Aerodynamics of different control surfaces for orbital booster landing

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Abstract

Recently private companies are striving to make commercial flights possible. It could be done for instance by improving the cost efficiency of orbital flights. The first step is to make boosters reusable. SpaceX was the first to achieve it. After SpaceX's success many companies started taking different approaches for orbital booster recovery. This inspired us to start the project.

The aim of this project is to test and compare the aerodynamics of different types of control surfaces used in landing environments. The most common control surface used for landing are grid fins. Some rockets that use grid fins are SpaceX´s Falcon 9 and the Super Heavy. Grid fins are used instead of the conventional planar fins. Grid fins have a smaller aerodynamic surface than the planar fins. There are various shapes that the grid fins can take.

To be able to compare the aerodynamics between different types of control surfaces we first had to build a wind tunnel. We built it 3 meters long and 1 meter tall with the purpose of obtaining results as accurate as possible. The idea is that instead of moving the object at a certain speed, the air moves at the desired velocity. We designed different shapes of grid fins and attached them to a model rocket. With the help of a load cell we calculated the difference in performance of different grid fins. We concluded that there is a significant difference of efficiency among different shapes with the same grid fin area.

Introduction

Space flight was achieved for the first time in 1944 by Nazi Germany. Werner von Braun was a former nazi scientist. He developed the first ever artificial object to fly into space reaching 189km, the V-2 rocket. After the war he was secretly moved to the US mainland in the operation paperclip. Later in the US he played a pivotal role in the development of the Saturn V rocket which landed the first humans on the moon. During the cold war, the Soviet Union and The United States of America were, in simple terms, in a space race. The USSR sent the first human to orbit the Earth in 1961. A few years passed, and then the USA sent for the first-time humans to the moon, which is the well-known moon landing of 1969. From there the number of rockets reaching outer space significantly decreased to an average of only a 100 a year. The main reason of this steep decline was huge costs related with orbital flights. The estimated cost of spaceflight since Apollo program is 350 000 000 000 $. One of the major cost factors related with space flights was high cost of rocket boosters that were completely destroyed in each flight. In recent times, there has been a notable surge in private companies' efforts to facilitate commercial space travel, innovating around the booster designs to bring down the costs. Thanks to those efforts, recent years saw increasing the number of flights to over 220 in 2023[1]. New wave of spaceflights was triggered by multiple innovations, but the major breakthrough was SpaceX's successful endeavor to reuse rocket boosters which significantly reduced the costs. The cost of the production of the booster amounts to 60% of the total rocket's cost[2]. Space X managed to reuse them up to 19 times[3]. Multiple use of rocket boosters was possible due to several design changes, like grid fins, landing legs and gimbal engines.

Figure R4: Nazi V-2 rocket *credit(v2rockethistory.com)*

[1] https://spacestatsonline.com/launches/ accessed on 28/02/2024
[2] https://en.wikipedia.org/w/index.php?title=Falcon_9_Full_Thrust&oldid=1197841253 accessed on 28/02/2024
[3] https://en.wikipedia.org/w/index.php?title=List_of_Falcon_9_first-stage_boosters&oldid=1207954484 Accessed on 28/02/2024

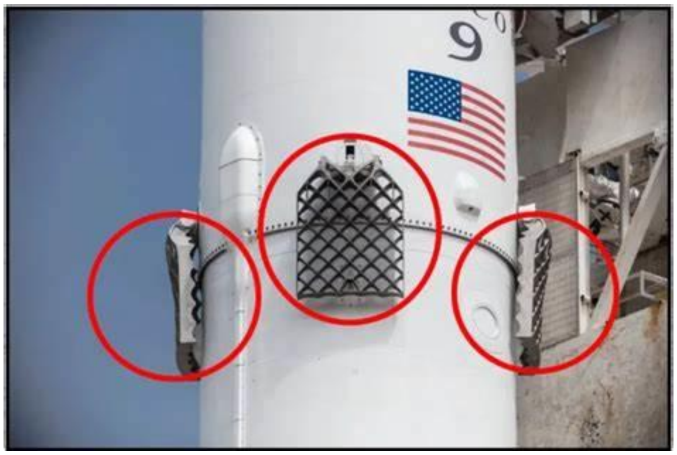


Figure R1: SpaceX's Falcon 9 rocket's grid fins credit(www.thespacetechie.com)

Our focus primarily revolved around investigating grid fins, a distinctive design prominently featured on rockets like SpaceX's Falcon 9/Falcon Heavy, the new Super Heavy or missiles. Grid fins were first developed in 1950 by a team led by Sergey Belotserkovskiy in the USSR and used since 1970 in various Soviet ballistic missile designs such as the SS-12 Scaleboard, SS-20 Saber or SS-25 Sickle and for the N-1. The N-1 was the Soviet counterpart to the US Saturn V. The first stage was the most powerful rocket stage to fly in 50 years generating 45.4 MN (mega newtons) of thrust. Although the N-1 lifted off the pad it never made a successful launch and the project was cancelled in 1976. The only rocket more powerful than the soviet N-1 is the current SpaceX's Star Ship's first stage, the Super Heavy with a mind blowing 74.4 MN of thrust. For comparison the Saturn V rocket had 40 MN of thrust.

Figure R2: SpaceX's Falcon 9 rocket after landing on a droneship in the middle of the ocean. Credit(RPP)

Unlike conventional fins, grid fins offer unique aerodynamic advantages during the landing phase, contributing to the maneuverability and stability of the descent process. Grid fins are essential for extremely precise landings which is crucial for allowing SpaceX to land their boosters on ships in the middle of the ocean and reuse the booster in later flights. This allows them to use more fuel to deliver bigger payloads to LEO, low earth orbit. Grid fins significantly decrease also fuel usage thus reducing the environmental impact of rocket launching. Grid fins usages eliminates the need for other types of manoeuvre hardware like gimbaling the engines or cold gas thrusters (hot used in the Star Ship), both using a lot of fuel. In this sense grid fins are somewhat of a "passive" manoeuvring hardware, being very effective, though using no fuel whatsoever. Cold and hot gas thrusters are still being used in rocket, mainly for use outside the atmosphere, but also to help make small adjustments while landing. Though other forms of manoeuvrability hardware are not replaced by the grid fins, they do make most of the work stabilizing as well as guiding the rocket, reducing fuel usage by a lot, and making this huge achievement possible.

Construction of the wind tunnel

To start our project, we constructed a wind tunnel—a pivotal tool in assessing the aerodynamic properties of control surfaces. What is a wind tunnel though?

A wind tunnel is used to study the aerodynamics of different objects. The main idea is that instead of moving an object to a certain speed, you keep that object still and move the air around it to the desired speed. It is used in the car racing and manufacturing industry, airplane industry, as well as the rocket industry to study and understand the way the air will move and interact with the rocket, or car. Engineers try to optimize the rocket so that the air resistance is as low as possible. The less air drag there is, the better. With low air drag a rocket can go faster without changing the power used.

After weeks of research and planning we started building the wind tunnel. We inspired the design on many online and NASA guides **(Check the references in the bibliograpy)**. We came up with a design (**Figure D1**) about 3 meters long and 1 meter wide.

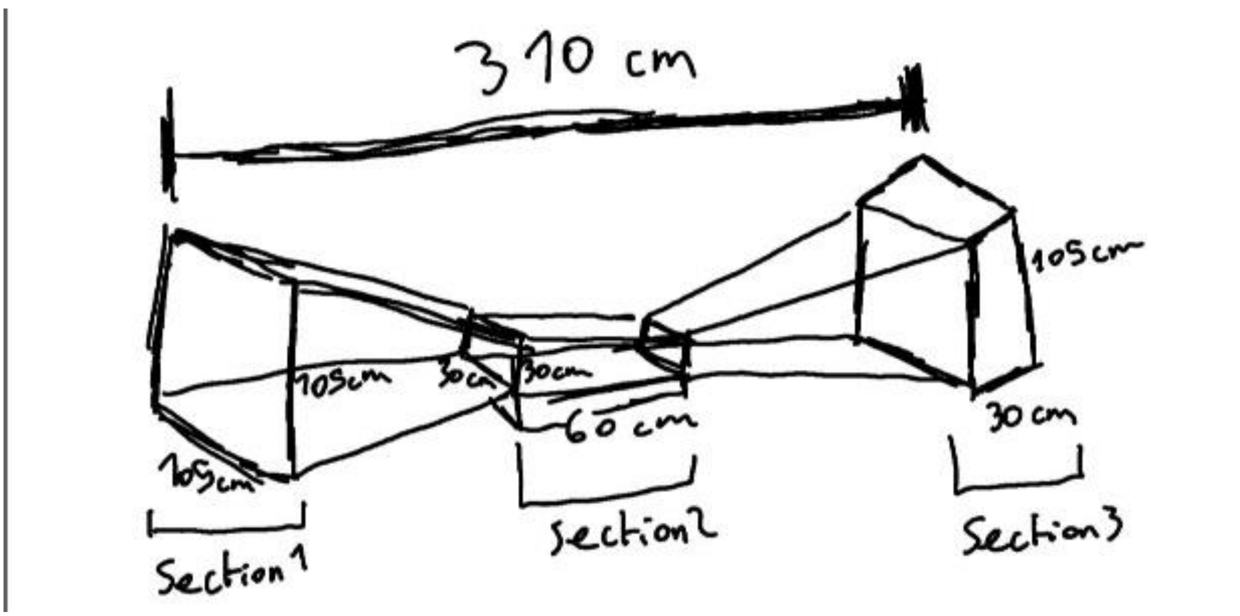


Figure D1: Design of the wind tunnel

The test section in a wind tunnel is smaller than the entrance because it creates a higher velocity and lower pressure for the air flow, which simulates the conditions of a moving object in the air. This is based on the principle of continuity and Bernoulli's equation, which state that the mass and energy of a fluid are conserved in a steady flow. By decreasing the cross-sectional area of the tunnel, the air speed increases and the pressure decreases, creating a dynamic pressure that acts on the object being tested. This allows the wind tunnel to measure the aerodynamic forces.

Reynols number calculations

In the design process we used calculations developed by Osborne Reynolds **(Reynolds, 1883)**. The Reynolds number is a dimensionless quantity that it is used for predicting airflows. To achieve flight like environments you first calculate the Reynolds number of the rocket and then modify the speed of the wind tunnel so the Reynold's number match. The equation can be used for all environments not only earth's atmosphere.

$$R_e = \frac{V \cdot L}{\nu}$$

Equation 1: Reynolds equation for kinematic viscosity

The R_e stands for the Reynold's number, the output from the equation. V being the velocity of the fluid relative to the object in m/s. The L is the length of the object, by convention the diameter. The last parameter, ν, is the kinematic viscosity. With the setup we have, calculating the Reynold's equation $R_e = \frac{10 \cdot 0.1}{1.47923 \cdot 10^{-5}}$, with the kinematic viscosity being $1.47923 \cdot 10^{-5}$ at sea level and 15 degrees Celsius. The diameter is 10 cm or 0.1 m and the speed relative to the object is around 10 m/s. which returns a value of 67 603. If we then want to calculate what velocity we're simulating, we just have to solve the equation for x. In this case we simulated a scenario in higher atmosphere which in our case it would be like this: $67\ 603 = \frac{2 \cdot \mathrm{x}}{7.04431 \cdot 10^{-4}}$ using the kinematic viscosity of the air at around 30 km of height and -60 degrees Celsius. when we solve for x gives a value of 23.81 m/s or 85.716 km/h. This means that with our set up we can simulate rockets of a diameter of 2 m.

Sections of the wind tunnel

We made two cones with a bigger aperture of 100cm and a smaller one of 30cm. Afterwards we built the test section using 4 planks of wood 30x60 cm. We designed it to be 30cm of aperture so we could fit the rocket model inside. Using Reynold's equation, we calculated the size of the aperture to simulate the speed of the rocket in upper Earth atmosphere to be more than 85 km/h. Smaller tunnel did not guarantee to obtain data of the needed accuracy.

The wind tunnel is supported by a wooden skeleton. The skeleton is made of wooden pillars 34x34x2400 mm (**Figure T1 and Figure T6**).

Figure T1: Wind tunnel's frame

Figure T6: Wind tunnel during construction

Jan Kazimierczak (right) and Tobias Van Bavel (left) next to the wind tunnel.

Section 1. Entrance.

We started by making the frame for the honeycomb mesh (**Figure T2**). A wind tunnel needs a honeycomb mesh to straighten the air flow and reduce the swirl and turbulence in the test section. The ratio between the honeycomb panel (**Figure D2**) and the test section (**Figure D3**) is approximately 4:1.

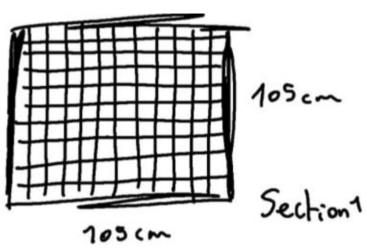
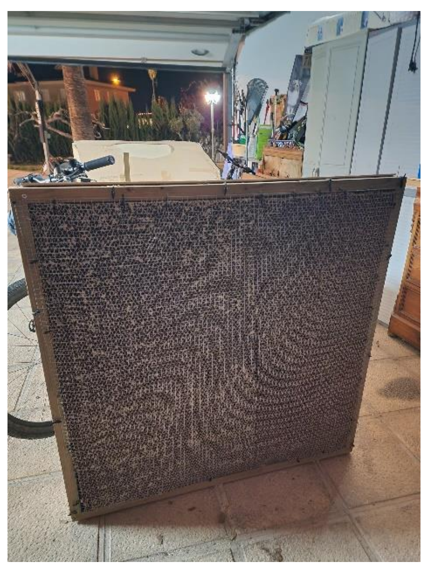


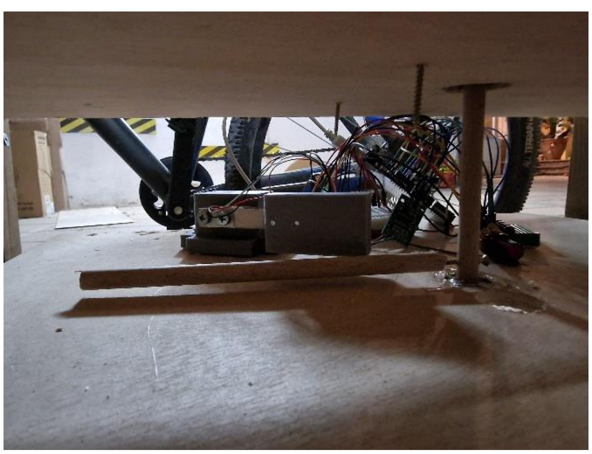
Figure D2: Honeycomb mesh in section 1 of the tunnel



Honeycomb mesh in section 1 of the tunnel

Section 2. Test section

The test section is made up of 2 plain planks and 2 planks with a hole for viewing the inside. The inside is completely flat on all 4 sides for an optimal laminar flow. On the walls and the ceiling there are LEDs attached so the observer can view the behaviour of the grid fans. In the centre of the section there is a 10 mm wooden tube passing through the lower wall (**Figure D3**). Below the test section there's a wooden surface to support the sensors and the Arduino UNO board. The tube passes through with both planks with the help of 2 bearings (**Figure D3**). A smaller wooden tube is attached to the main one with a screw. When the rocket swings in the test section, the tube below turns as well, without letting air out thanks to the bearings.



Sensor section, where the wooden tube

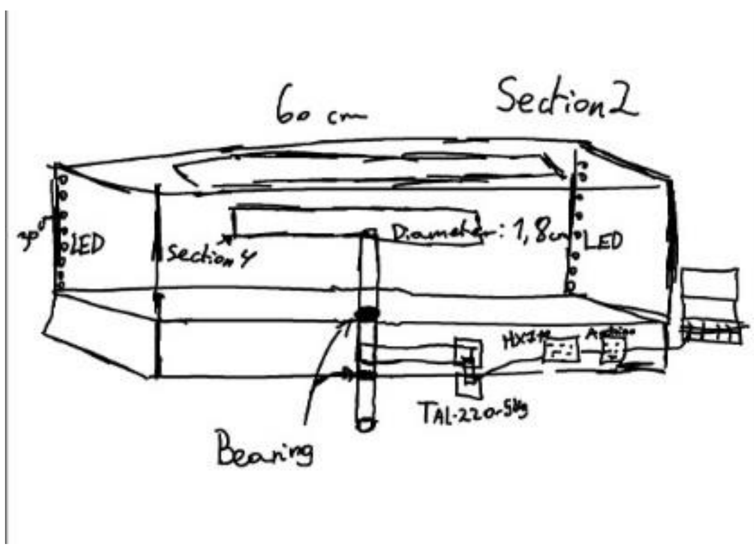


Figure D3: Test section of the wind tunnel

Model rocket connected to the wooden tube

Grid fin connected to the model rocket

Section 3. Diffuser and fan

After the test section of the wind tunnel there is the diffuser. The diffuser is just the wind tunnel getting wider to a desired width of 1.05 m. The wind tunnel gets wider gradually to balance the pressures and avoid creating an unintentional vacuum. At the end sits the ventilator which instead of throwing air in, is sucking the air out allowing therefore laminar flow to form inside the tunnel.

The fan sits on a base for which we left 30 cm of space for the fan (**Figure D4**) on the other side of the honeycomb mesh (**Figure D1**), the honeycomb mesh consists of cardboard with the honeycomb mesh pattern and a very thin net with very small holes. The fan we bought has approximately 4000 CFM/6600m^3/h, which is twice the recommended. After constructing skeleton, we bought 8 wooden planks 110x102x0,5 cm, which we them connected to the main body to make up the walls.

Section 3 of the wind tunnel (ventilator)

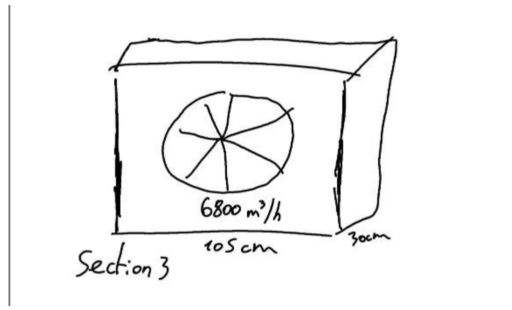
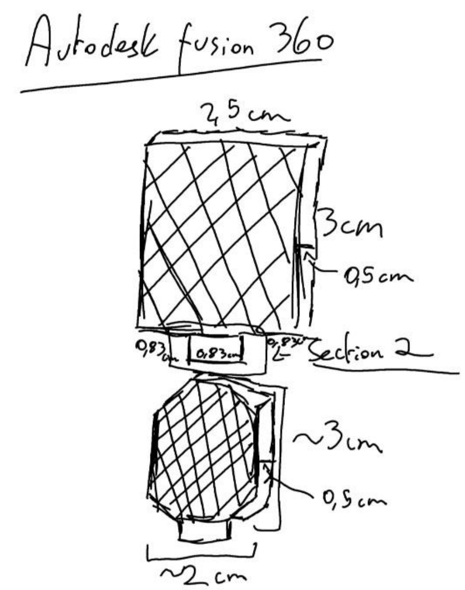


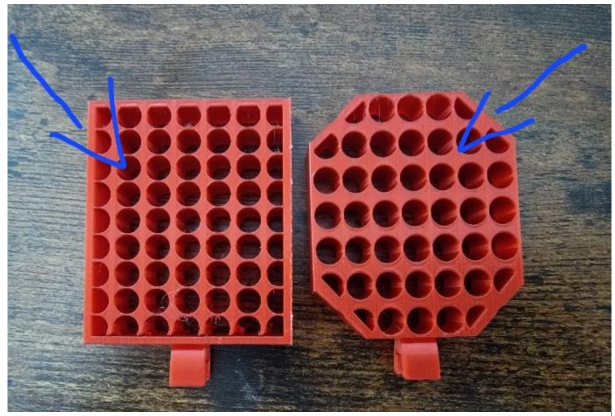
Figure D4: Section 3 of the wind tunnel (ventilator)

Grid fins design and production

We designed grid fins in a program called *Autodesk Fusion 360* (**Figure D6**). It is a well-known program used to make 3D models. We made 2 different shapes of grid fins, each with several types and size of holes. One kind of grid fin we made was a square-shaped one. The other one had all its corners cut out. To distinguish between the grid fins, we called the ones with the overall square shape "simple" grid fins and the ones with the corners cut out "complex" grid fins (**Figure T5**).



Simple



Complex

Figure T5: The two grid fin overall shapes

Figure D6: Designs for the grid fins

For each of these shapes we made 9 slightly different ones, making a total of 18 grid fins we tested. The main difference was in the shape and size of the grid fins' holes. The shapes we used were circles, squares, and hexagons, and made them 2, 4 and 6 mm wide. Among all hole sizes, the grid fin area was the same so we could test if the hole shape influences the grid fin's efficiency. (Figure T12)

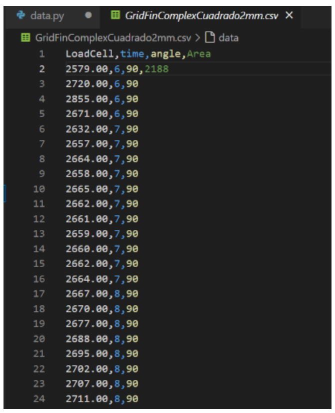
Figure T12: All 18 grid fins

To test the efficiency of the grid fins we had to attach them to a model rocket **(Figure D7) (Figure T12)**. The dimensions of grid fins were chosen in accordance with Reynold's equation to make the results comparable to the ones that may be obtained with a realistic rocket size. The grid fins were printed using a Prusa MK4 3d printer. For the filament we chose a normal PLA filament a PETG filament was not necessary.

Figure T12: Grid fin attached to the model rocket

Performance tests and data gathering

To calculate the efficiency of each grid fin design, we attached a TAL-220-5 Kg load cell to the bottom wall. The wooden tube collides with the load cell giving us a value on the pressure force exerted by the grid fins. To get the value, we connected the load cell to a HX 711 amplifier. The data from the load cell goes through the cables to the amplifier which returns the data to the Arduino board. We use an Arduino UNO board to get, process and send the data to the laptop (**Figure T7**). A python scripts opens the port COM3 where the Arduino is connected and retrieves its data. The Arduino code returns the data in a csv file format ready to be analyzed. (**Figure C1**). Using these sensors we generated roughly 10 000 observations for each of the tested grid fins' design, giving in total more than 180 000 observations for the analysis.




```
LoadCell,time,angle,Area
2579.00,6,90,2188
2720.00,6,90
2855.00,6,90
2671.00,6,90
2632.00,7,90
2657.00,7,90
2664.00,7,90
2658.00,7,90
2665.00,7,90
2662.00,7,90
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2677.00,8,90
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2707.00,8,90
2711.00,8,90
```

Figure C1: CSV file format

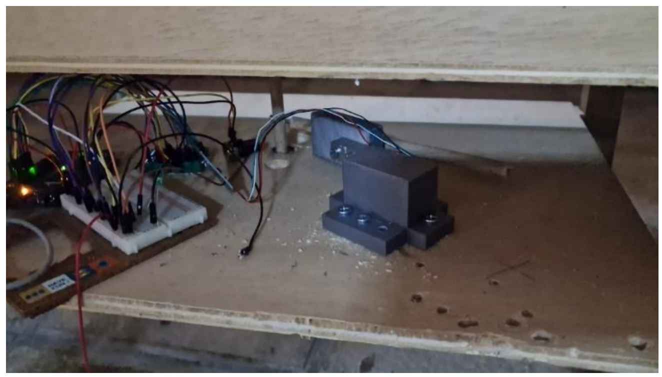

Figure T7: Sensor implementation into the wind tunnel

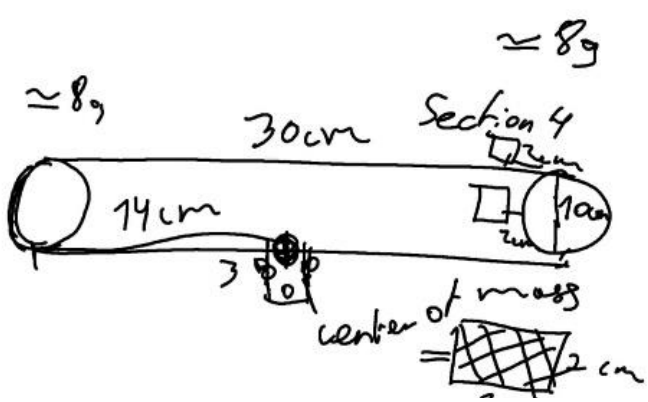

Figure D5: Design of the model rocket

Data analysis

The last step is to analyze the data with R statistical program. R is a programming language widely used for data analysis by such organizations as Google, Amazon, Deloitte among other[4], as well as European institutions like EUIPO. For the gathering and analysis of data we coded more than 1000 lines of R code.

Differences in the data related with the different designs might be result of a pure chance and may not reflect the genuine differences in the performance. We performed the ANOVA test followed by the post-hoc test to assess whether those differences have systematic character. ANOVA, or Analysis of Variance, is a statistical method used to compare the means of three or more groups to determine whether there are statistically significant differences between them. In the context of our experiment, the ANOVA test is used to compare the mean LoadCell values across different datasets (grid fins' designs)

The ANOVA test performed on all data sets indicates that the probability of obtaining the similar results by chance is very low ($2e^{-16}$). ANOVA test does not indicate whether pairwise comparisons between different designs also give statistically significant differences. For that reason, we ran complementary post-hoc tests.

[4] https://careerkarma.com/blog/who-uses-r/ accessed on 02/03/2024

Simple 2, 4 and 6 mm

All results are represented with a boxplot graph. This is to make visualization as easy as possible. On the x axis the load cell output value is represented, while on the y axis, the different grid fins are named. On the boxplot graph (**Figure G1**) we can clearly see the circular shape is more efficient than the square on which is in second place followed by the hexagon shape being on last place.

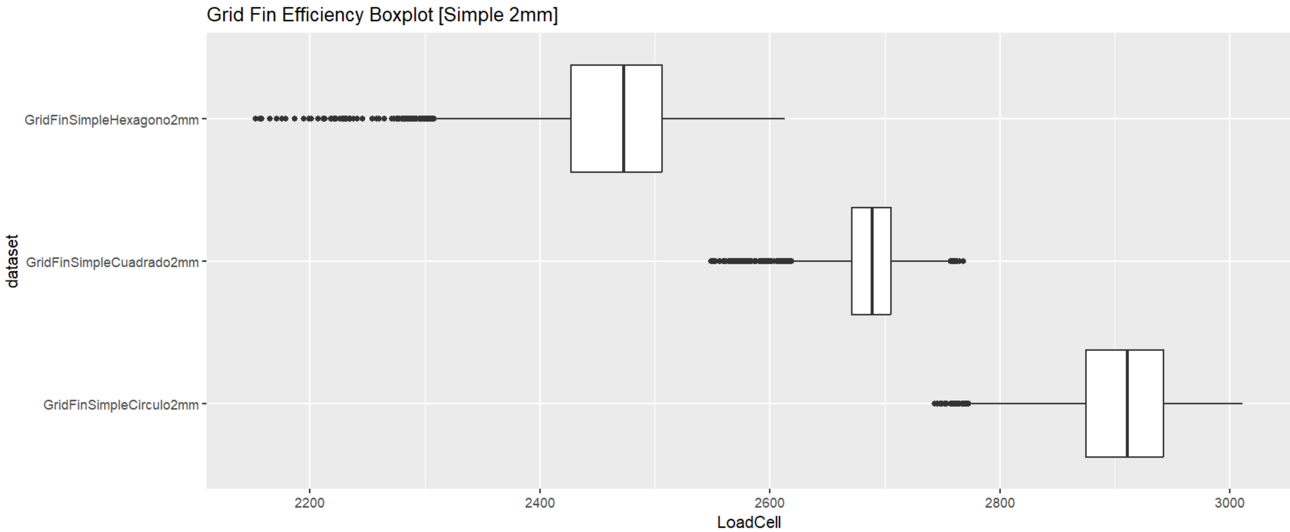

Figure G1

Next we can analyze the data from the same overall grid fin shape but different hole sizes (4mm) (**Figure G2**). In this case we can see the square shape wins by a landslide followed by the hexagon and in the last place the circle.

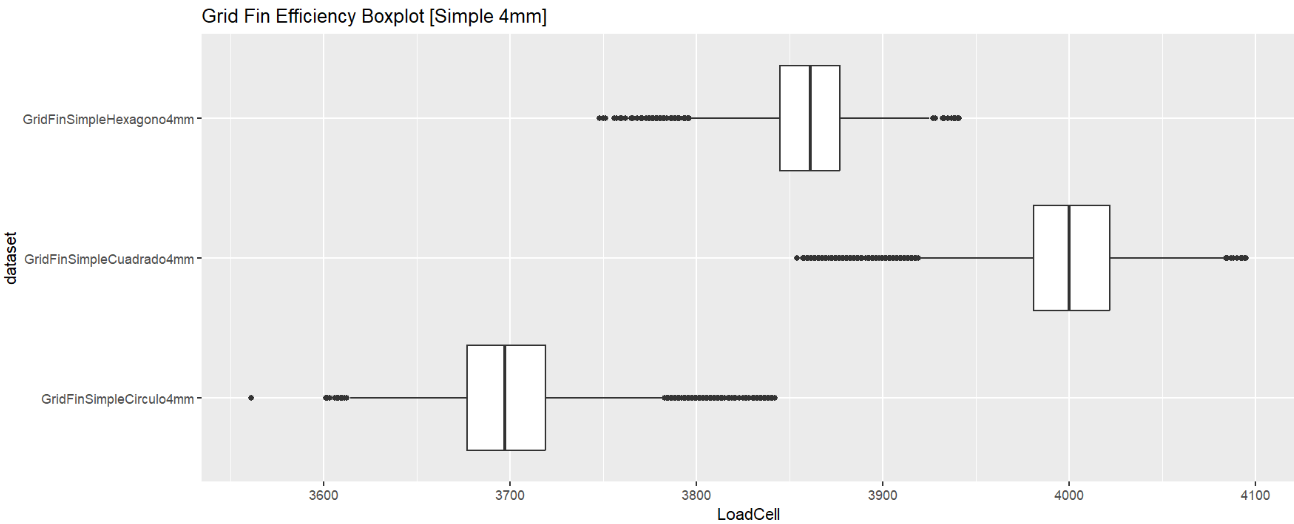

Figure G2

After this we analyzed the last size of the openings being 6mm. On the graph (**Figure G3**) we can appreciate once again the square shape being the most efficient one followed by the circle and then the hexagon. After analyzing all the simple grid fins with the overall square shape we can see the square was the most efficient one in 2 occasions while the circle was the most efficient only once. After analyzing the first 9 grid fins with the simple overall shape we moved on to analyze the ones with the overall cut out corners shape (complex)

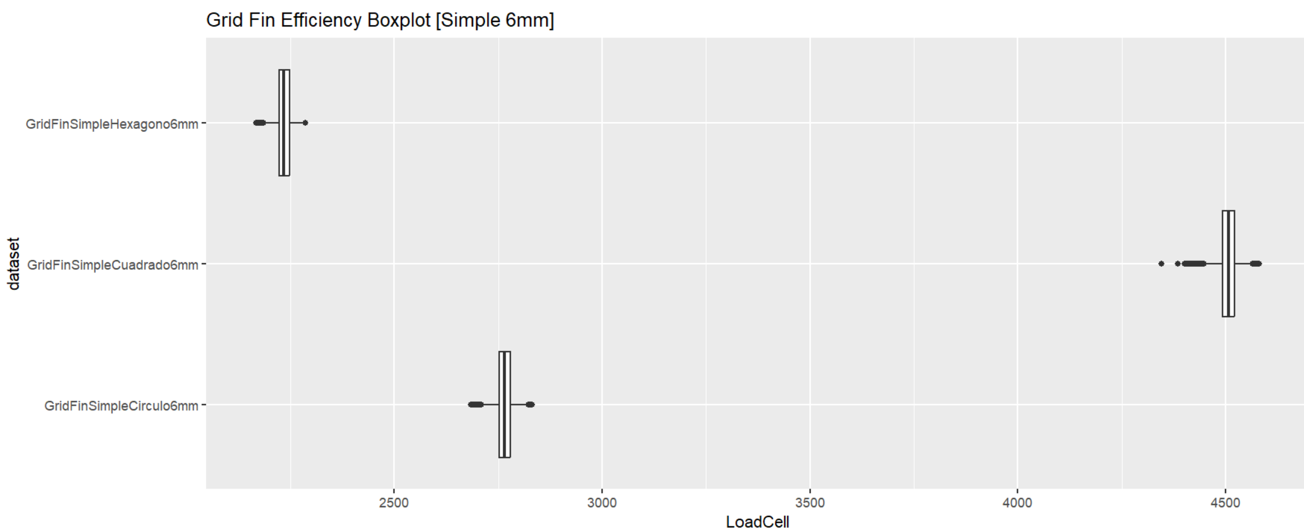

Figure G3

Complex 2, 4 and 6 mm

The first graph of the 3, (**Figure G4**) shows the square shape, once again being the most efficient one and the circle shape being in second place letting the hexagon shape on last place.

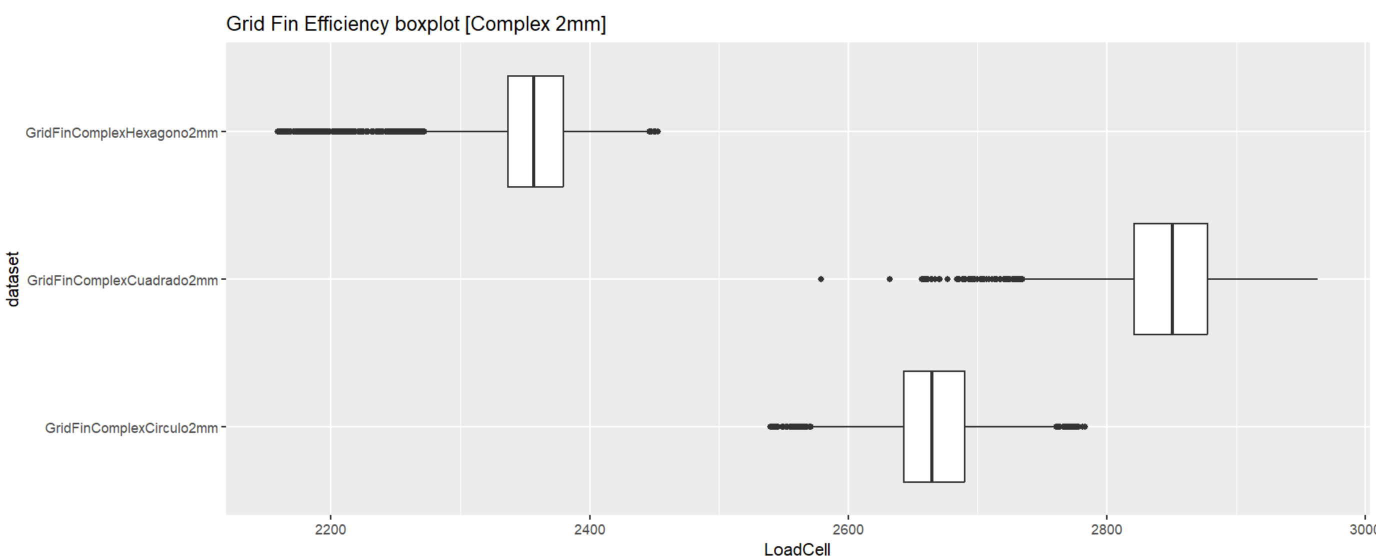

Figure G4

With the 4mm holes (**Figure G5**) the square shape fell on second place behind the hexagons, the circle shape was on last place and the hexagon the first.

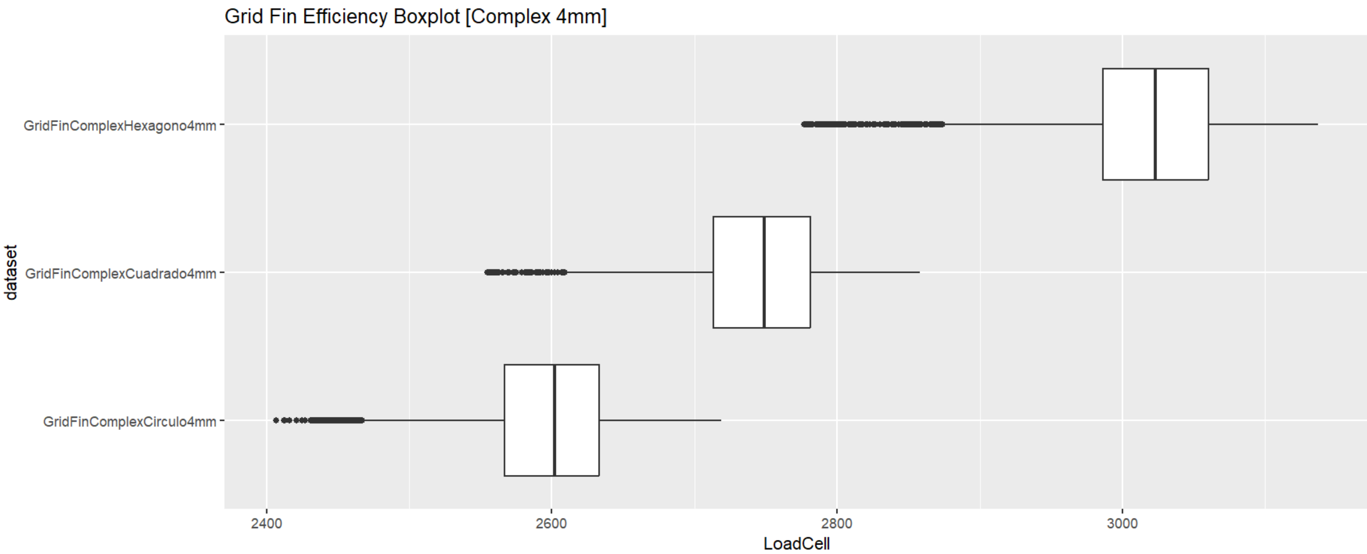

Figure G5

With the last size (6mm) (**Figure G6**) the most efficient grid fin hole shape was the hexagon, on second place was the square shape and one again falling on last place was the circle hole grid fin shape.

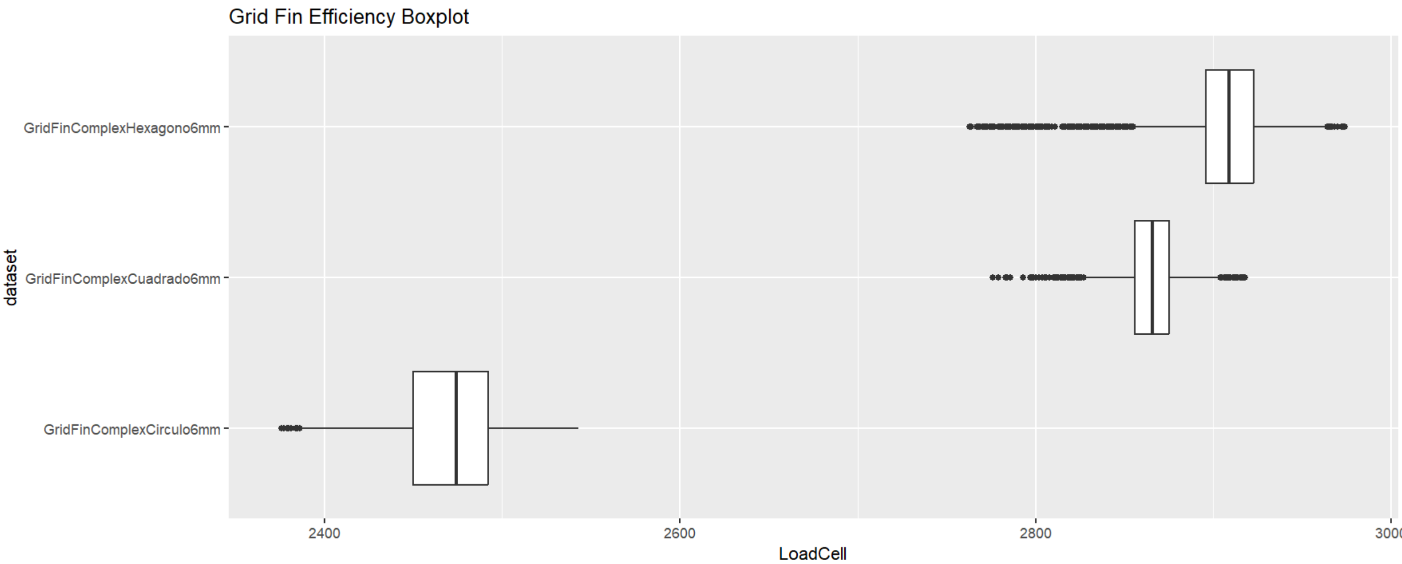

Figure G6

Having analyzed all 3 complex overall grid fin shape grid fin graphs we can conclude that the square shape was the most efficient once, the circle never and the hexagon twice. When we count the simple overall grid fin shape as well we can conclude that the square shape was the better and most efficient one 3 times, or 50% of the times, the hexagon shape was the most efficient 2 times, or 33% of the times and the circle shape was the least efficient one being the better one once or 16,7% of the times. With these results we can conclude that when having the same shape grid fin and same size holes the most rational and effective solution is to make the holes square, as it is the most efficient the most times.

Different shapes

After analyzing which grid fin shape is the most efficient when the size and overall grid fin shape stays the same we reviewed what happens when you change the overall and hole shape but leave the size the same. On the first case (**Figure G7**) which compares the efficiency of different overall and hole shapes but at the same hole size of 2mm. On the boxplot graph we can see that among the 2mm hole size the simple circle shape is the most efficient one followed by the complex square shape and the simple square being on third place. Behind these 3, the 4th most efficient grid fin among the 2mm hole size is the complex circle and the last 2 places are the simple hexagon and on last place complex hexagon.

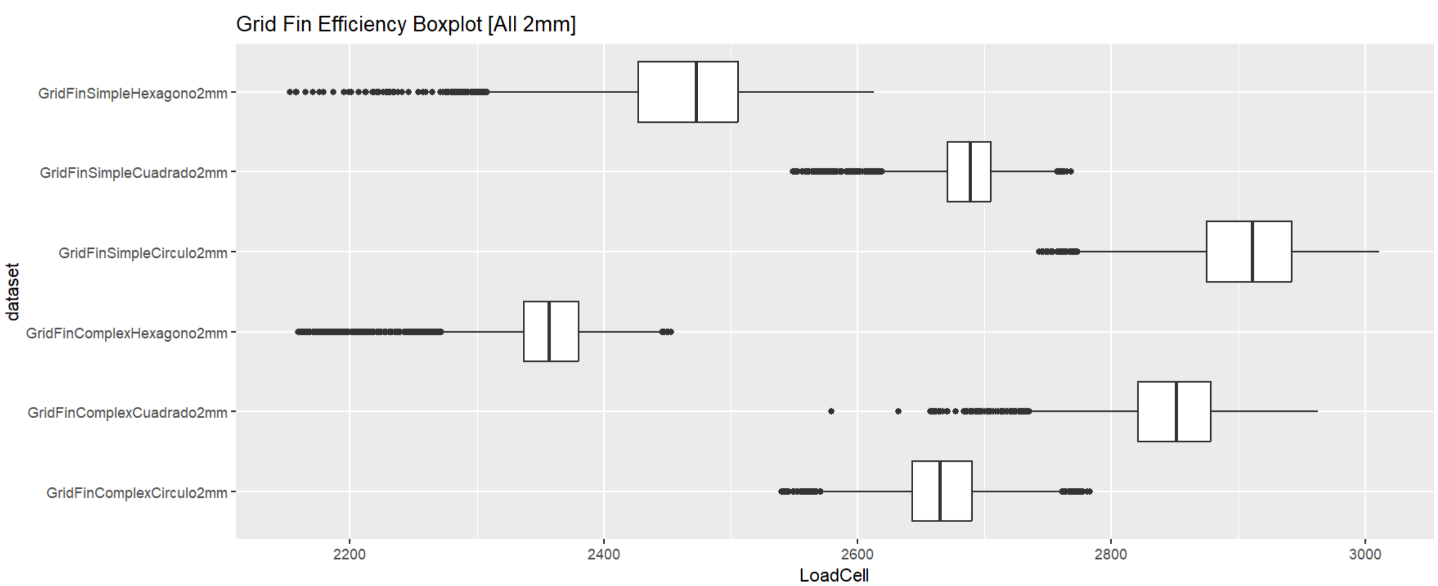

Figure G7

When we analyze the graph made by grid fins with hole sizes of 4mm (**Figure G8**) we see all simple grid fins are more efficient than all complex grid fins. The most efficient in the simple shape category is the square shape, followed by the hexagon and then the circle. In the complex category we can see that the most efficient one is the Hexagon shape followed by the square shape and then the circle one.

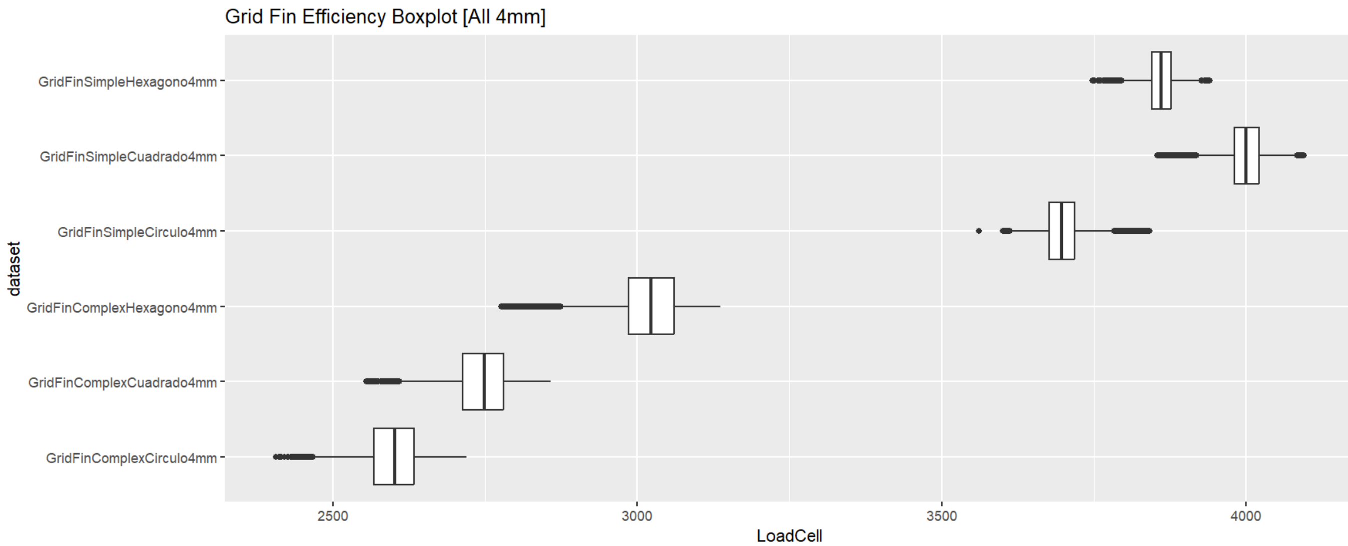

Figure G8

The last graph in this category is the one with the 6mm holes (**Figure G9**). This graph shows the simple square shape being the most efficient by a landslide. Following the square shape is the complex hexagon by the complex square and simple circle. The last two grid fins are simple hexagon and complex circle. Analysing the gathered data we can conclude that among same size but different shapes squares have been the most efficient ones overall with 2 times being the most efficient followed by the circle which was once at the top.

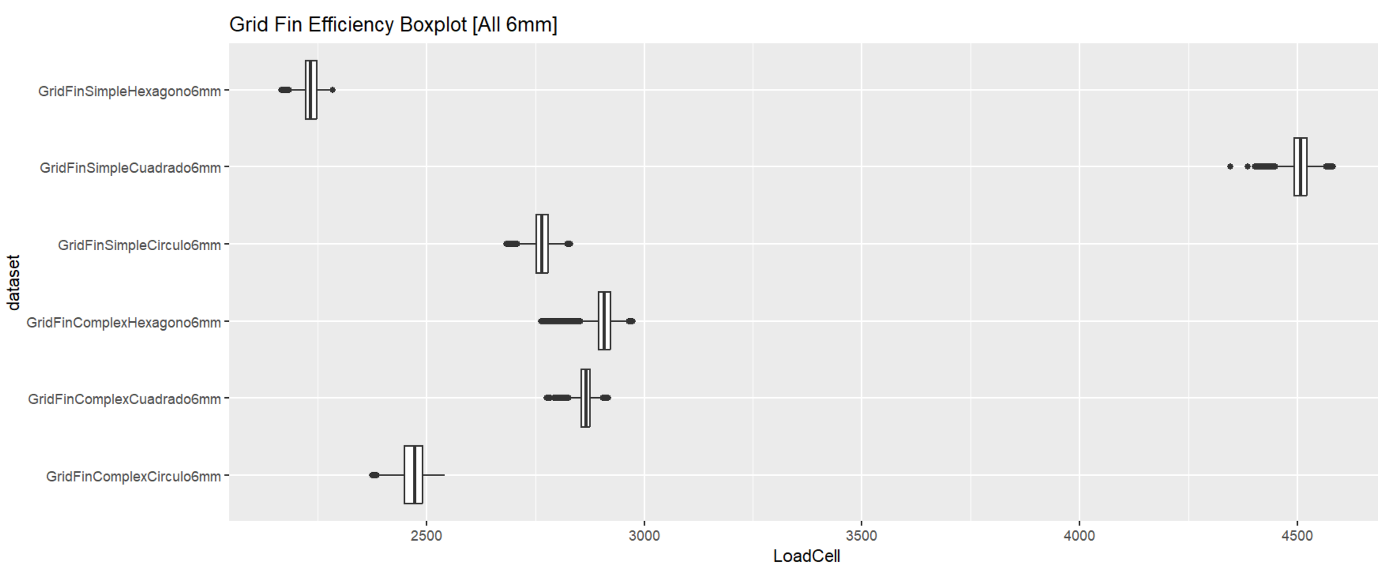

Figure G9

Different hole sizes.

Next we compared all same shape grid fins but different hole sizes. Graph (**Figure G10**) shows the 3 different hole sizes with circle hole shape and complex overall grid fin shape. On this graph we can see that in the case of the circle as the holes get bigger the efficiency gets smaller.

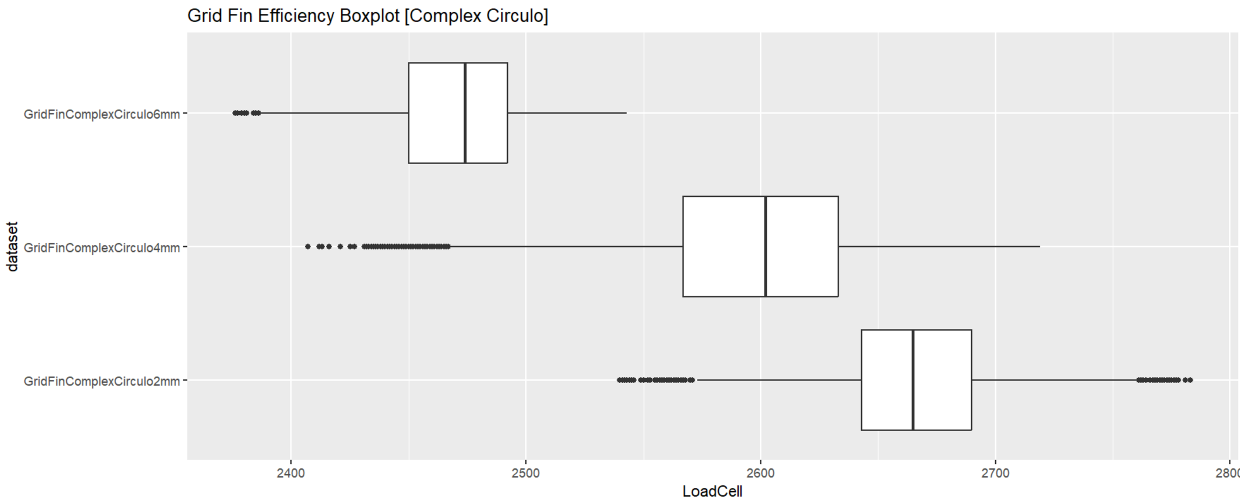

Figure G10

On graph (**Figure G11**) we can see the evolution of the efficiency of the complex square shape when the hole size increases. In contrast of what happens to the circle shape, the squares efficiency gets higher when the hole size gets higher.

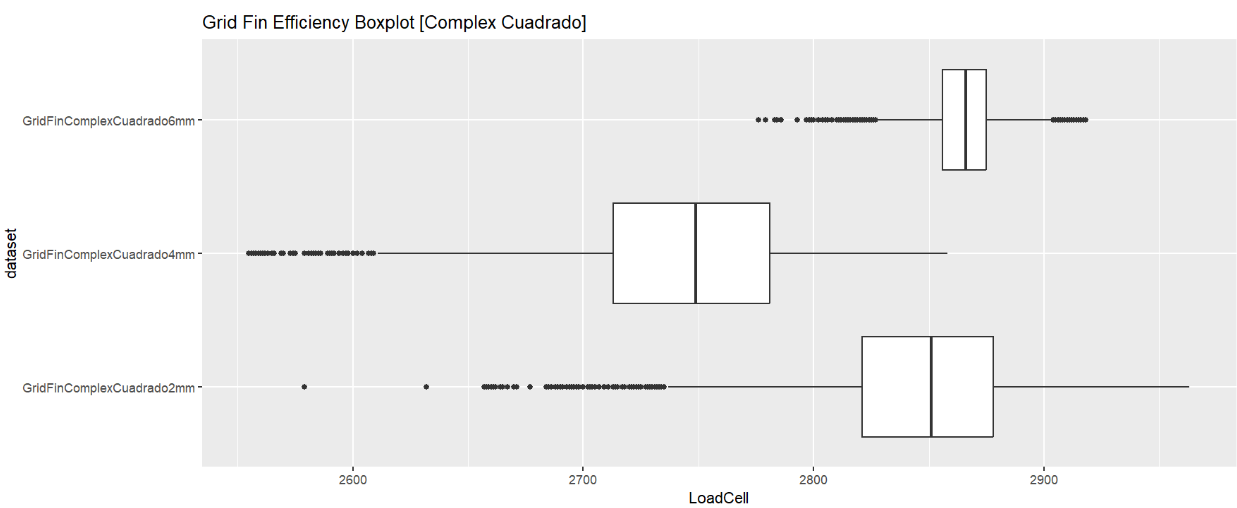

Figure G11

(**Figure G12**) shows the efficiency of hexagon shaped holes in complex overall shaped grid fins. In this case we can see a huge increase in the efficiency when the hole size increases but then it drops so it does not get higher the bigger the hole.

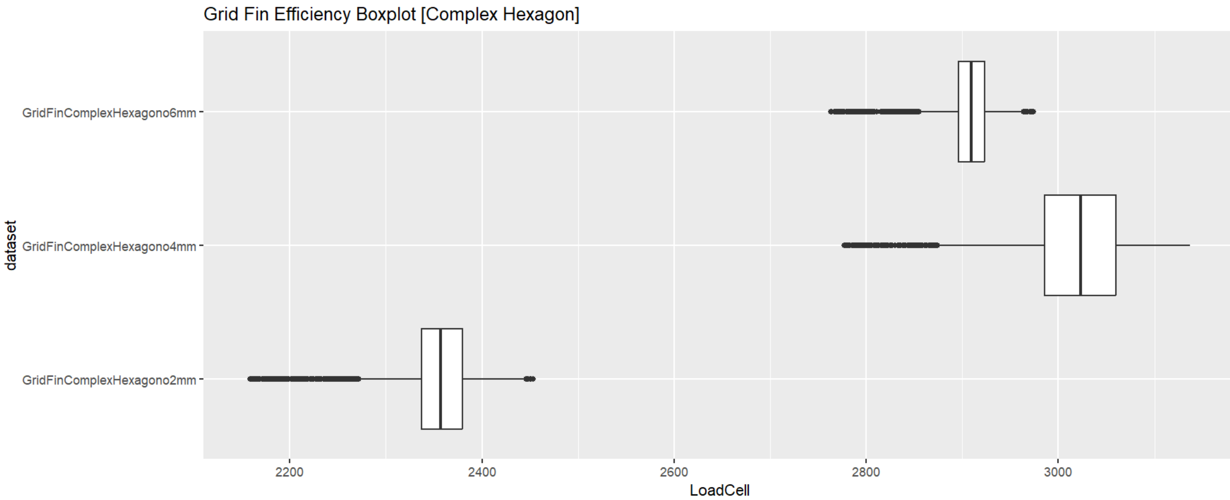

Figure G12

Next we changed the overall grid fin shape to simple. The first graph (**Figure G13**) shows the efficiency of the same hole shape (hexagon) different hole shape grid fin. The boxplot graph clearly shows the grid fin being really efficient in mid sizes, but the efficiency falling drastically when the hole size increases.

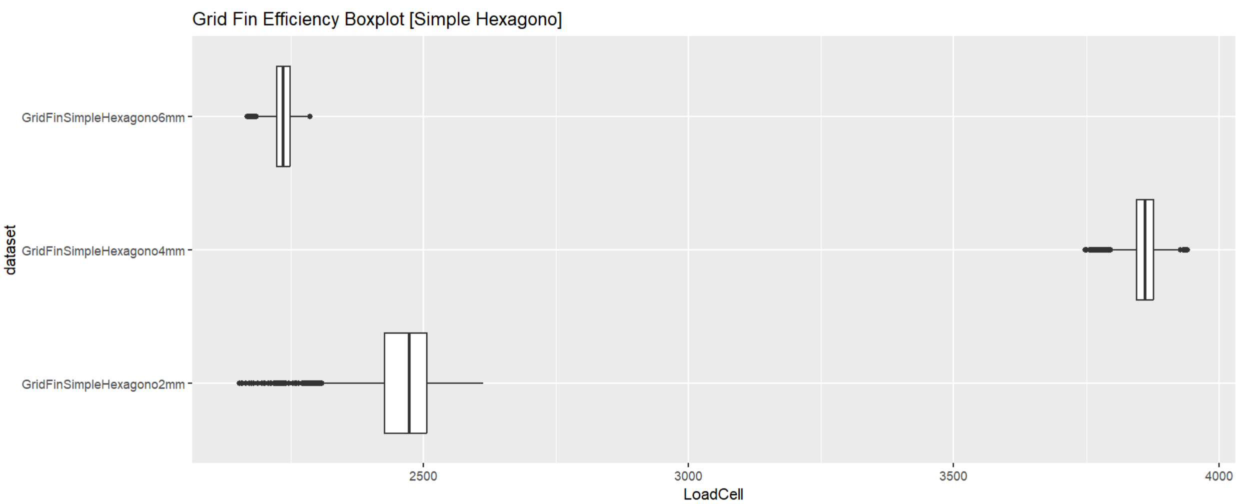

Figure G13

Graph (**Figure G14**) represents the load cell values from same hole shape (square) but different size. This graph as well as the complex overall grid fin shape shows that the square grid fins efficiency keeps increasing. The most efficient square hole grid fin is the one which has 6mm holes.

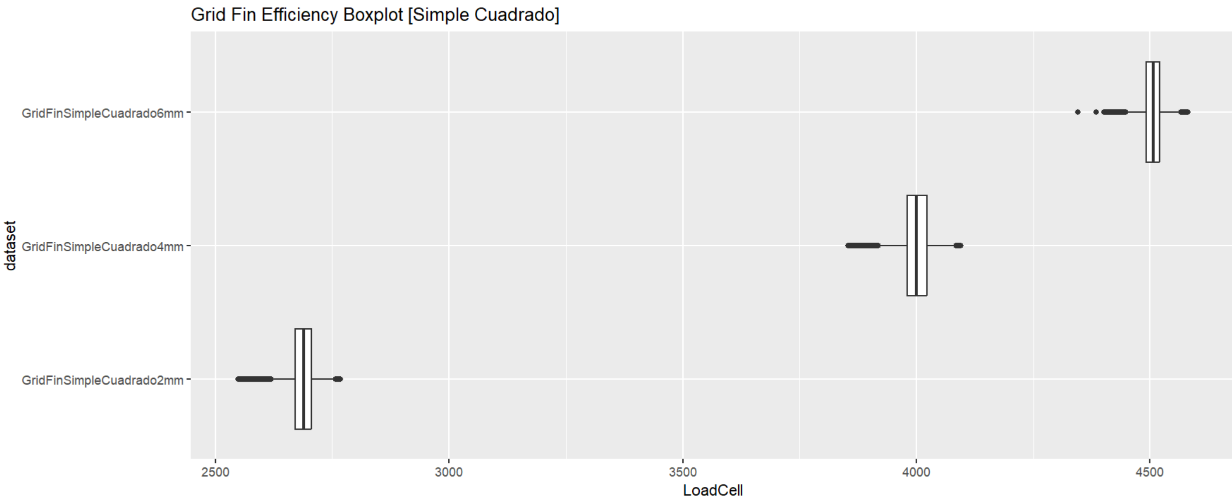

Figure G14

The last graph (**Figure G15**) shows the efficiency of circle hole shaped grid fins when hole size changes. In this graph we can see the same thing happens as in the other cases but the squares. The most efficient one is the middle size, 4mm, but the efficiency drops drastically when it goes to 6mm.

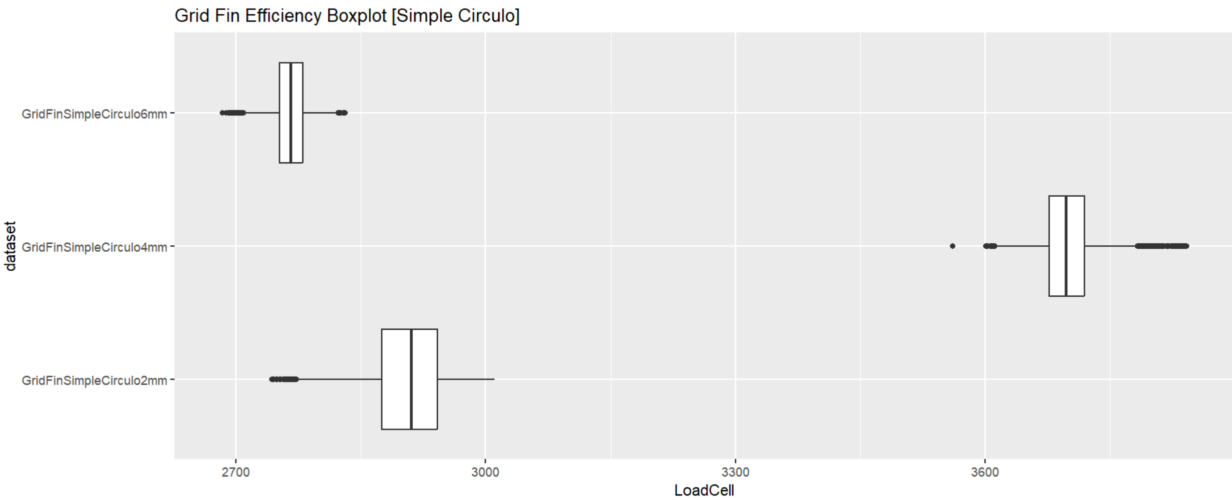

Figure G15

All this gathered data shows that the square shaped holes increase their efficiency when getting bigger, while the other two shapes, circle and hexagon decrease their efficiency when getting too big. In both cases the most efficient shapes were biggest (6mm) square holes.

All data in the same graph.

The last graph (**Figure G16**) compares all the 18 grid fins tested. We added this graph to see which grid fins are most efficient without looking at a narrow spectrum of the grid fins designs. Looking at the boxplot we can observe the most efficient grid fin of them all is the simple square 6mm grid fin, followed by the simple square 4mm grid fin. This shows that from all the designs bigger square shapes are more efficient than any other grid fin shape tested. The square designs, especially the 4mm simple is closely followed by the simple hexagon 4mm. But then the next grid fin is the circle 4mm. These results resonate with the previously made conclusion that 4mm circle and hexagon size is the more efficient among their respective shape, but the square keeps winning in the efficiency axis.

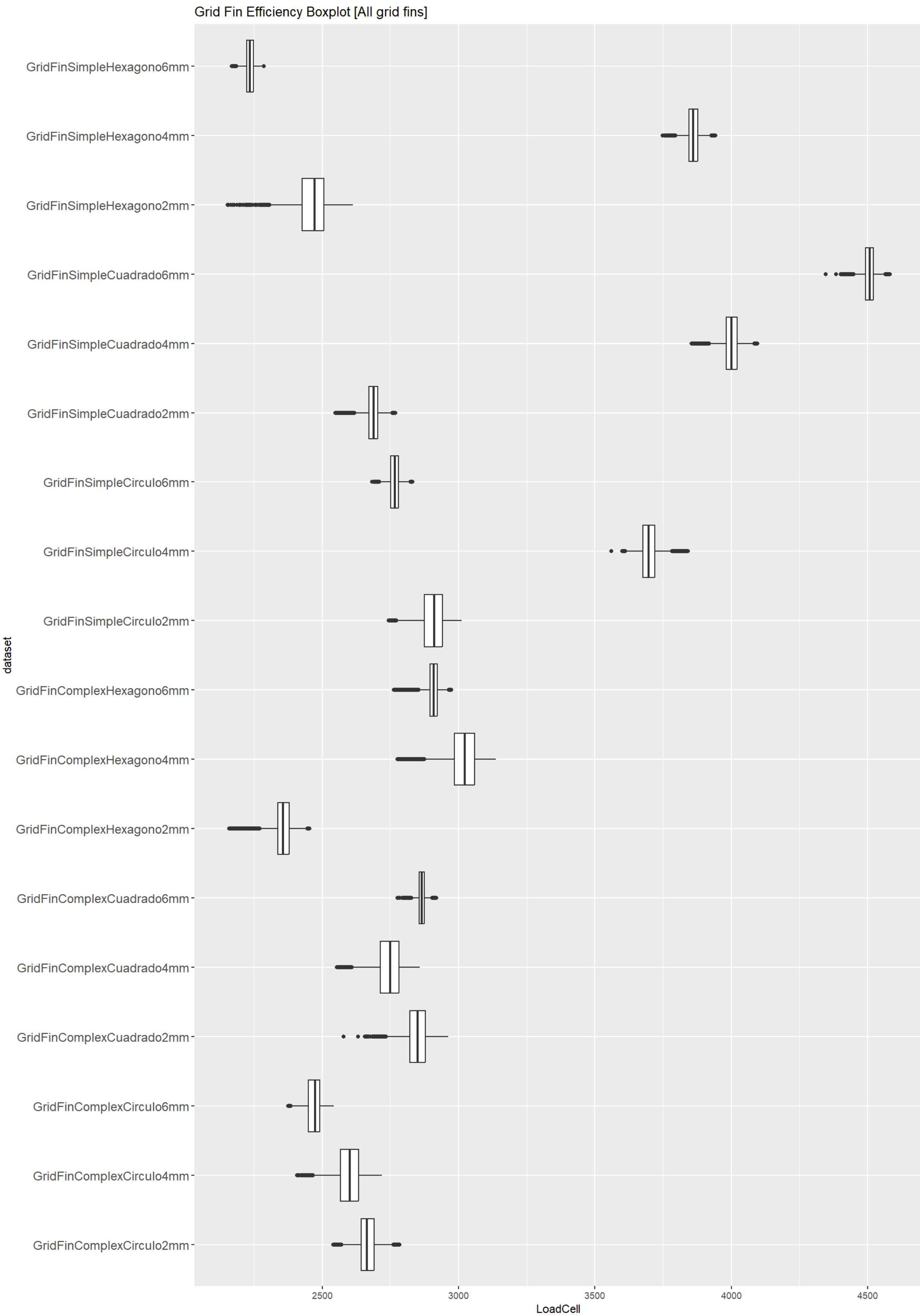
Grid Fin Efficiency Boxplot [All grid fins]
dataset
GridFinSimpleHexagono6mm
GridFinSimpleHexagono4mm
GridFinSimpleHexagono2mm
GridFinSimpleCuadrado6mm
GridFinSimpleCuadrado4mm
GridFinSimpleCuadrado2mm
GridFinSimpleCirculo6mm
GridFinSimpleCirculo4mm
GridFinSimpleCirculo2mm
GridFinComplexHexagono6mm
GridFinComplexHexagono4mm
GridFinComplexHexagono2mm
GridFinComplexCuadrado6mm
GridFinComplexCuadrado4mm
GridFinComplexCuadrado2mm
GridFinComplexCirculo6mm
GridFinComplexCirculo4mm
GridFinComplexCirculo2mm
2500
3000
3500
4000
4500
LoadCell

Figure G16

Conclusions

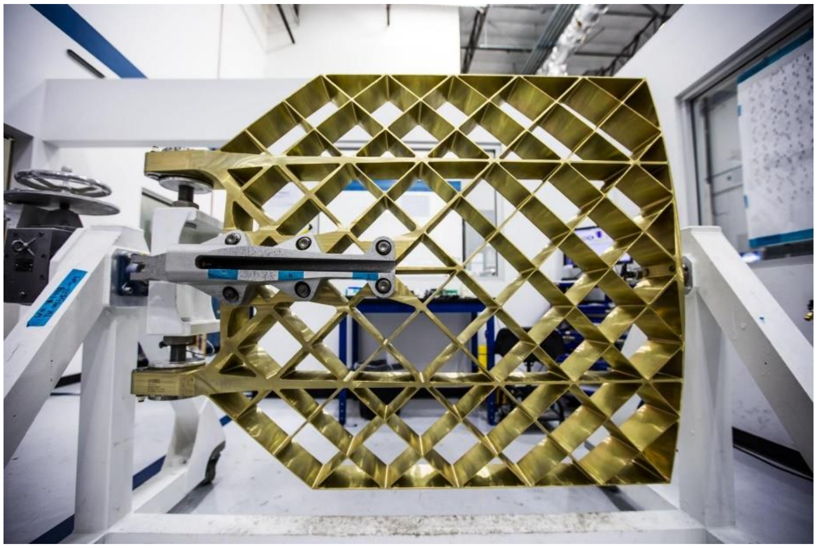

Figure R3: Falcon 9's grid fin during production credit(SpaceX)

By doing the post-hoc TukeyHSD test we see that the differences between the various grid fins designs are statistically significant. The post-hoc test compares the statistical significance of all 18 grid fins with each other. With all the data collected we can see that hole and overall grid fin shape do matter in the grid fins performance. Even when the area is the same, but the hole shape is different the performance of the grid fin changes. This is relevant, because when it comes to designing a grid fin you need to take into account the shape of the holes, not only the area. With all the hole shapes but the square we found the critical point to be around 4 mm. The critical point is when the derivative of the function equals 0 and in this case, it represents the maximum of the graph, meaning the maximum efficiency value the grid fin can generate with these hole shapes. On the other hand, as we did not find the critical point for the square shape it means the grid fin with square holes can achieve much higher efficiency than other hole shapes. On thing we can say for certain is that among all the grid fins, the simple square 6mm and simple square 4mm are the most efficient. This again shows the square pattern being the best. On the other hand, our experiments shows that besides hole pattern, overall grid fin shape also matters. We got better results using the simple grid fin overall shape rather than the complex one. Concluding we see that the best shape we could achieve according to our experimental data is simple square. This coincides with SpaceX's grid fin shape being simple overall (with the exception of the connector) and big square hole pattern (**Figure R3**). This pattern we can also see on missiles like the GBU-43 or the R-77.

Limitations and indications for future research

For future continuations on the project, we suggest with the square simple hole grid fin gradually increasing the hole size and calculating the point in which the grid fin's efficiency begins to drop and plotting the graph thus showing the maximum. The maximum would equal to the hole size which makes the grid fin the most efficient. Calculating this critical point would help in the development of grid fins. Given the crucial importance of reusable boosters it would be advisable to research other design innovations to achieve this goal.

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