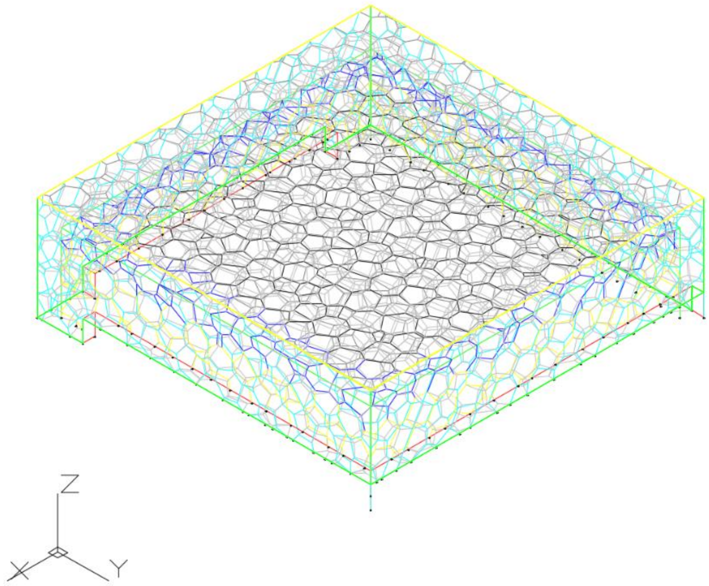


Figure 34: WC-Bigroom-Geo2-Scale1

The fourth model:

The fourth model is named “WC-Bigroom-Geo2-Scale1,2”. The geometry of this model is turned in the same way as model “WC-Bigroom-Geo2-Scale1”. The model is scaled with a factor of 1,2 which gives a bigger width of the water bubbles and less beams and connections. In total there are 5754 steel beams present in this model and 2891 joints. The structure weights 7.745Ton.

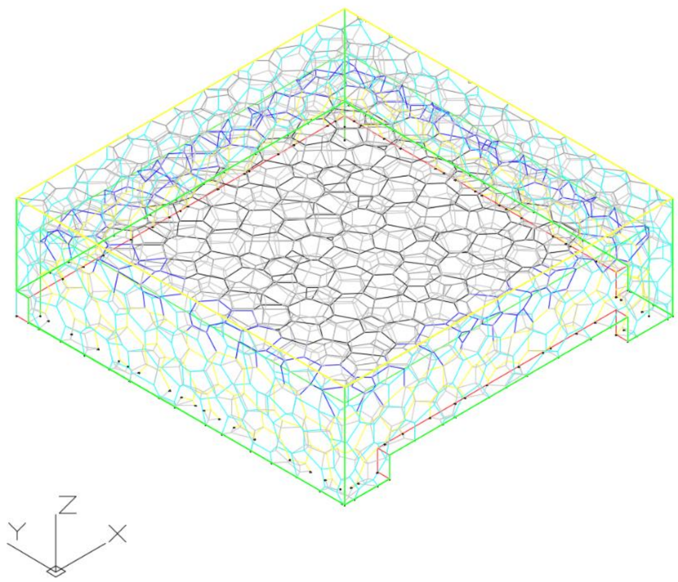


Figure 35: WC-BigRoom-Geo2-Scale1,2

To make the comparison easier to understand the general information will be summed up as following:

	Beams	Joints	Weight
Model 1	11422	5709	10.723Ton
Model 2	5247	2656	7.148Ton
Model 3	9715	4852	10.560Ton
Model 4	5754	2891	7.745Ton

10 Comparisons

Before starting with the comparison, a small word of explanation is necessary for the calculation of the stiffness of the structure. The algorithm does not take the maximum total deflection of a structure into account. This means that the user will have to check this manually in architrave. Because this is a simplified model it is possible to apply the maximal deflection in the Z direction in the argument file, but this is not possible for more complex structures.

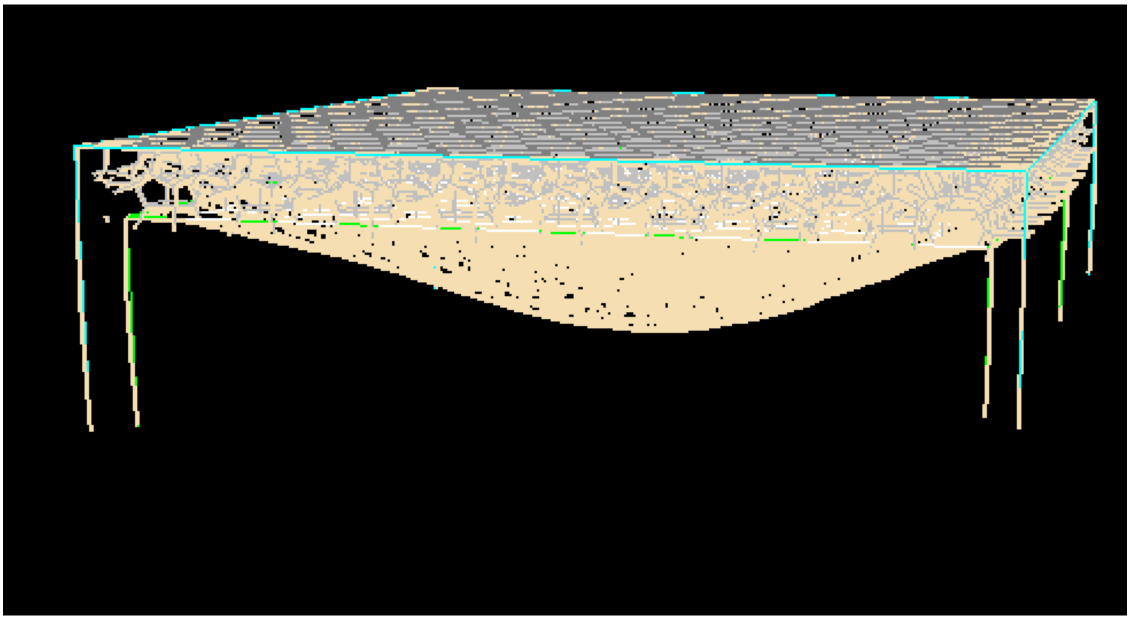


Figure 36: Deflection of the total structure

Stiffness of a construction can be considered as the structural stability with a view to resistance and deflection. Stiffness of a building does not mean that a structure cannot be able to "move", a structure that is too solid does not have the ability to compensate the loads and forces and will eventually break.

There are different types of stiffness that apply to the possible movements of a structural component: strain stiffness, bending stiffness and torsional stiffness.

A structure needs a certain stiffness to absorb loads:
- permanent loads (the own mass of a building, the permanent building elements resting on, and in the structure)
- variable loads (wind, snow)
- internal and external loads (shrinkage, settlements, temperature differences).

The degree of stiffness of a steel beam can be given by the deflection value, for example with a value of L/250 (i.e. length of the beam/250).

The following three aspect play significant part in the stiffness of a building:
- the strength and stability of a structure is related to the resistance to failure (breakage or permanent deformation of permanent loads)
- the stiffness of a structure or structures is related to the resistance of bending (elastic deformations, variable loads)
- the stability of a structure is mainly related to the resistance to horizontal forces.

If we apply this information to the test files of the WaterCube, knowing that this construction will be a cube with the dimensions 100mx100mx31m the main deflection problem will be in the center of the structure because of length of the over span. This deflection will happen along the Z-ax of the structure. Because the building is a cube and the height in comparison with the width is small the deflection in the X– and Y-direction can be neglected. As Shown in Figure 36 the deflection of the structure in the middle and in the Z-direction will be of the greatest value.

The maximum deflection for the over span can be calculated with the formula:

$$\delta < \frac{L}{500} \tag{22}$$

Diverted from equation 22, knowing that the length of the building is 100m, the maximal deflection in this construction cannot be more then 0,20m. To meet with this maximum value, the argument file with be revised with a maximal deflection in the Z-ax of 200mm.

10.1 Results diverted from architrave

Before implementing the different .AVEX files extracted from the architrave program in the VTAM algorithm each test model was analyzed manually in architrave to get a better understanding on how the structure works. According to the results given in architrave, after the analyzation of each individual model, some assumptions could be made without implementing the models in the VTAM algorithm. The dimensions and shapes of beams assigned to the different groups are the same in all the files. So, the change in errors due to resistance, buckling and deflection comes from the change in the scale or the rotation of the structural component of the building.

- WC-Bigroom-Geo1-Scale1

	Without external forces	With external forces
Errors	0	0
Maximal displacement in Z direction	-13,504cm	-14,387cm

Remarks: This test file has 0 errors, meaning that it is stable and that there is an optimal solution to creating this construction. The used dimensions for achieving this are probably not the optimal solution but this proofs that the structure works and can be designed without problems.

- WC-Bigroom-Geo1-Scale1.2

	Without external forces	With external forces
Errors	22	24
Maximal displacement in Z direction	-18,157cm	-19,908cm

Remarks: The errors occurring in architrave are due to deflection. In the first model, without implementing the factor of the failure goes from 1,36 to 1,01. In the second model, with forces the factor of failure from 1,44 to 1,01.

- WC-Bigroom-Geo2-Scale1

	Without external forces	With external forces
Errors	10	13
Maximal displacement in Z direction	-14,65cm	-15,66cm

Remarks: The errors occurring in architrave are due to deflection and resistance. In the first model, without implementing the factor of the failure goes from 1,24 to 1,01. In the second model, with forces the factor of failure from 1,31 to 1,01

- WC-Bigroom-Geo2-Scale1,2

	Without external forces	With external forces
Errors	14	23
Maximal displacement in Z direction	-18,41cm	-19,45cm

Remarks: The errors occurring in architrave are due to deflection and resistance. In the first model, without implementing the factor of the failure goes from 1,44 to 1,01. In the second model, with forces the factor of failure from 1,53 to 1,01.

According to these results, the geometry of the structure and the number of beams according to the stiffness of the structure is important. When the Weaire phenom model is scaled, or in other words the width of the water bubbles and the dimensions of the beams will be larger, the structure has more troubles with deflection. This comes due the fact that it has less beams or the geometry in the corners is not ideal to guide the loads from the structure to the ground. Also, due to a smaller number of beams the dimensions of the beams and the plate thickness of the beams will become bigger.

Also, similar problems occur in the three last files. Due to deflection, the corners of the inside structure will fail. The geometry of the structure has is an important factor for this. Each different geometry will transfer the forces in a different method. Because this deflection is quite small and only applies on a small number of beams and would in the real situation not lead to failure of the structure this will be overseen when optimizing the structure. Meaning that during the use of the VTAM algorithm the deflection of the of the bars individually will not be considered.

10.2 Results diverted from the VTAM algorithm

With the use of the algorithm there will be a stress checking not only for axial forces but also for bending the moments. There are different options to analyze the structure according to what sort of structure it is. The two used optimization options for this research are:

1) To check only axial forces. The type of structure will be **Steel3DTruss**

** ProblemNameAndType **
EX. WCBigRoomGeo1Scale1_Steel3DTruss _TFG

2) To check axial forces and bending moments. The type of structure will be **Steel3DFrame**

** ProblemNameAndType **
EX. WCBigRoomGeo1Scale1Complete_Steel3DFrame_TFG

Because the computing time is not that different for the both options there has always been checked on axial forces and bending moments. This option will give the best representation of the actual beam sizes necessary in this construction. The optimization option will be implemented in the arguments file.

The following paragraphs will show a more detailed explanation of the actual optimization process. To have a better understanding of what exactly is happening a word in advance:

All the test models started with a large weight. After optimizing these models for the first time with the VTAM algorithm the weight was reduced significant. The reason for the big difference in weight with the first optimization comes from the fact that initial dimensions used to create the building were too big for the actual loads applied on the structure. The original weight is not included in the comparison on the charts of the total weight of the structure. The reasoning behind this is to have a better understanding on how the metaheuristic approach of the algorithm works after the first optimization. Also, by having values that are laying closer to each other the charts are more specific.

The weight differences after the first optimization are not that immense anymore. To have a good optimization technic the optimized structure will be manually checked before the following optimization will start. For this reason, different colors will be present in the comparison of the total weight for each individual model. The stats with a red color mean that the group of dimensions assigned to an individual layer had reach his minimum section and had to be replaced with a group were the range of dimensions is larger. Because of the change in groups, the weight of the first optimization after this adjustment will be greater than the previous one. To have a better understanding on how the dimensions changed and to what groups they were assigned a table with the dimension changes is added to show in detail each user changed dimension that happened during the optimization process.

To have a better understanding on how the evolution of a singular group evolves within a layer, the area is calculated after each optimization process. These areas are then placed in charts to see the improvement that is progressively obtained throughout the optimization process. According to these values, conclusion according to each test model in general could be made.

10.2.1 WC-Bigroom-Geo1-Scale1

Test model one started with an own weight of the structure of 10723 Ton. After the first optimization, this value was reduced to 1117,79Ton. As shown in Table 8 dimensions of the layers 0,1,4,7,12,13 and 14 already reached their minimum dimensions available in the assigned group. These layers where then manually changed to other groups. The changes of group happened in AutoCAD and the newly assigned groups where pre-designed groups that are available in the architrave. After the third correction similar minimum values occurred.

The follow figures and tables are according to the first Test Model and give a better prospective on how the optimization was preformed and what dimensions were used during the optimization process.

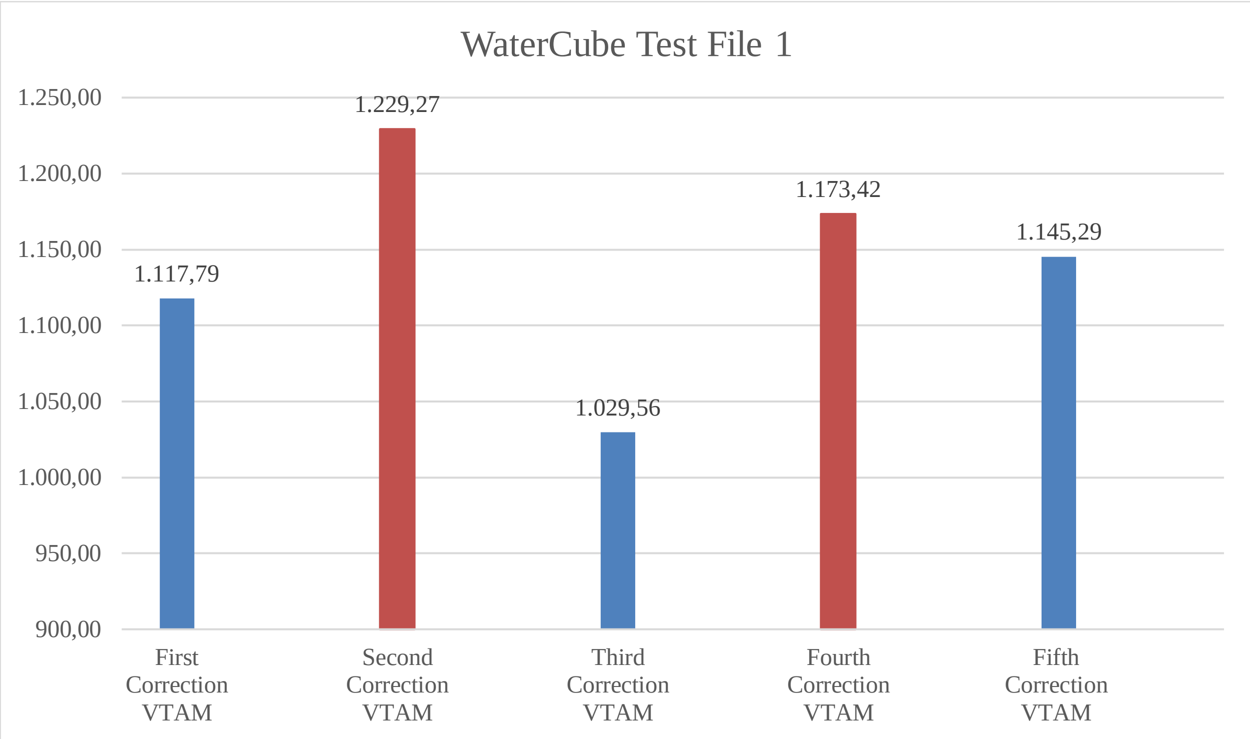


Figure 37: Total Weight WaterCube Test File 1

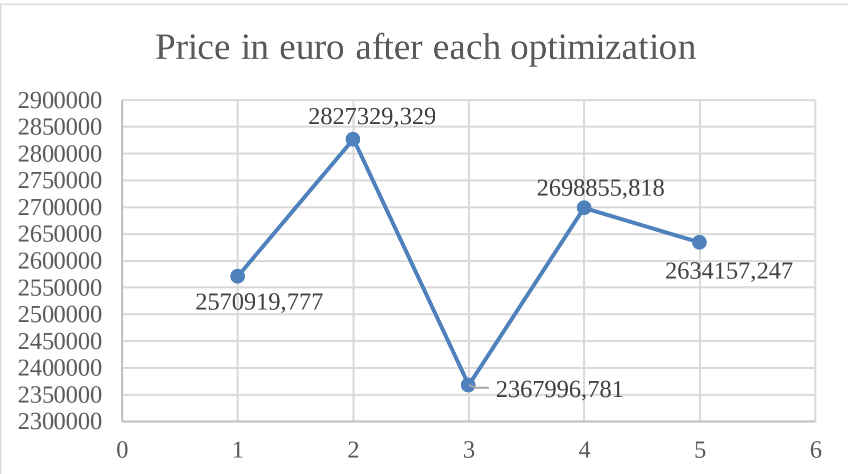


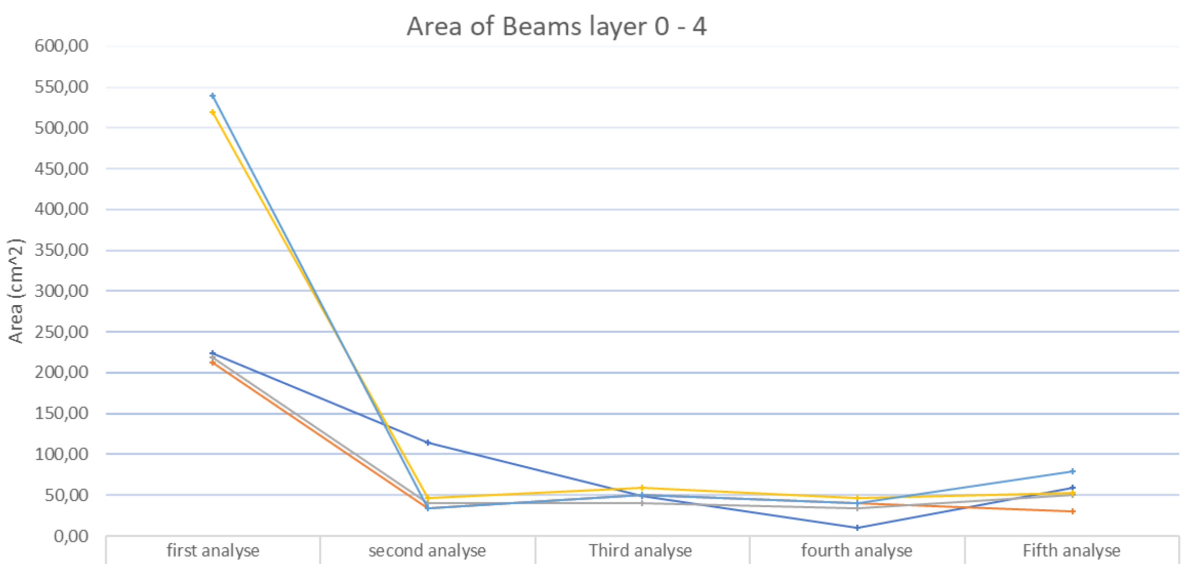
Figure 38: Price comparison model 1

Table 8: Dimensions changes - Test model 1

Geometrie 1 - Scale 1 - WithForces - Diemension change of beams																	
Layer	Name	Type of beam	Dimensions Given by me without any errors	First Correction VTAM		Changes made in Dimensions manually		Second Correction VTAM		Third Correction VTAM		Changes made in Dimensions manually		Fourth Correction VTAM		Fifth Correction VTAM	
0	Entarence public	SHS	300x300x20	0	250x250x12	PHCS355UNIIc	250x250x12,5	50	200x200x6,3	12	80x80x3,2	-		56	160x160x10,0	33	140x140x5,0
1	innerwebroof 1	CHS	269x28	0	269x4	PH0S355UNE1c	-	62	323,9x5	1	319x4	PH0S355UNIc	273x5	45	193,7x5	45	193,7x5
2	innerwebroof 2	CHS	369x20	1	319x4	-	-	1	319x4	0	269x4	PH0S355UNIc	244,5x5	62	323,9x5	62	323,9x5
3	innerwebroof 3	CHS	469x40	2	369x4	-	-	4	469x4	2	369x4	-	-	3	419x4	3	419x4
4	innerwebroof 4	CHS	469x40	0	269x4	PH0S355UNE1c	-	62	323,9x5	1	319x4	PH0S355UNIc	273x5	76	406,4x6,3	76	406,4x6,3
5	innerwebroof 5	CHS	610x40	3	419x4	-	-	3	419x4	3	419x4	-	-	3	419x4	3	419x4
6	innerwalls	CHS	469x40	1	319x4	-	-	1	319x4	2	369x4	-	-	3	419x4	3	419x4
7	InsideFacade	SHS	300x300x20	0	250x250x12	PHCS355UNIIc	250x250x12,5	55	150x150x10	30	120x120x5	-	-	35	150x150x5	31	100x100x6,3
8	InsideRoof	RHS	500x300x40	1	250x300x4	-	-	0	180x300x4	1	250x300x4	PHRS355UNEIc	300x200x6,3	64	250x150x6,3	64	250x150x6,3
9	InsideWall	RHS	450x300x30	1	250x300x4	-	-	2	350x300x4	1	250x300x4	PHRS355UNEIc	300x200x6,3	67	260x180x6,3	67	260x180x6,3
10	InsidewallBuckeling	RHS	500x300x40	5	250x300x10	-	-	6	350x300x10	3	450x300x4	-	-	3	450x300x4	3	450x300x4
11	InsidewallResistance	RHS	500x300x40	7	450x300x10	-	-	18	350x300x40	3	450x300x4	-	-	3	450x300x4	3	450x300x4
12	OutsideFacade	SHS	300x300x20	0	250x250x12	PHCS355UNIIc	250x250x12,5	53	220x220x6,3	45	140x140x8	-	-	59	140x140x12,5	57	200x200x8,0
13	OutsideRoof	RHS	500x300x40	0	180x300x4	PHRS355UNEIc	250x150x8	64	250x150x6,3	72	300x200x6,3	-	-	64	250x150x6,3	64	250x150x6,3
14	OutsideWall	RHS	450x300x30	0	180x300x4	PHRS355UNEIc	250x150x8	45	180x100x5,0	47	200x100x5,0	-	-	41	200x100x4,0	33	150x100x4,0
Bending moment in Z direction				19,884				19,052		19,998				19,938		19,98	
Total cost: Steel Weight And Built Up Costs (kg)				1.117.791,207558				1.229.273,621088		1.029.563,817644				1.173.415,572848		1.145.285,759440	
Total cost: Steel Weight And Built Up Costs (Ton)				1.117,79				1.229,27		1.029,56				1.173,42		1.145,29	

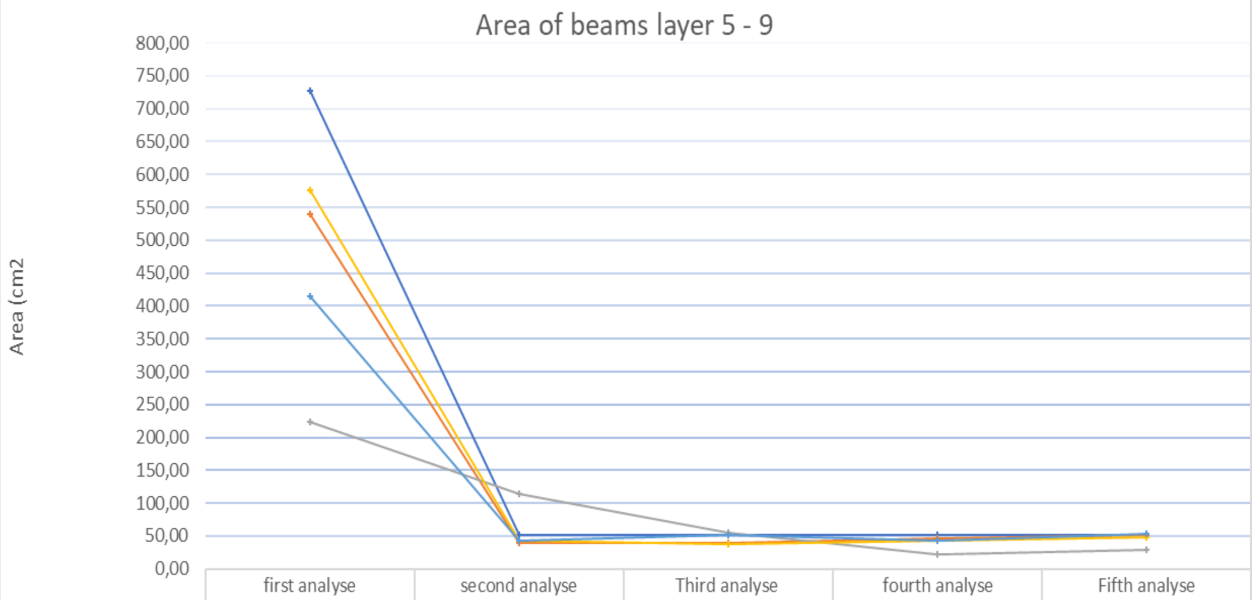
Table 9: Area of the beams - Test model 1

Geometrie 1 - Scale 1 - WithForces - Area of Beams					
Layer	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
0	224,00	114,24	48,37	9,72	58,88
1	211,97	33,3	50,09	39,58	29,64
2	219,29	39,58	39,58	33,30	50,09
3	519,14	45,87	58,44	45,87	52,15
4	539,14	33,3	50,09	39,58	79,19
5	727,70	52,15	52,15	52,15	52,15
6	539,14	39,58	39,58	45,87	52,15
7	224,00	114,24	54,88	22,72	28,72
8	576,00	43,36	37,76	43,36	48,37
9	414,00	43,36	51,36	43,36	53,41
10	576,00	106	126,00	59,36	59,36
11	576,00	146	456,00	59,36	59,36
12	224,00	114,24	53,41	41,52	62,00
13	576,00	37,76	48,37	60,97	48,37
14	414,00	37,76	26,72	28,72	23,18



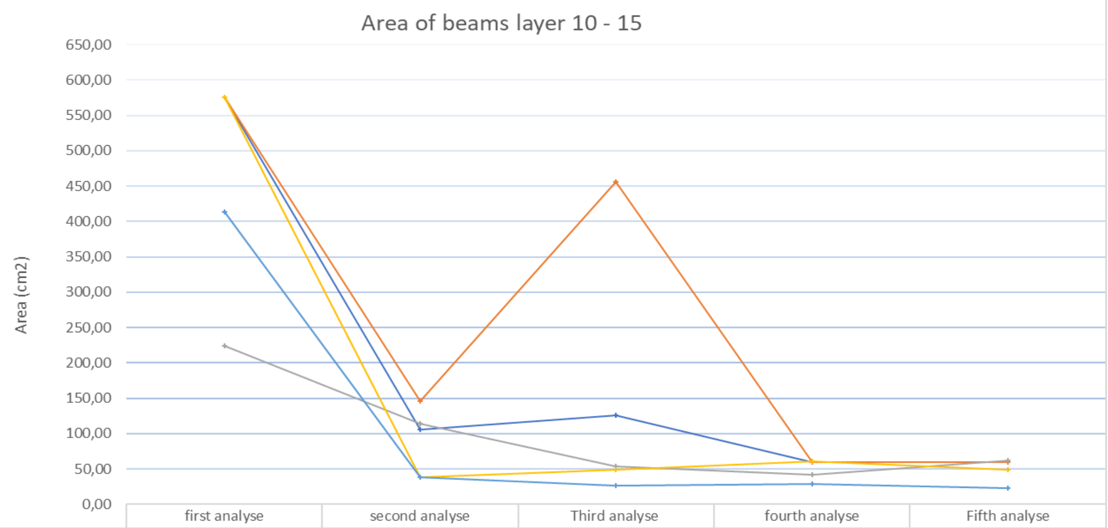
	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
Entrance hal	224,00	114,24	48,37	9,72	58,88
InnerRoof 1	211,97	33,3	50,09	39,58	29,64
InnerRoof 2	219,29	39,58	39,58	33,30	50,09
InnerRoof 3	519,14	45,87	58,44	45,87	52,15
InnerRoof 4	539,14	33,3	50,09	39,58	79,19

Figure 39: Test Model 1 - Area of beams layer 0-4



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
innerwebroof 5	727,70	52,15	52,15	52,15	52,15
innerwalls	539,14	39,58	39,58	45,87	52,15
InsideFacade	224,00	114,24	54,88	22,72	28,72
InsideRoof	576,00	43,36	37,76	43,36	48,37
InsideWall	414,00	43,36	51,36	43,36	53,41

Figure 40: Test model 1 - Area of beams 5-9



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
InsidewallBuckeling	576,00	106	126,00	59,36	59,36
InsidewallResistance	576,00	146	456,00	59,36	59,36
OutsideFacade	224,00	114,24	53,41	41,52	62,00
OutsideRoof	576,00	37,76	48,37	60,97	48,37
OutsideWall	414,00	37,76	26,72	28,72	23,18

Figure 41: Test Model 1 - Area of beams layer 10 - 15

<u>Conclusion Test Model 1:</u>

The best optimal solution found during the optimization process for model 1 is established after the third optimization with a steel weight and build up cost of 1.029,56Ton this equals a price cost of 2.367.996,781€. The area of beams represented in Figure 39, Figure 40 and Figure 41 show a natural process of the positive evolution of each group individual. After each optimization a certain group will, according to the other groups, achieve a bigger or smaller area, with the main goal of making the total cost as optimal as possible.

10.2.2 WC-Bigroom-Geo1-Scale1.2

Test model one started with an own weight of the structure of 7148 Ton. After the first optimization this weight was reduced to 1124,9Ton. As shown in Table 10 dimensions of the layers 0,12 and 13 reached their minimum dimensions available in the assigned group after the second analysis. These layers where then manually changed to other groups. The changes of group happened in AutoCAD and the newly assigned groups where pre-designed groups that are available in the architrave. After the third correction similar issues occurred.

The follow figures and tables are according to the second Test Model and give a better prospective on how the optimization was preformed and what dimensions were used during the optimization process.

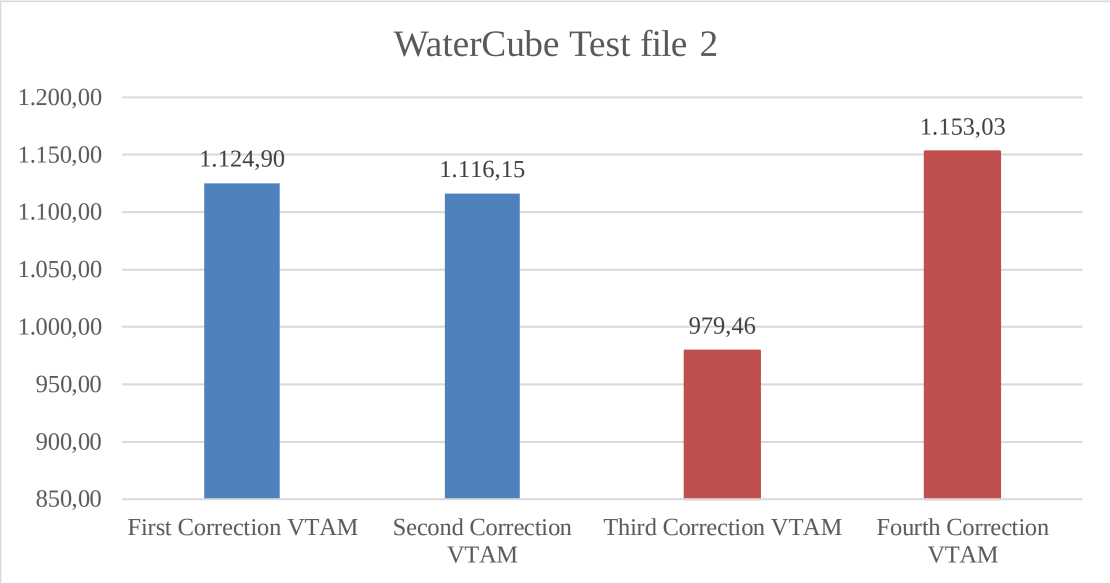


Figure 42: Total weight WaterCube Test File 2

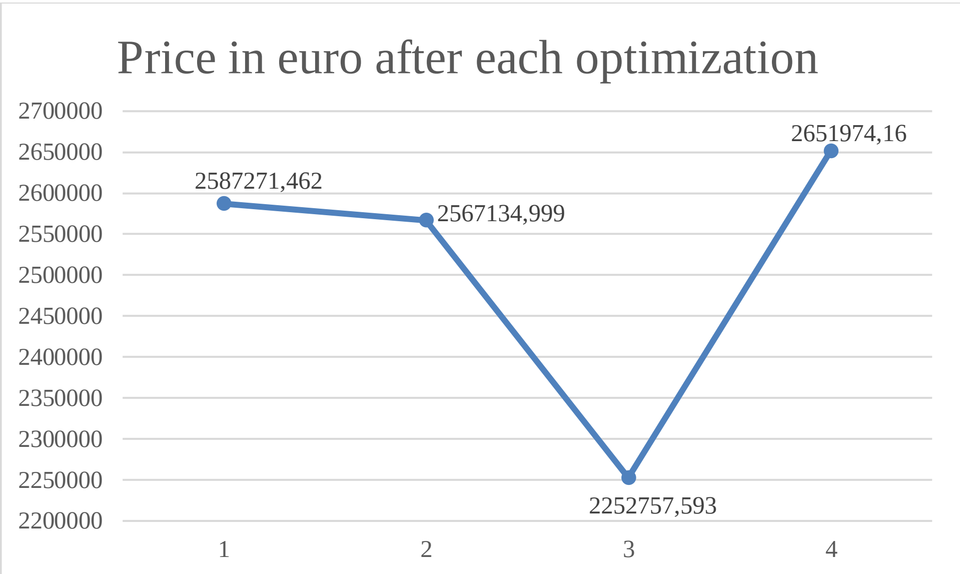


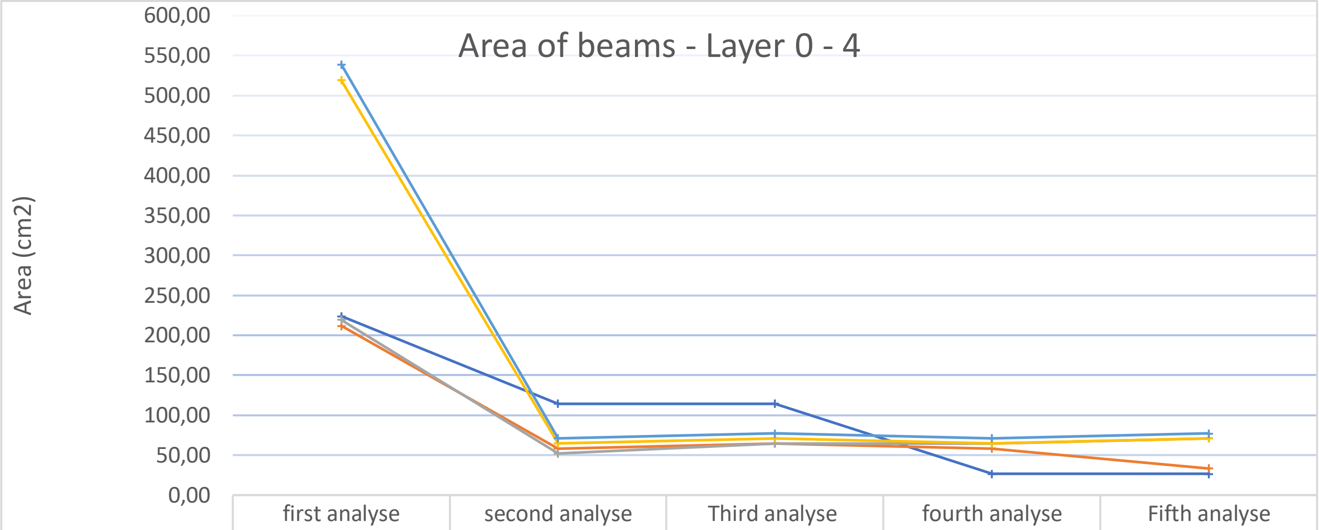
Figure 43: Price comparison model 2

Table 10: Dimension changes - Test model 2

Geometrie 1 - Scale 2 - WithForces - Dimensions change of beams															
Layer	Name	Type of beam	Dimensions Given by me without any errors	First Correction VTAM		Second Correction VTAM		Changes made in Dimensions manually		Third Correction VTAM		Changes made in Dimensions manually		Fourth Correction VTAM	
0	Entarence public	SHS	300x300x20	0	250x250x12	0	250x250x12	PHCS355UNIIC	250x250x12,5	33	140x140x5	-	-	33	140x140x5,0
1	innerwebroof 1	CHS	269x28	4	469x4	5	519x4	-	-	4	469x4	-	-	0	269x4
2	innerwebroof 2	CHS	369x20	3	419x4	5	519x4	-	-	5	519x4	-	-	6	569x4
3	innerwebroof 3	CHS	469x40	5	519x4	6	569x4	-	-	5	519x4	-	-	6	569x4
4	innerwebroof 4	CHS	469x40	6	569x4	7	610x4	-	-	6	569x4	-	-	7	610x4
5	innerwebroof 5	CHS	610x40	12	369x12	12	369x12	-	-	12	369x12	-	-	16	469x12
6	innerwalls	CHS	469x40	2	369x4	2	369x4	-	-	1	319x4	-	-	3	419x4
7	InsideFacade	SHS	300x300x20	6	300x300x20	6	300x300x20	-	-	0	250x250x12	PHCS355UNIIC	140x140x5	54	180x180x8
8	InsideRoof	RHS	500x300x40	2	350x300x4	2	350x300x4	-	-	3	450x300x4	-	-	3	450x300x4
9	InsideWall	RHS	450x300x30	2	350x300x4	2	350x300x4	-	-	3	450x300x4	-	-	0	180x300x4
10	InsidewallBuckeling	RHS	500x300x40	7	450x300x10	7	450x300x10	-	-	7	450x300x10	-	-	9	250x300x20
11	InsidewallResistance	RHS	500x300x40	15	350x300x30	15	350x300x30	-	-	12	450x300x20	-	-	10	350x300x20
12	OutsideFacade	SHS	300x300x20	0	250x250x12	0	250x250x12	PHCS355UNIIC	250x250x12,5	33	140x140x5	-	-	94	250x250x16
13	OutsideRoof	RHS	500x300x40	3	450x300x4	0	180x300x4	-	-	1	250x300x4	-	-	1	250x300x4
14	OutsideWall	RHS	450x300x30	1	250x300x4	1	250x300x4	-	-	0	180x300x4	PHRS355UNEIc	200x100x4,0 (41)	77	350x250x6,3
Bending moment in Z direction				19,985		19,9863				19,944				19,976	
Total cost: Steel Weight And Built Up Costs (kg)				1.124.900,635498		1.116.145,651813				979.459,82				1.153.032,243686	
Total cost: Steel Weight And Built Up Costs (Ton)				1.124,90		1.116,15				979,46				1.153,03	

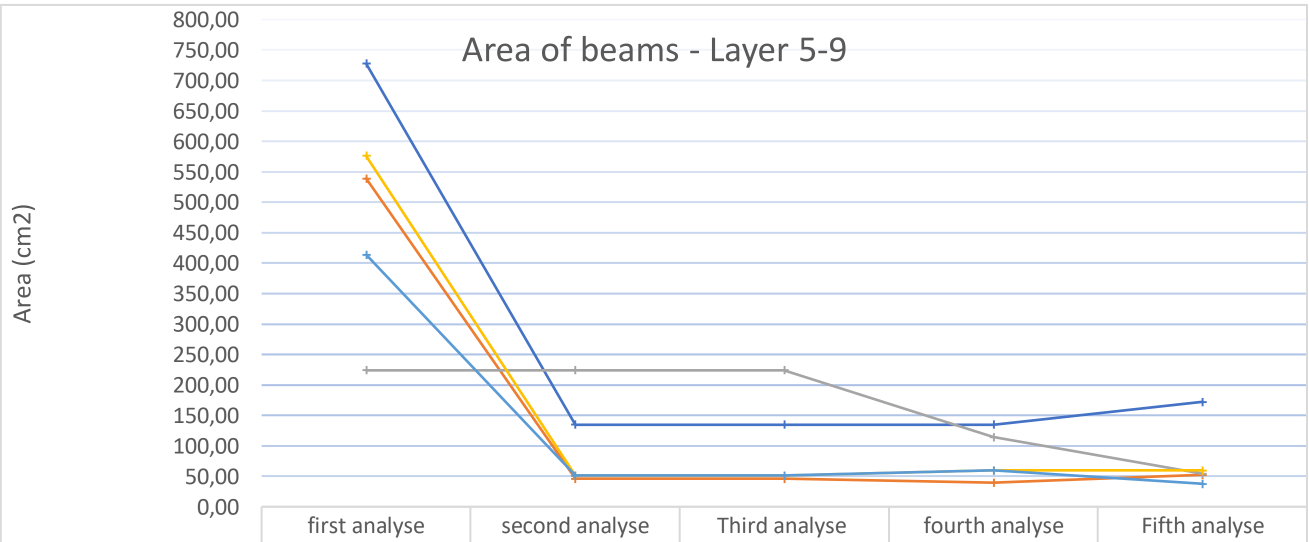
Table 11: Area changes - Test model 2

Geometrie 1 - Scale 2 - WithForces - Area of Beams					
Layer	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
0	224,00	114,24	114,24	26,72	26,72
1	211,97	58,44	64,72	58,44	33,3
2	219,29	52,15	64,72	64,72	71,01
3	519,14	64,72	71,01	64,72	71,01
4	539,14	71,01	77,3	71,01	77,3
5	727,70	134,59	134,59	134,59	172,3
6	539,14	45,87	45,87	39,58	52,15
7	224,00	224	224	114,24	54,32
8	576,00	51,36	51,36	59,36	59,36
9	414,00	51,36	51,36	59,36	37,76
10	576,00	146	146	146	204
11	576,00	354	354	284	244
12	224,00	114,24	114,24	26,72	146,9
13	576,00	59,36	37,76	43,36	43,36
14	414,00	43,36	43,36	37,76	73,57



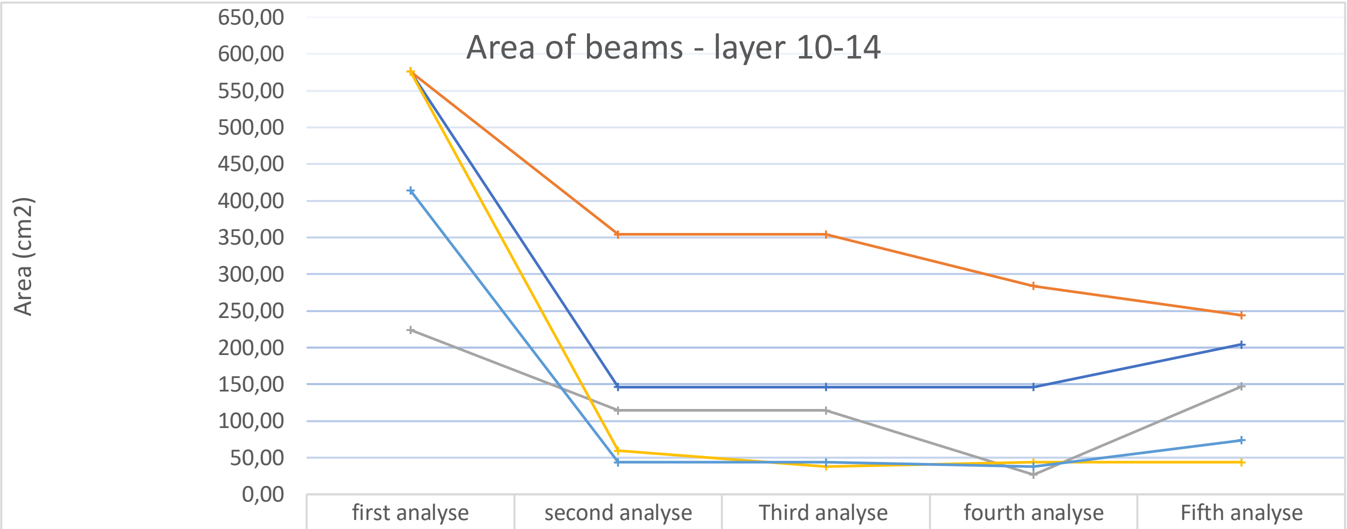
	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
Entrance hall	224,00	114,24	114,24	26,72	26,72
InnerRoof 1	211,97	58,44	64,72	58,44	33,3
InnerRoof 2	219,29	52,15	64,72	64,72	71,01
InnerRoof3	519,14	64,72	71,01	64,72	71,01
InnerRoof 4	539,14	71,01	77,3	71,01	77,3

Figure 44: Test model 2 - Area of beams 0-4



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
innerwebroof 5	727,70	134,59	134,59	134,59	172,3
innerwalls	539,14	45,87	45,87	39,58	52,15
InsideFacade	224,00	224	224	114,24	54,32
InsideRoof	576,00	51,36	51,36	59,36	59,36
InsideWall	414,00	51,36	51,36	59,36	37,76

Figure 45: Test model 2 - Area of beams 5-9



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
InsidewallBuckeling	576,00	146	146	146	204
InsidewallResistance	576,00	354	354	284	244
OutsideFacade	224,00	114,24	114,24	26,72	146,9
OutsideRoof	576,00	59,36	37,76	43,36	43,36
OutsideWall	414,00	43,36	43,36	37,76	73,57

Figure 46: Test model 2 - Area of beams 10-14

<u>Conclusion Test Model 2:</u>

The best optimal solution found during the optimization process for model 2 is established after the third optimization with a steel weight and build up cost of 979,46Ton this equals a price cost of 2.252.757€. The area of beams represented in Figure 44, Figure 45 and Figure 46 show a natural process of the positive evolution of each group individual. After each optimization a certain group will, according to the other groups, achieve a bigger or smaller area, with the main goal of making the total cost as optimal as possible.

10.2.3 WC-Bigroom-Geo2-Scale1

Test model one started with an own weight of the structure of 10560 Ton. After the first optimization this weight was reduced to 1462,20 Ton. As shown in Table 10 dimensions of the layers 0, 7, 8, 12 and 13 reached their minimum dimensions available in the assigned group after the first analysis. These layers where then manually changed to other groups. The changes of group happened in AutoCAD and the newly assigned groups where pre-designed groups that are available in the architrave.

The follow figures and tables are according to the third Test Model and give a better prospective on how the optimization was preformed and what dimensions were used during the optimization process.

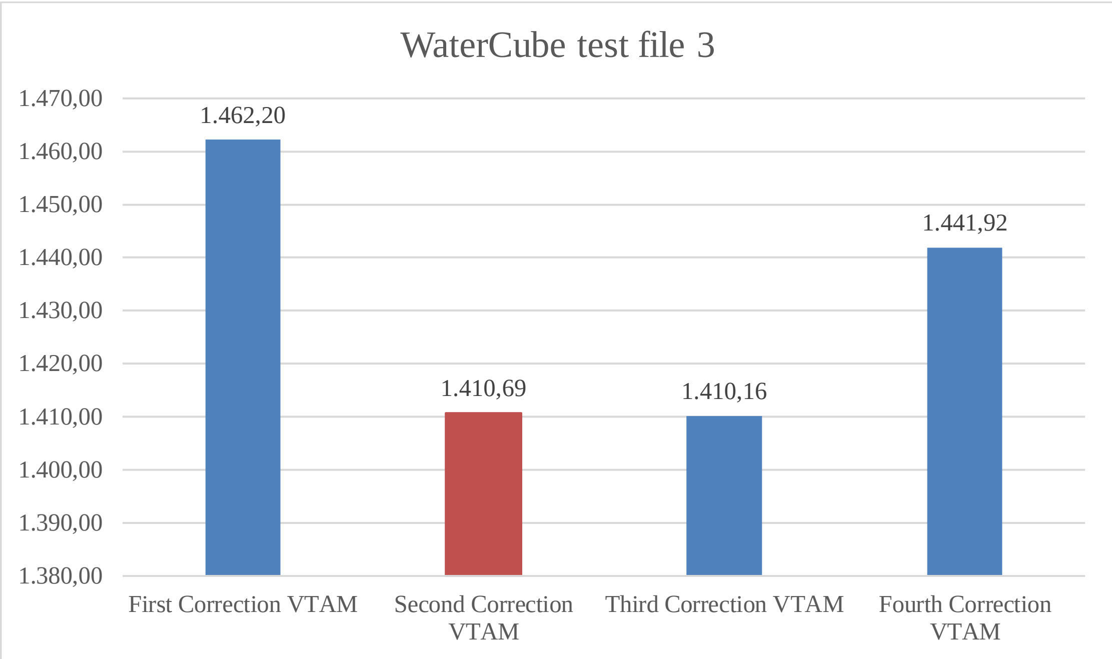


Figure 47: Total weight WaterCube test file 3

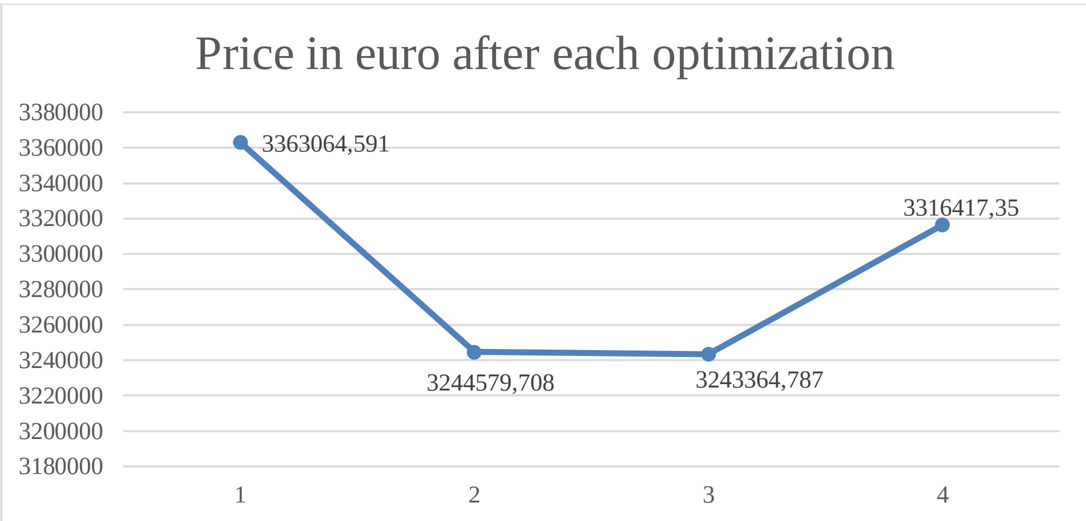


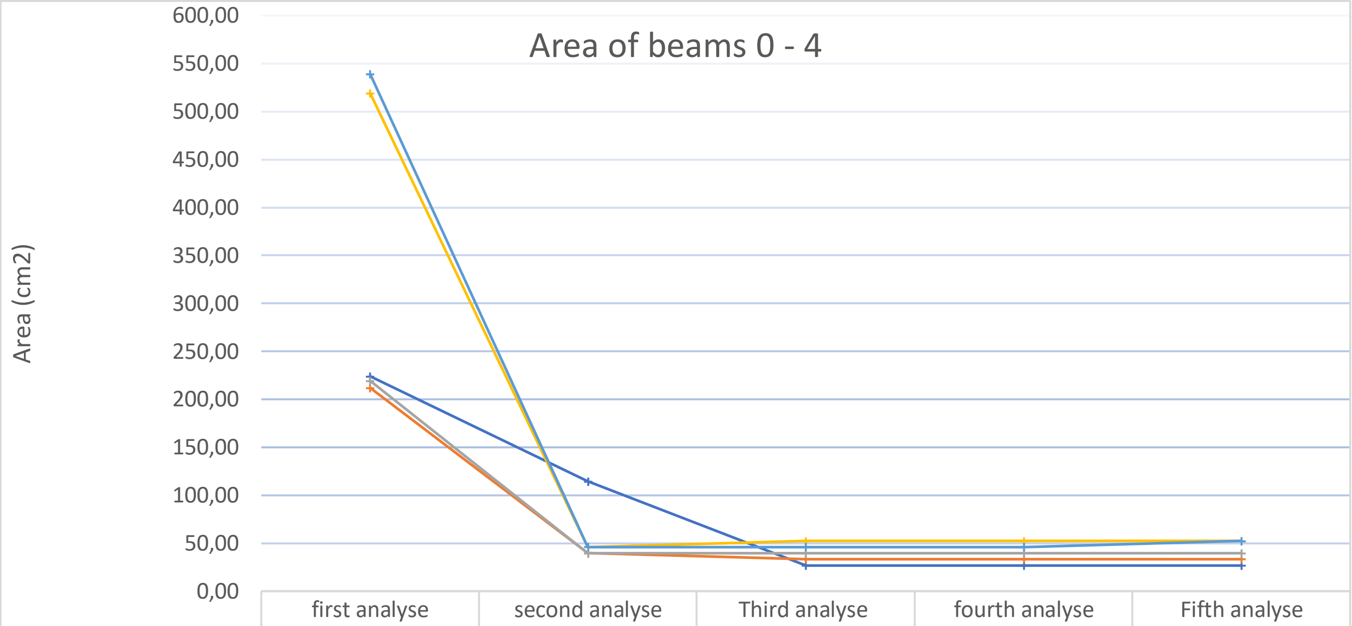
Figure 48: Price comparison model 3

Table 13: Dimension change - Test model 3

Geometrie 2 - Scale 1 - WithForces												
Layer	Name	Type of beam	Dimensions Given by me without any errors	First Correction VTAM		Changes made in Dimensions manually		Second Correction VTAM		Third Correction VTAM		Fourth Correction VTAM	
0	Entarence public	SHS	300x300x20	0	250x250x12	PHCS355UNIIC	250x250x12,5	33	140x140x5,0	33	140x140x5,0	33	140x140x5,0
1	innerwebroof 1	CHS	269x28	1	319x4	-	-	0	269x4	0	269x4	0	269x4
2	innerwebroof 2	CHS	369x20	1	319x4	-	-	1	319x4	1	319x4	1	319x4
3	innerwebroof 3	CHS	469x40	2	369x4	-	-	3	419x4	3	419x4	3	419x4
4	innerwebroof 4	CHS	469x40	2	369x4	-	-	2	369x4	2	369x4	3	419x4
5	innerwebroof 5	CHS	610x40	12	369x12	-	-	12	369x12	12	369x12	12	369x12
6	innerwalls	CHS	469x40	5	519x4	-	-	5	519x4	5	519x4	5	519x4
7	InsideFacade	SHS	300x300x20	0	250x250x12	PHCS355UNIIC	250x250x12,5	34	120x1206,3	33	140x140x5,0	93	300x300x12,5
8	InsideRoof	RHS	500x300x40	0	180x300x4	PHRS355UNEIc	200x120x6,3	55	200x100x6,3	55	200x100x6,3	57	200x120x6,3
9	InsideWall	RHS	450x300x30	1	250x300x4	-	-	1	250x300x4	1	250x300x4	1	250x300x4
10	InsidewallBuckeling	RHS	500x300x40	6	350x300x10	-	-	7	450x300x10	7	450x300x10	6	350x300x10
11	InsidewallResistance	RHS	500x300x40	6	350x300x10	-	-	7	450x300x10	7	450x300x10	6	350x300x10
12	OutsideFacade	SHS	300x300x20	0	250x250x12	PHCS355UNIIC	250x250x12,5	30	120x120x5	30	120x120x5	30	120x120x5
13	OutsideRoof	RHS	500x300x40	0	180x300x4	PHRS355UNEIc	200x120x6,3	63	200x120x8	63	200x120x8	63	200x120x8
14	OutsideWall	RHS	450x300x30	4	180x300x10	-	-	4	180x300x10	4	180x300x10	4	180x300x10
Bending moment in Z direction				19,975				19,886		19,887		19,789	
Total cost: Steel Weight And Built Up Costs				1.462.201,996039				1.410.686,829511		1.410.158,603250		1.441.920,586858	
Total cost: Steel Weight And Built Up Costs (Ton)				1.462,20				1.410,69		1.410,16		1.441,92	

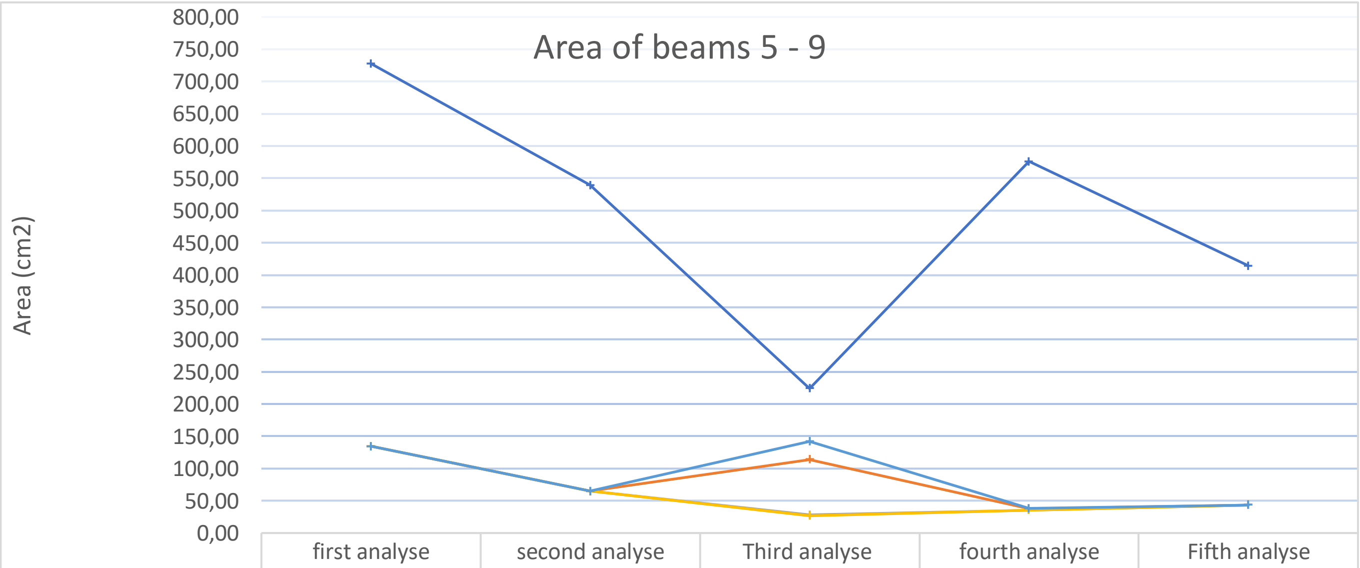
Table 12: Area change - Test model 3

Geometrie 2 - Scale 1 - WithForces - Area of Beams					
Layer	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
0	224,00	114,24	26,72	26,72	26,72
1	211,97	39,58	33,3	33,3	33,3
2	219,29	39,58	39,58	39,58	39,58
3	519,14	45,87	52,15	52,15	52,15
4	539,14	45,87	45,87	45,87	52,15
5	727,70	134,59	134,59	134,59	134,59
6	539,14	64,72	64,72	64,72	64,72
7	224,00	114,24	28,21	26,72	142
8	576,00	37,76	35,77	35,77	38,29
9	414,00	43,36	43,36	43,36	43,36
10	576,00	126	146	146	126
11	576,00	126	146	146	126
12	224,00	114,24	22,72	22,72	22,72
13	576,00	37,76	47,92	47,92	47,92
14	414,00	92	92	92	92



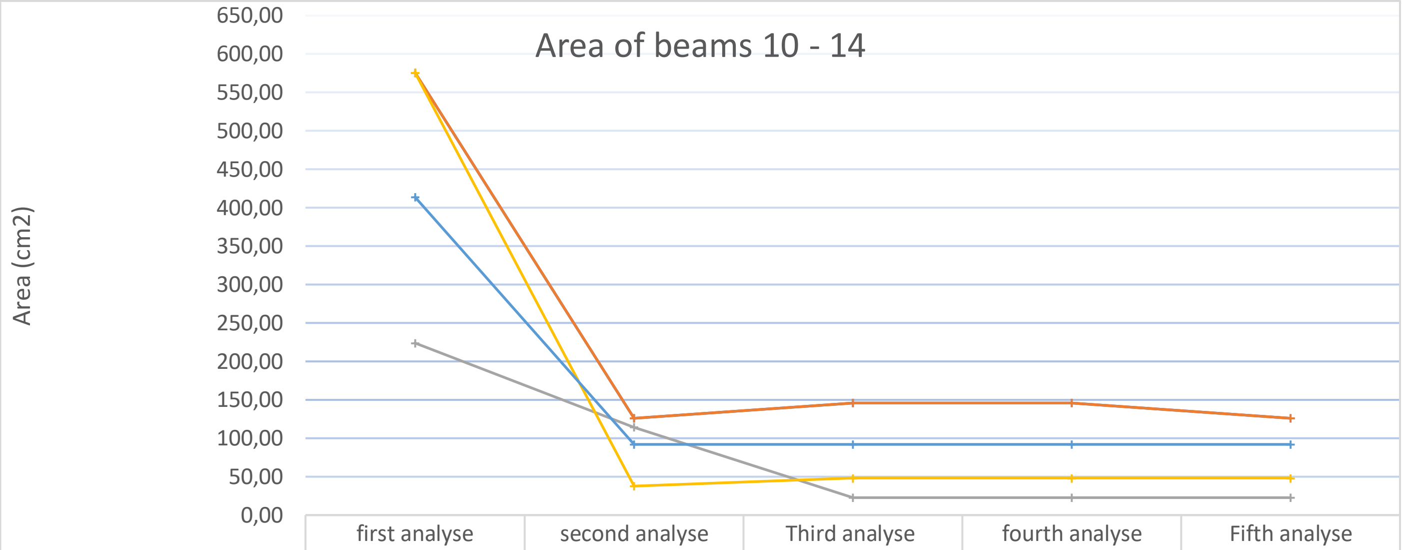
	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
entrance public	224,00	114,24	26,72	26,72	26,72
innerwebroof 1	211,97	39,58	33,3	33,3	33,3
innerwebroof 2	219,29	39,58	39,58	39,58	39,58
innerwebroof 3	519,14	45,87	52,15	52,15	52,15
innerwebroof 4	539,14	45,87	45,87	45,87	52,15

Figure 50: Test model 3 - Area of beams 0 - 4



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
innerwebroof 5	727,70	539,14	224,00	576,00	414,00
innerwalls	134,59	64,72	114,24	37,76	43,36
InsideFacade	134,59	64,72	28,21	35,77	43,36
InsideRoof	134,59	64,72	26,72	35,77	43,36
InsideWall	134,59	64,72	142	38,29	43,36

Figure 49: Test model 3 - Area of beams 5 - 9



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
InsidewallBuckeling	576,00	126	146	146	126
InsidewallResistance	576,00	126	146	146	126
OutsideFacade	224,00	114,24	22,72	22,72	22,72
OutsideRoof	576,00	37,76	47,92	47,92	47,92
OutsideWall	414,00	92	92	92	92

Figure 51: Test model 3 - Area of beams 10 – 14

Conclusion Test Model 3:

The interesting part about this individual optimization is that the fourth correction is higher than the third correction. Here it is clear that the best solution found of the algorithm not always means that it is the global best solution. As spoken about before, the algorithm can get stuck in a local global best and it does not explore the other surroundings more. The reason why these results are higher than the third correction is because no OK-list was added to the fourth optimization, therefore the algorithm used new random values spread over the area which, in this case, were higher than previous collected results.

The best optimal solution found during the optimization process for model 3 is established after the third optimization with a steel weight and build up cost of 1410,16Ton this equals a price cost of 3.243.364,79€. The area of beams represented in Figure 49, Figure 50 and Figure 51 show a natural process of the positive evolution of each group individual. After each optimization a certain group will, according to the other groups, achieve a bigger or smaller area, with the main goal of making the total cost as optimal as possible.

10.2.4 WC-Bigroom-Geo2-Scale1,2

Test model one started with an own weight of the structure of 7745 Ton. After the first optimization this weight was reduced to 1886,96Ton. As shown in Table 14 dimensions of the layers 0, 1, 7 and 12 reached their minimum dimensions available in the assigned group after the fsecond analysis. These layers where then manually changed to other groups. The changes of group happened in AutoCAD and the newly assigned groups where pre-designed groups that are available in the architrave.

The follow figures and tables are according to the fourth Test Model and give a better prospective on how the optimization was preformed and what dimensions were used during the optimization process.

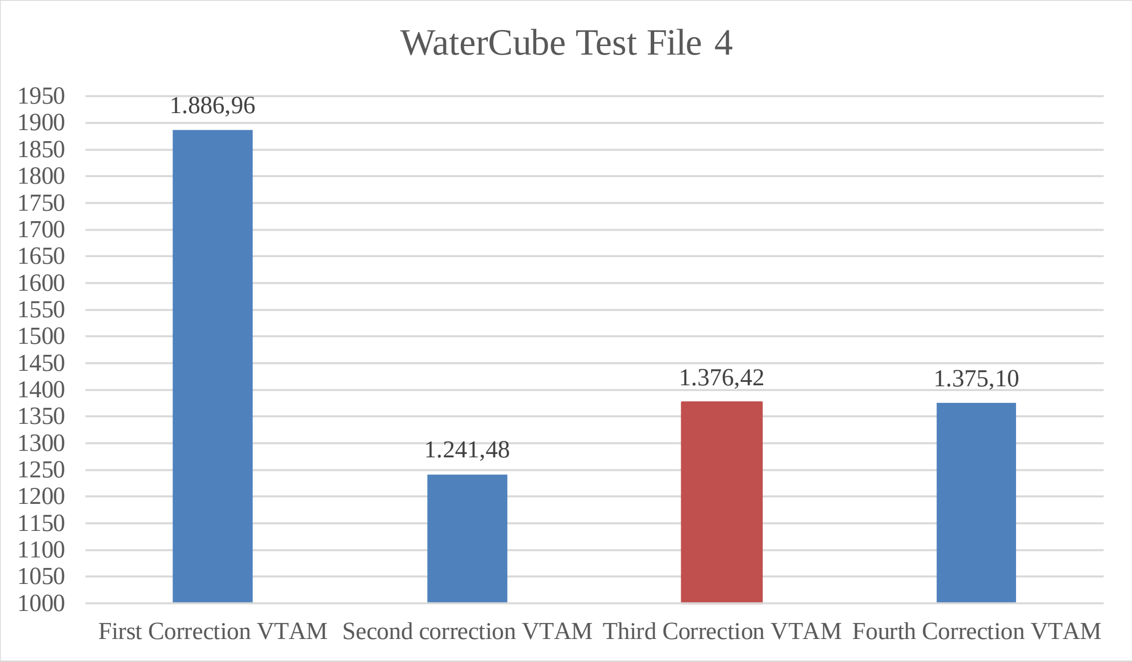


Figure 52: Total weight WaterCube - Test file 4

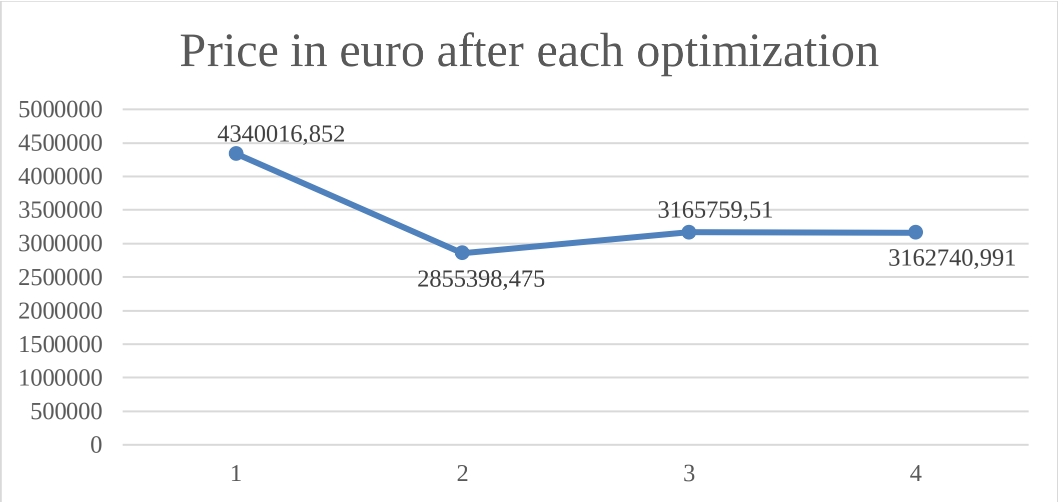


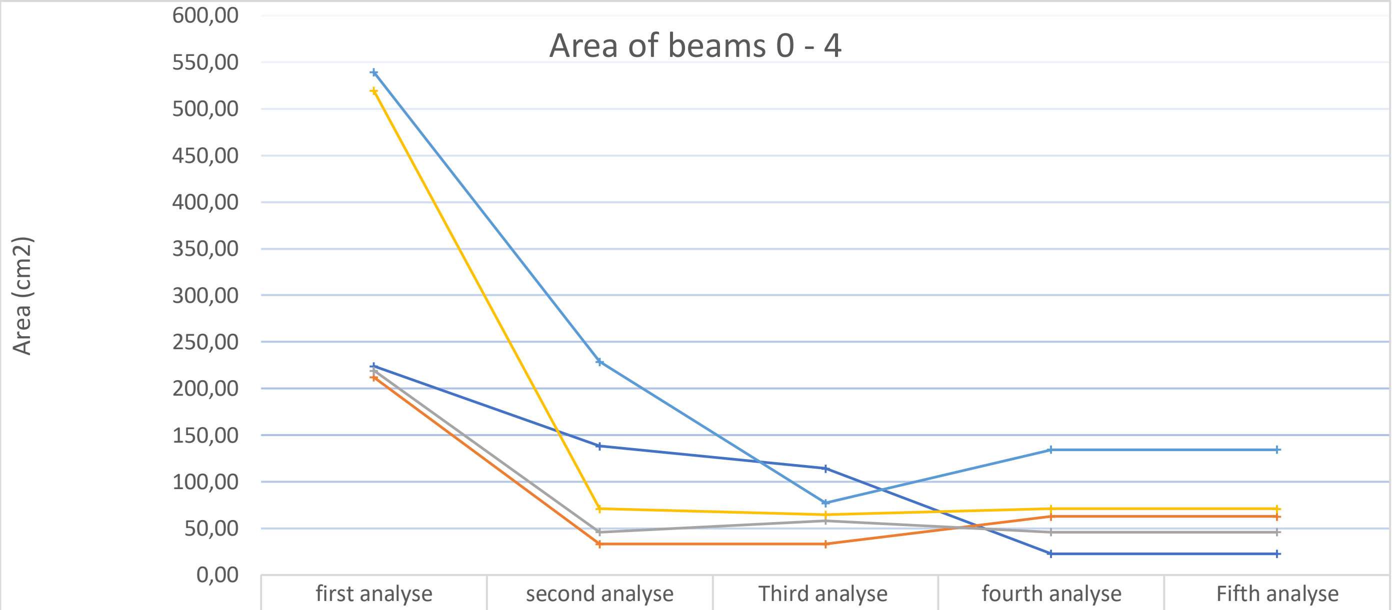
Figure 53: price comparison model 4

Table 15: dimension change - Test model 4

Geometrie 2 - Scale 2 - WithForces - Dimensions change of beams													
Layer	Name	Type of beam	Dimensions Given by me without any errors	First Correction VTAM		Second correction VTAM		Changes made in Dimensions manually		Third Correction VTAM		Fourth Correction VTAM	
0	Entarence public	SHS	300x300x20	1	300x300x12	0	250x250x12	PHCS355UNIIC	250x250x12,5	30	120x120x5,0	30	120x120x5,0
1	innerwebroof 1	CHS	269x28	0	269x4	0	269x4	PH0S355UNIc	244,5x5	69	323,9x6,3	69	323,9x6,3
2	innerwebroof 2	CHS	369x20	2	369x4	4	469x4	-	-	2	369x4	2	369x4
3	innerwebroof 3	CHS	469x40	6	569x4	5	519x4	-	-	6	569x4	6	569x4
4	innerwebroof 4	CHS	469x40	25	610x12	7	610x4	-	-	12	369x12	12	369x12
5	innerwebroof 5	CHS	610x40	16	469x12	12	369x12	-	-	22	369x20	22	369x20
6	innerwalls	CHS	469x40	23	219x4	4	469x4	-	-	6	569x4	6	569x4
7	InsideFacade	SHS	300x300x20	0	250x250x12	0	250x250x12	PHCS355UNIIC	250x250x12,5	44	200x200x5	44	200x200x5
8	InsideRoof	RHS	500x300x40	3	450x300x4	3	450x300x4	-	-	3	450x300x4	3	450x300x4
9	InsideWall	RHS	450x300x30	6	350x300x10	6	350x300x10	-	-	7	450x300x10	7	450x300x10
10	InsidewallBuckeling	RHS	500x300x40	9	250x300X20	7	450x300x10	-	-	7	450x300x10	7	450x300x10
11	InsidewallResistance	RHS	500x300x40	12	450x300x20	7	450x300x10	-	-	9	250x300x20	9	250x300x20
12	OutsideFacade	SHS	300x300x20	3	300x300x16	0	250x250x12	PHCS355UNIIC	250x250x12,5	45	140x140x8	43	160x160x6,3
13	OutsideRoof	RHS	500x300x40	3	450x300x4	3	450x300x4	-	-	3	450x300x4	3	450x300x4
14	OutsideWall	RHS	450x300x30	3	450x300x4	2	350x300x4	-	-	2	350x300x4	2	350x300x4
Bending moment in Z direction				19,826		19,834				19,998		19,999	
Total cost: Steel Weight And Built Up Costs				1.886.963,848661		1.241.477,597623				1.376.417,178393		1.375.104,778823	
Total cost: Steel Weight And Built Up Costs (Ton)				1.886,96		1.241,48				1.376,42		1.375,10	

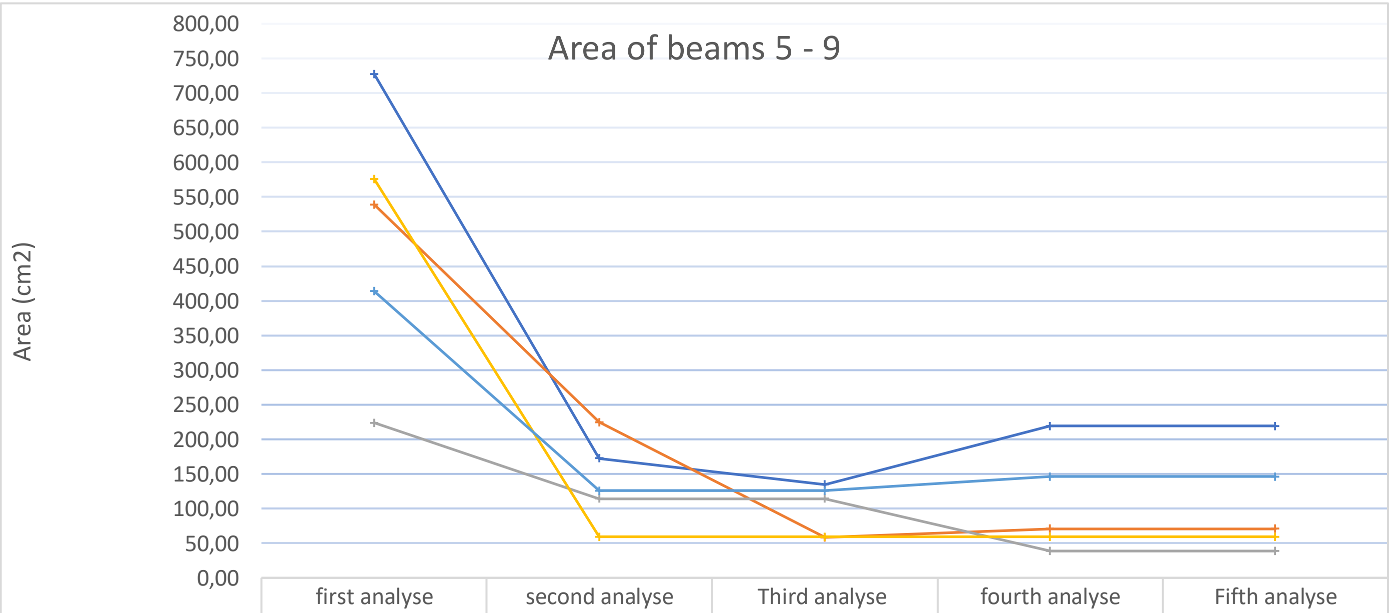
Table 14: Area of beams - Test model 4

Geometrie 2 - Scale 2 - WithForces - Area of Beams					
Layer	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
0	224,00	138,24	114,24	22,72	22,72
1	211,97	33,3	33,3	62,86	62,86
2	219,29	45,87	58,44	45,87	45,87
3	519,14	71,01	64,72	71,01	71,01
4	539,14	228,87	77,3	134,59	134,59
5	727,70	172,3	134,59	219,29	219,29
6	539,14	224,88	58,44	71,01	71,01
7	224,00	114,24	114,24	38,72	38,72
8	576,00	59,36	59,36	59,36	59,36
9	414,00	126	126	146	146
10	576,00	204	146	146	146
11	576,00	284	146	204	204
12	224,00	181,76	114,24	41,52	38,29
13	576,00	59,36	59,36	59,36	59,36
14	414,00	59,36	51,36	51,36	51,36



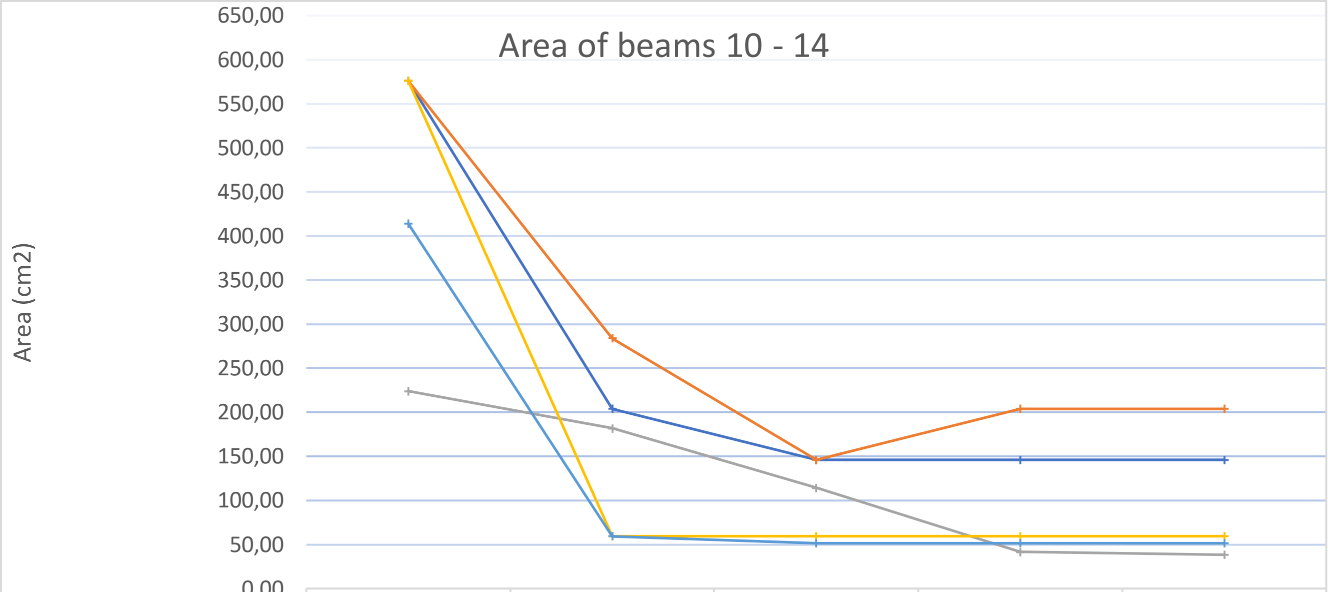
	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
Entrance hall	224,00	138,24	114,24	22,72	22,72
innerwebroof 1	211,97	33,3	33,3	62,86	62,86
innerwebroof 2	219,29	45,87	58,44	45,87	45,87
innerwebroof 3	519,14	71,01	64,72	71,01	71,01
innerwebroof 4	539,14	228,87	77,3	134,59	134,59

Figure 55: Test model 4 - area of beams 0 - 4



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
innerwebroof 5	727,70	172,3	134,59	219,29	219,29
innerwalls	539,14	224,88	58,44	71,01	71,01
InsideFacade	224,00	114,24	114,24	38,72	38,72
InsideRoof	576,00	59,36	59,36	59,36	59,36
InsideWall	414,00	126	126	146	146

Figure 54: Test model 4 - Area 5 - 9



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
InsidewallBuckeling	576,00	204	146	146	146
InsidewallResistance	576,00	284	146	204	204
OutsideFacade	224,00	181,76	114,24	41,52	38,29
OutsideRoof	576,00	59,36	59,36	59,36	59,36
OutsideWall	414,00	59,36	51,36	51,36	51,36

Figure 56: Test model 4 - Area 10 - 14

<u>Conclusion Test Model 4:</u>

The best optimal solution found during the optimization process for model 4 is established after the second optimization with a steel weight and build up cost of 1241,48Ton this equals a price cost of 2.855.398,47€. The area of beams represented in Figure 54, Figure 55 and Figure 56 show a natural process of the positive evolution of each group individual. After each optimization a certain group will, according to the other groups, achieve a bigger or smaller area, with the main goal of making the total cost as optimal as possible.

10.3 Comparison in between the models

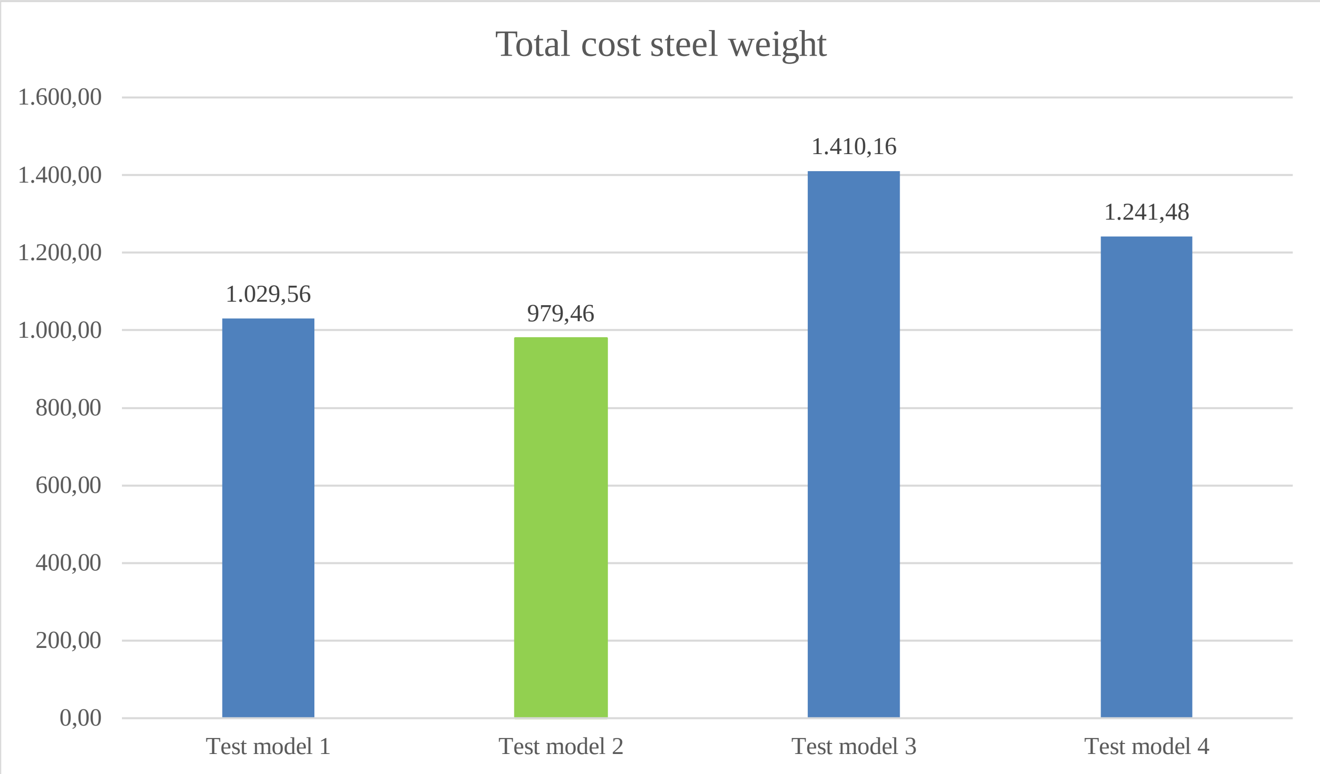


Figure 57: Comparison Total cost steel weight in between the models

After comparing the four testing models through an excel spreadsheet some conclusion could be made:

- As explained before, test model 1 and 2 have the same geometry but a different scale. Test model 2 has a lower total cost than test model 1. Even though the dimensions used in the two models are almost similar. The reason for the difference in the total weight is the amount beams used in two models. As test model 1 has almost the double of beams of test model 2 the total cost of steel will be higher because of the dimensions. This assumption is also similar with the difference in the total cost of steel weight in test model 3 and 4.
- Test model 1 and test model 3 have a similar number of beams and nodes used to build up the structure but the geometry of the two models is different. The geometry used in the first test model (this geometry is the closed to the actual geometry and is used to create the real building) will have a difference of 380,6Ton or in other words a difference in price of 602.640,89€. Meaning that the geometry and the rotation of the Weaire Phenom have an important effect on the total cost of steel weight of the structure. This assumption is also similar with the difference in the total cost of steel weight in test model 3 and 4.
- Intrinsically test model 2 has the most profitable outcome with a total cost of steel weight of 979,46Ton. Due to the price/kg of steel for a steel grade of S355 the total cost would be 2.252.757,59€

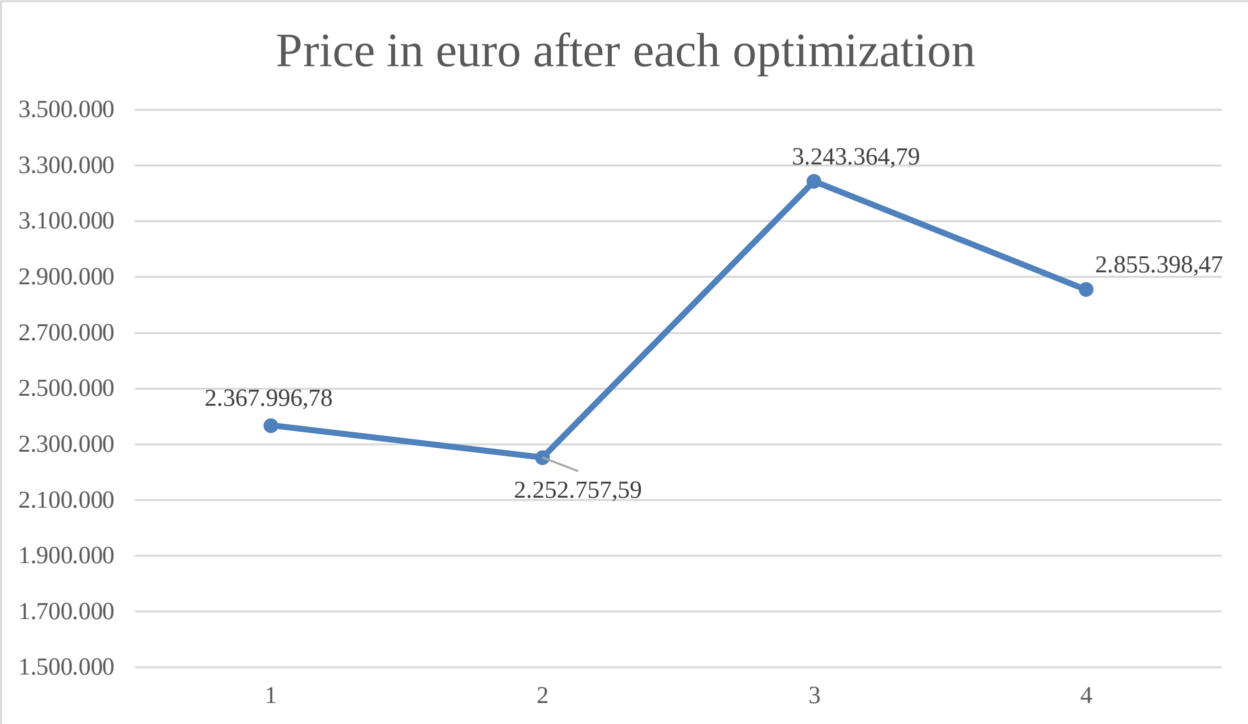


Figure 58: Price comparison between the four models

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10.4 Comparison in between different steel grades

The total cost of the steel price does not only depend on the weight of the structure but also on the kind of steel quality that is used to create the structure. To create a comparison in between different steel grades test model one is analyzed with two different kinds of steel grades. The two used steel grades are S355 and S275. The difference in between these two grades is the manufacturing price. Steel with grade S355 costs around 2,30/Kg and S275 costs around 1,90/Kg, depending on the stock at that time. The total amount of kilograms will then be multiplied by the cost price and a comparison in between the two different grades can be made.

The difference in the prices are mainly due to the mechanical properties. These properties say a lot about the applicability of the structural steel. There are many mechanical properties, such as hardness, toughness, etc., but for steel, the yield strength and tensile strength are the most important. To be precise, S235, S275 and S355 even derive their name from one of the most important mechanical properties: the yield strength.

To create the comparison, test model one is reanalyzed. In the argument file used for this analyze the steel strength will be changed to 275000Pa. In this way the VTAM algorithm knows it can only use these specifics. In Figure 59 the total cost for the steel weight is given for a steel grade of S275. The lowest value has become after the second optimization and has a weight of 1278,03Ton.

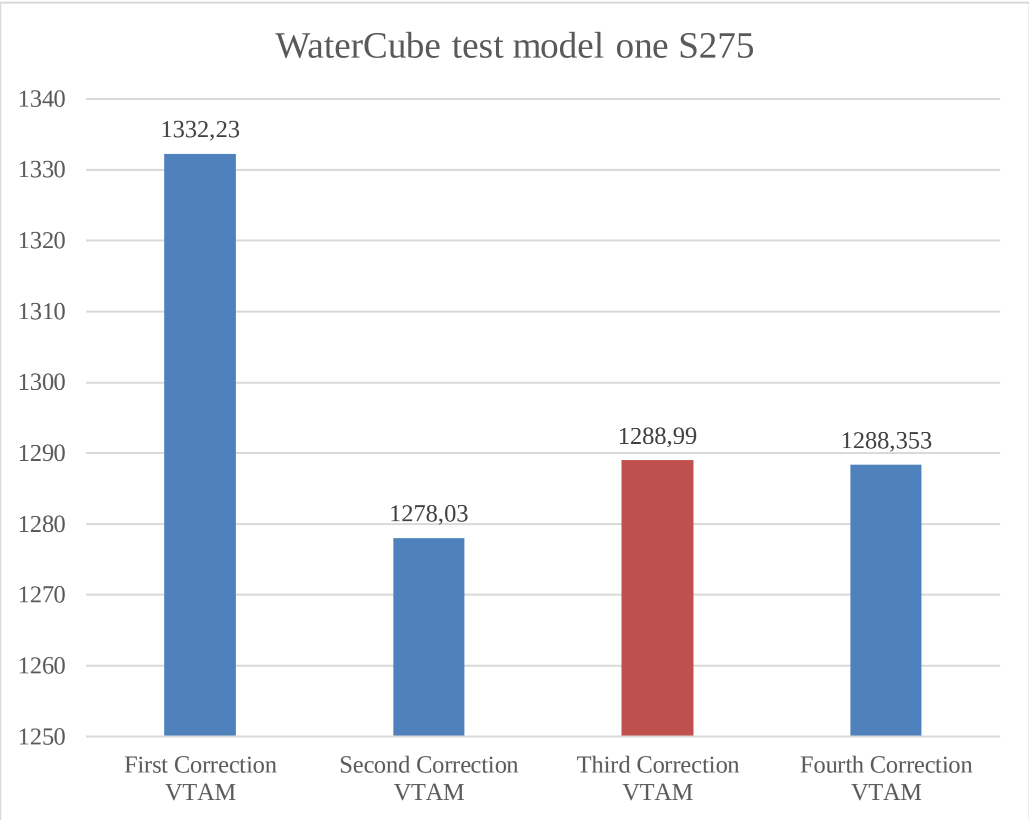


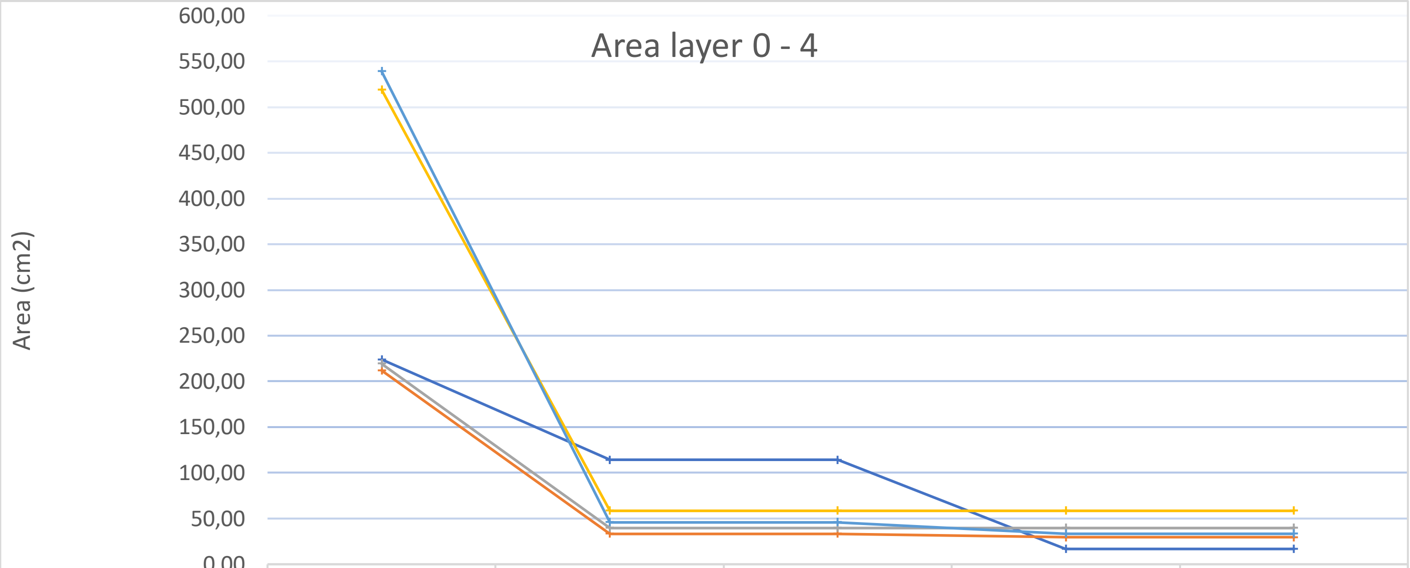
Figure 59: WaterCube test model one S275

Table 17: Test model 1, S275 - Dimension change

Geometrie 1 - Scale 1 - WithForces													
Layer	Name	Type of beam	Dimensions Given by me without any errors	First Correction VTAM		Second Correction VTAM		Manual corrections		Third Correction VTAM		Fourth Correction VTAM	
0	Entarence public	SHS	300x300x20	0	250x250x12	0	250x250x12	PHCS355UNIIc	250x250x12,5	24	90x90x5,0	24	90x90x5,0
1	innerwebroof 1	CHS	269x28	0	269x4	0	269x4	PH0S355UNE1c	244,5x5,0	45	193,7x5	45	193,7x5
2	innerwebroof 2	CHS	369x20	1	319x4	1	319x4			1	319x4	1	319x4
3	innerwebroof 3	CHS	469x40	4	469x4	4	469x4			4	469x4	4	469x4
4	innerwebroof 4	CHS	469x40	2	369x4	2	369x4			0	269x4	0	269x4
5	innerwebroof 5	CHS	610x40	4	469x4	4	469x4			6	569x4	6	569x4
6	innerwalls	CHS	469x40	3	419x4	3	419x4			5	519x4	5	519x4
7	InsideFacade	SHS	300x300x20	7	300x300x24	2	250x250x16			0	250x250x12	0	250x250x12
8	InsideRoof	RHS	500x300x40	0	180x300x4	0	180x300x4	PHCS355UNIIc	250x150x8	57	200x120x6,3	57	200x120x6,3
9	InsideWall	RHS	450x300x30	3	450x300x4	3	450x300x4			6	350x300x10	6	350x300x10
10	InsidewallBuckeling	RHS	500x300x40	7	450x300x10	7	450x300x10			7	450x300x10	7	450x300x10
11	InsidewallResistance	RHS	500x300x40	7	450x300x10	7	450x300x10			7	450x300x10	7	450x300x10
12	OutsideFacade	SHS	300x300x20	1	300x300x12	0	250x250x12	PHCS355UNIIc	250x250x12,5	19	90x90x4,0	16	80x80x4
13	OutsideRoof	RHS	500x300x40	0	180x300x4	0	180x300x4	PHRS355UNEIc	250x150x8	57	200X120x6,3	57	200X120x6,3
14	OutsideWall	RHS	450x300x30	1	250x300x4	0	180x300x4	PHRS355UNEIc	250x150x8	33	150x100x4,0	33	150x100x4,0
Bending moment in Z direction				17,759		17,92				19,118		19,119	
Total cost: Steel Weight And Built Up Costs (kg)				1.332.232,185342		1.278.030,199009				1.288.995,741403		1.288.353,674102	
Total cost: Steel Weight And Built Up Costs (ton)				1332,23		1278,03				1288,99		1288,353	

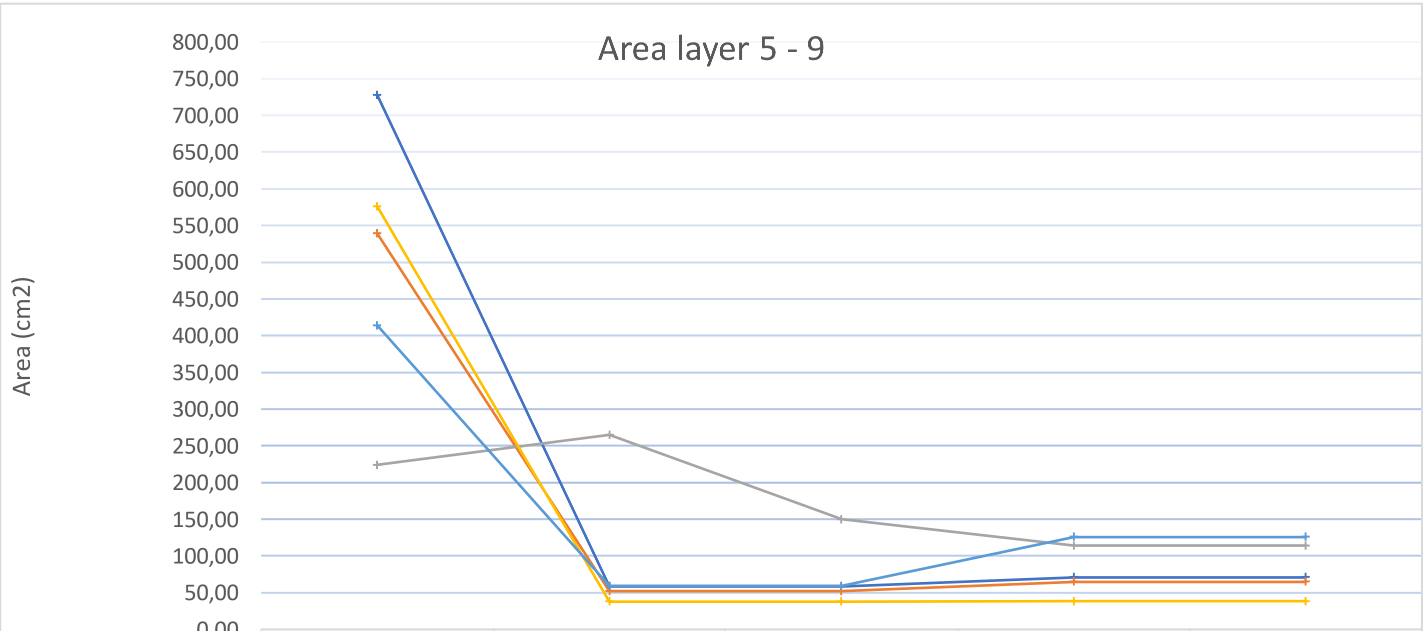
Table 16: Test model 1, S275 - Area change

Geometrie 2 - Scale 2 - WithForces - Area of Beams					
Layer	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
0	224,00	114,24	114,24	16,72	16,72
1	211,97	33,3	33,3	29,64	29,64
2	219,29	39,58	39,58	39,58	39,58
3	519,14	58,44	58,44	58,44	58,44
4	539,14	45,87	45,87	33,3	33,3
5	727,70	58,44	58,44	71,01	71,01
6	539,14	52,15	52,15	64,72	64,72
7	224,00	264,96	149,76	114,24	114,24
8	576,00	37,76	37,76	38,29	38,29
9	414,00	59,36	59,36	126	126
10	576,00	146	146	146	146
11	576,00	146	146	146	146
12	224,00	138,24	114,24	13,58	11,98
13	576,00	37,76	37,76	38,29	38,29
14	414,00	43,36	37,76	19,18	19,18



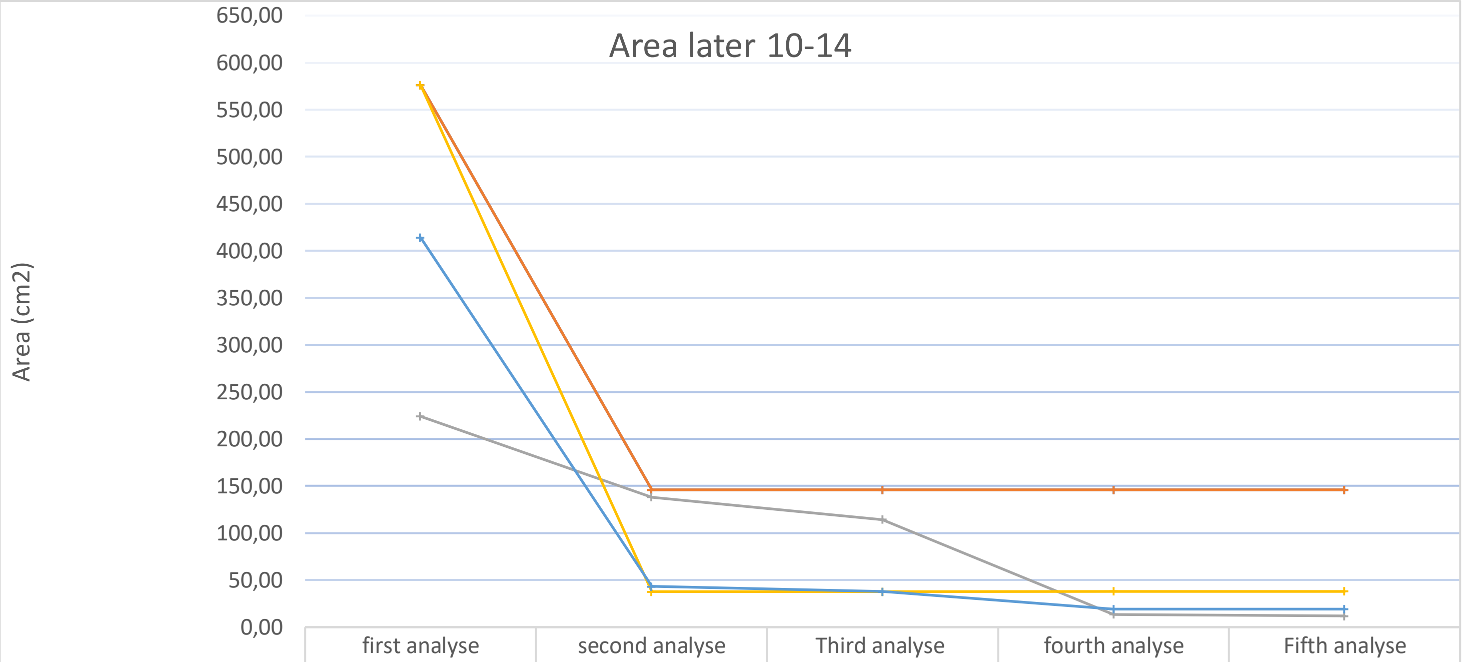
	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
Entarence public	224,00	114,24	114,24	16,72	16,72
innerwebroof 1	211,97	33,3	33,3	29,64	29,64
innerwebroof 2	219,29	39,58	39,58	39,58	39,58
innerwebroof 3	519,14	58,44	58,44	58,44	58,44
innerwebroof 4	539,14	45,87	45,87	33,3	33,3

Figure 61: Test model 1, S275 – Area layer 0 - 4



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
innerwebroof 5	727,70	58,44	58,44	71,01	71,01
innerwalls	539,14	52,15	52,15	64,72	64,72
InsideFacade	224,00	264,96	149,76	114,24	114,24
InsideRoof	576,00	37,76	37,76	38,29	38,29
InsideWall	414,00	59,36	59,36	126	126

Figure 60: Test model 1, S275 - Area layer 5 - 9



	first analyse	second analyse	Third analyse	fourth analyse	Fifth analyse
InsidewallBuckeling	576,00	146	146	146	146
InsidewallResistance	576,00	146	146	146	146
OutsideFacade	224,00	138,24	114,24	13,58	11,98
OutsideRoof	576,00	37,76	37,76	38,29	38,29
OutsideWall	414,00	43,36	37,76	19,18	19,18

Figure 62: Test model 1, S275 - Area layer 10 - 14

According to Figure 59 and Table 17 the optimization process goes in a similar way as with the steel grade of S355. The model started originally with a high weight due to the by big dimensions give to the original test model. After the first optimization the weight is reduced to 1332,23Ton. Also, the area of the beams shows a positive improvement during the process.

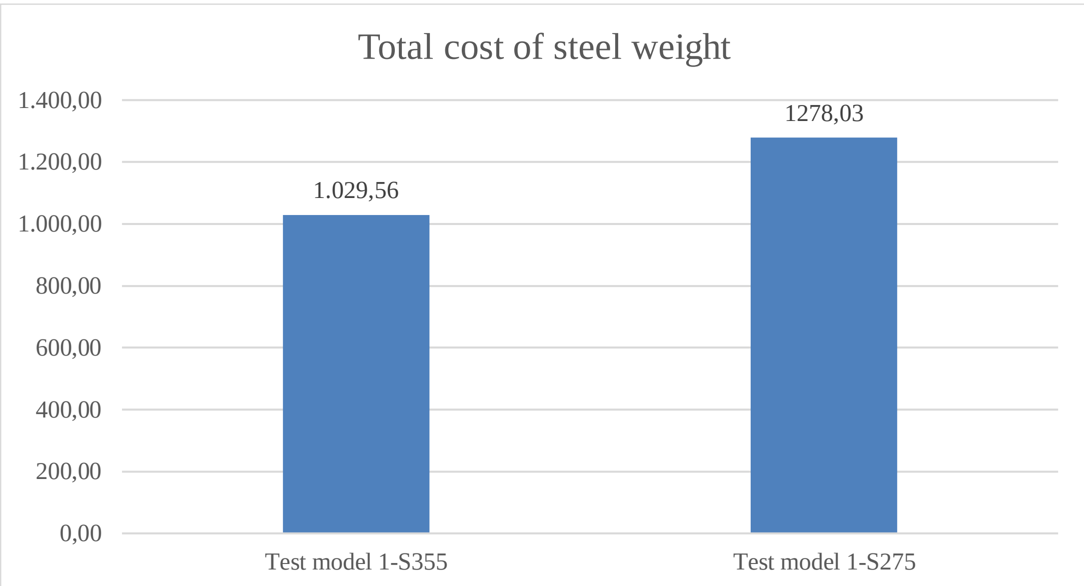


Figure 63: Comparison between S355 and S275

Conclusion in between S275 and S355:

The results of the cost according to the weight needed are obvious, a higher steel grade will allow the structure to comply with beams that have a smaller dimension. But this does not necessarily mean that the option of using a higher steel grade will be the cheapest option to build the construction. According to Figure 64 the first test model with a steel grade of S355 has a total cost of 2.367.996,781€ and the first test model with a steel grade of S275 has a total cost of 2.492.158,888€. The difference in cost in between the two analyses is 124.162,107€. Meaning that, in this case, using a steel with a grade of S355 will be the most profitable.

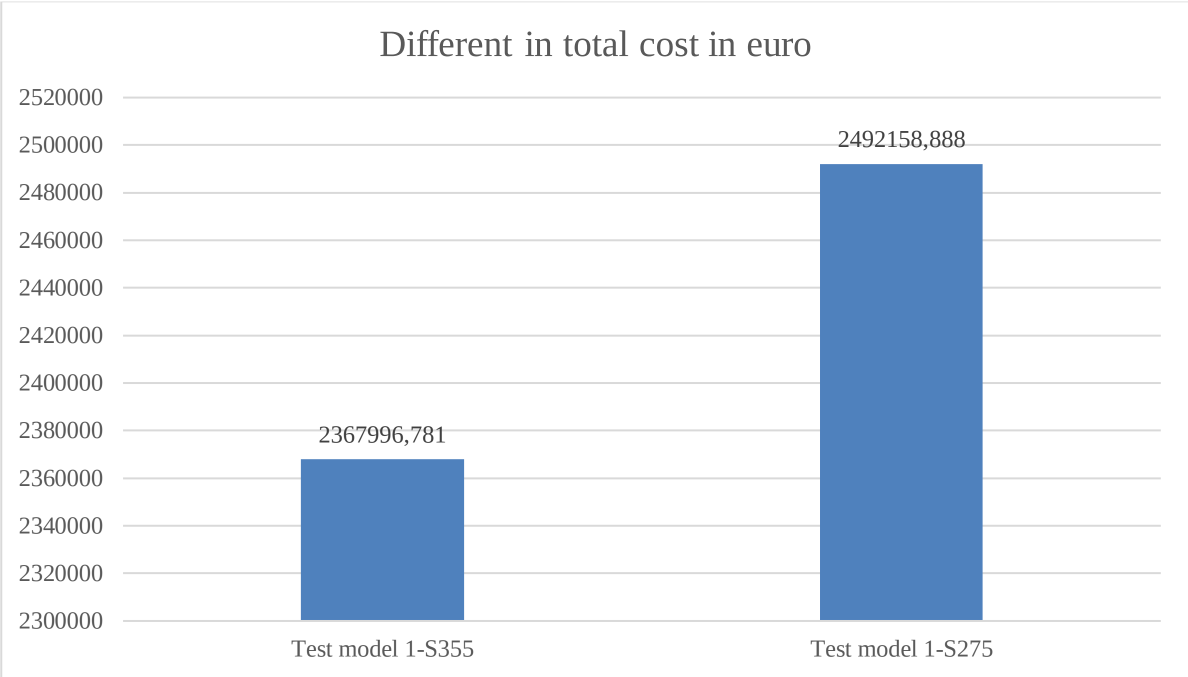


Figure 64: price comparison between different steel classes

11 Conclusion

This research studies the different types of algorithms present today and the answer to the question on "How to optimize The WaterCube building located in Beijing using the Architrave program and the VTAM-algorithm?".

Currently there are all sorts of different metaheuristic algorithms, each one of them diverted from a certain process in nature or a population. These algorithms have the power to solve complex cases with millions of different solutions that would take too long for mankind to figure out manually. The VTAM-algorithm based on the mapping of an area has proven its qualities during the research through the combination of a collaboration between man and machine using the architrave program and the algorithm. The computing time needed to optimize one singular process depends strongly on how the user handles the algorithm. Many groups with a lot of different dimensions equal a longer computing time. Also, the number of slots used and retries without improvement have a strong impact because the algorithm will have to wait for the slowest CPU. So, it is recommended to make these groups and optimization specifics as appropriate as possible. The most ideal way to create a fluent optimization process is the continues interaction between man and machine. According to the results, the algorithm provides a positive improvement obtained through a progressively optimization process.

The WaterCube is internally made from the Weaire Phenom model. How this model is used to create a certain structure is essential. Derived from the four different test models the total weight after the optimization process through the VTAM algorithm were completely different and had significant differences in their values. These weight differences clarify that the changes occurred due to the geometry and the scale of the Weaire Phenom model have an impact on the total weight and cost of the structure. Also, with the implementation of the algorithm, the use of the different steel grades has shown to have an impact on the total cost of the structure. Meaning that, using a higher steel quality, does not necessarily mean that the total cost of the structure will be lower.

12 References

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