Design of a lightweight & sustainable economy seat for short haul flights

Graduation report:
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Summary:

Short-haul flights are currently one of the most carbon-intensive modes of travel. Weight and fuel economy are closely linked. Therefore, weight reduction in the aviation industry is one of the critical factors in making commercial aviation more sustainable.

This project focuses on aircraft efficiency by developing a lightweight aircraft seat for the economy segment during short-haul flights.

The result of this project is a concept proposal for a 3-seater bench with a per-seat weight of approximately 6.5 kg.

The low weight is achieved, on one side, by addressing the structure of the seat, where the core element of the concept is a single-piece compression-moulded shell made of CFRTP that consolidates conventional multi-component assemblies. On the other hand, comfort is provided by replacing traditional and heavy PU foams with a lightweight fabric suspension system.

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Introduction

For the last few years, the aviation industry has increasingly been confronted with its impact on the environment concerning their emissions of greenhouse gases.

Flightshame became a popular discussion topic in the media, and it is predicted that more travellers will become aware of the negative impact their flying behaviour has on the environment. (McKinsey,2020)

Right now, the global aviation sector accounts for 2-3% percent of the global carbon footprint and 12 percent of all transportation sources (ATAG, 2020), in comparison to the
74 per cent for road transportation this may seem like a small number, yet aviation is one of the fastest-growing sources of greenhouse gases. The acceleration in globalization and an inability to innovate as fast as other industries are forcing the aviation sector to make changes.

According to IATA (IATA, 2020) and the United Nations World Tourism Organization (UNWTO, 2019), airlines could focus on three areas to address climate change: aircraft efficiency, operations efficiency and alternative fuels.

This project focuses on aircraft efficiency by developing an lightweight aircraft seat for the economy segment during short-haul flights.

Weight and fuel-saving are closely related, saving significant cost and carbon emissions.
By developing a new lightweight seat concept I hope to create a design that can benefit the planet, airline companies and its passengers.

Problem definition

Short-haul flights (700 km or less) are one of the most carbon-intensive ways of travel right now, emitting more CO_2 per person km than long haul flights (BEIS-Deftra greenhouse gas conversions, 2020), (fig.1).

This project will therefore focus on the design of a lightweight economy class seat for short-haul flights. While comfort will be of high priority it will be less critical than for long haul flights giving more opportunity to push the limits of weight reduction in the design.

This project aims to design a lightweight economy class seat concept for the near future (5-10 years) with a particular focus on sustainable flight. It will be important that this concept is attractive to both the airlines and their passengers so that both parties can work towards the common goal of making short-haul flights more sustainable.

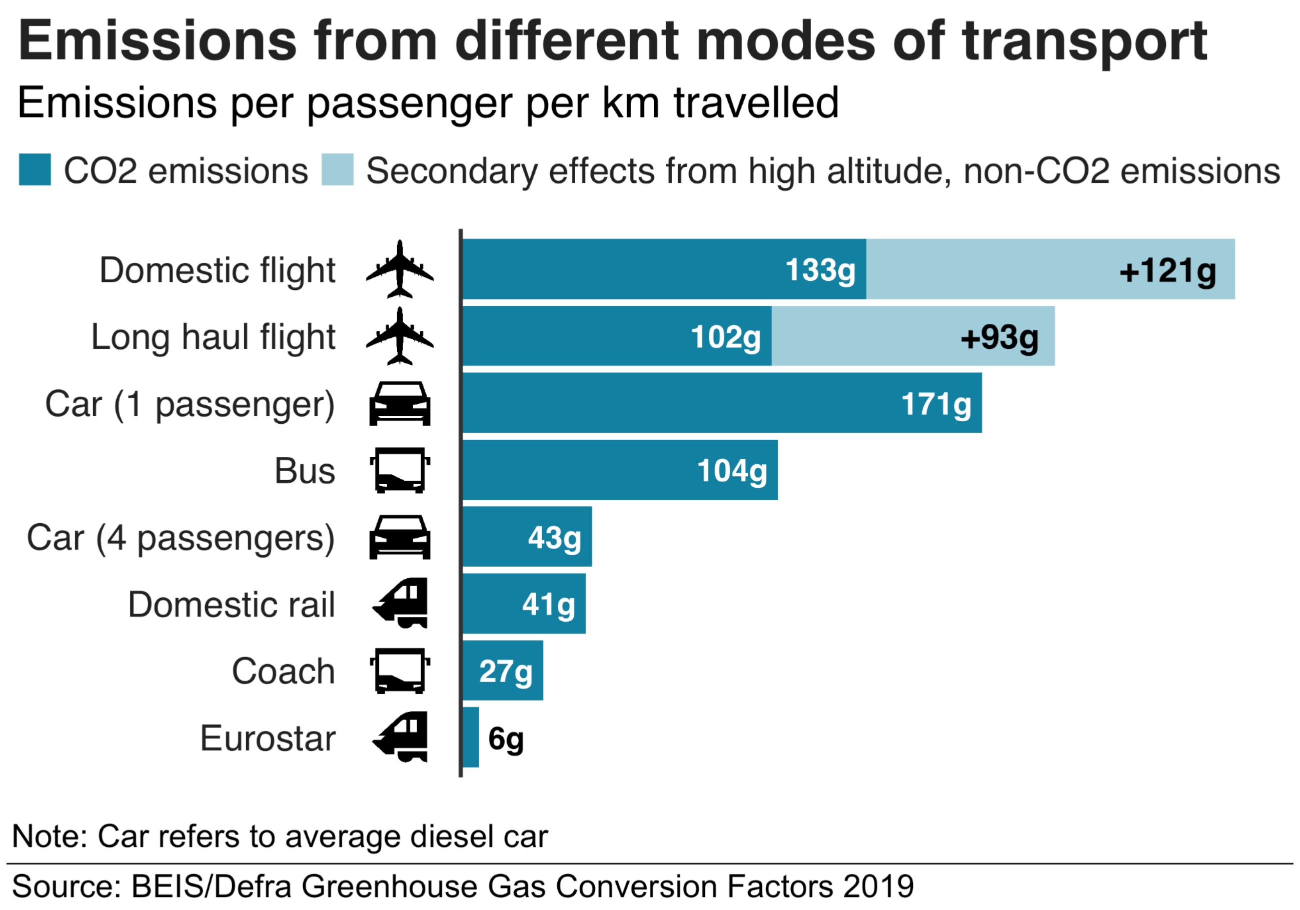


Fig. 1 Emissions from different modes of transport

Assignment

In this project, I will investigate how the design of short-haul economy airline seats can be optimized in weight-saving, comfort and experience. Designing the maximum value for the minimum amount of mass.

As a solution, I expect to deliver a lightweight seat design concept achievable through the combination of advanced materials and production methods. At the same time, I strive for the seat to be attractive (comfort, aesthetics, experience) to passengers and demonstrate the airline's commitment to sustainability and comfort through innovation.

On the one hand, the outcome will be a digital concept design (CAD) with weight estimation and limited structural validation (FEA) and, on the other hand, a physical prototype model to evaluate ergonomic aspects.

Approach and methodology

For this project, the methods of design thinking, lean startup and agile thinking will be combined. Design thinking will be used in the first phase to explore the topic, empathize with the users, define a clear vision, ideate to come up with solutions and conclude with a clear concept direction.

The lean startup method will be applied to start validating and improving on the concept, by building physical prototypes and iterating on it through 3 repeated cycles of measure, learn and build.

In the final phase, Agile thinking will be used to work towards the final deliverables. Using defined design sprints to work towards the end results which include: The defined 3d model, the presentation material and the finalization of the report.

1 Context research

1.1 Short haul flights airplanes

The new seat concept is intended for the near future (5-10 years). Therefore, it will be designed for the context of existing short-haul commercial aircraft in use today. Commercial aircraft develop incrementally, therefore we can assume that this is a safe starting point for the context of the design.

Airlines usually use narrow-body aircraft with two engines and a single aisle for their short-haul flights. The following is an overview of the two most commonly deployed narrow-body aircraft used for short-haul flights. The Boeing 737 and the Airbus A320.

Airbus A320

The Airbus A320 is one of the most widely used narrow-body aircraft for short-haul flights. By default, there are two types of layouts. A two-class layout (Business and economy class) with 150 seats and a one-class layout (economy) with 164 to 180 seats, depending on seat pitch. On either side of the row of 3 seats, there is one aisle, with the business class seats in rows of two.

Within the A320 family,there are several versions, ascending in size, the A318, A319, A320 and A321. Introduced in 2016 the latest model, the A320Neo with Neo standing for "new engine option", offers significant environmental improvements. It reduces fuel consumption by 15%, operating costs by 8%, noise emissions by 10% and nitrogen oxide (NOx) emissions by 10% compared to the existing A320. Airbus claims a per seat fuel improvement of 20% (Airbus, 2021).

The Airspace cabin (fig.2) is the latest interior for the Airbus A320neo, launched in 2021; this new cabin offers increased space use, comfort and cleanliness. The aisle's width is the largest in its class, and there are new extra-large baggage bins that have 40% more volume with a size of 24x16x10 inches so passenger belongings can always be close to the seat (see fig.2).

The window size has been maximized to allow more natural light into the cabin, and there is an artificial lighting system with ambient light that can be customized in colour. A new air conditioning system guarantees a pathogen-free cabin, and the bathroom offers touchless features and anti-microbial surfaces to ensure a sanitary environment (Airbus, 2021b).

Boeing 737

The Boeing 737 is the most popular commercial aircraft in history with more than 10000 aircraft sold since its launch in 1967. It is the main competitor of the Airbus A320. Both aircraft are narrow body aircraft with similar performance and accommodation. Depending on the Boeing 737 version there are between 85 and 215 passenger seats available. The 737 MAX is the latest version designed as a competitor to the Airbus A320 neo. It offers 14% reduction in carbon emissions to its previous version and a 40% smaller noise footprint (Boeing, 2020).

Much like the Airbus Airspace cabin, Boeing offers the sky interior (fig.3) in their new aircraft. The sky interior offers Design enhancements which create a larger sense of space. Design changes that contribute to this are the baggage bins that are less noticeable and larger than the old ones. The side walls are sculpted as in the interior of the airspace cabin. There is also similar ambient LED-lighting that can mimic daylight from sunrise to sunset. In addition, there are improvements to the PSU (Passenger Service Unit), and there is the ability to store live vest overhead (Boeing, 2020).

Fig. 2. Airbus A320 neo Airspace cabin

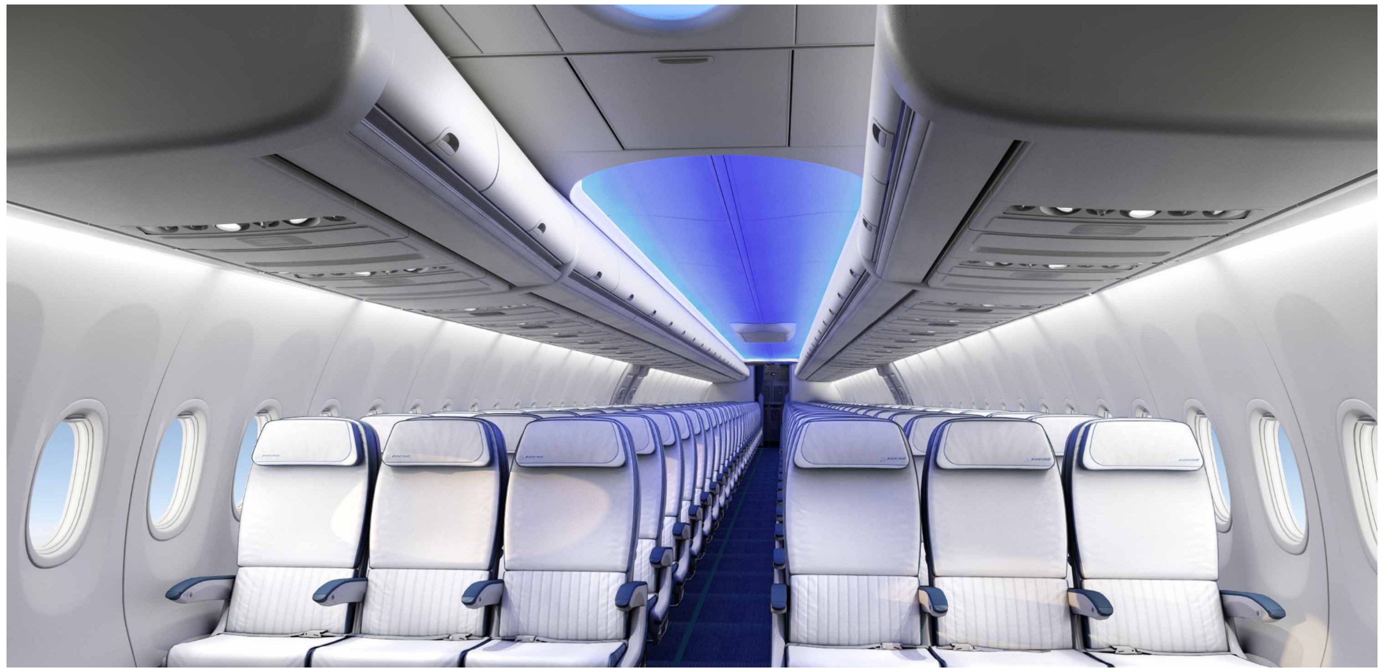


Fig. 3. Boeing 737 Sky interior

Conclusion:

Two main attributes define the aircraft's latest cabin development.:

1. Making the aircraft more efficient for economic and environmental reasons.

2.Enhancing the cabin experience in a way where key values such as comfort, cleanliness and spaciousness are more present.

1.2 Seat classes: short haul & medium haul flights

Regular Economy class

Economy class accommodates the most passengers on an aircraft and is often the least expensive travel option. The seat pitch in economy class ranges from 28-34. Depending on the airline and the flight duration, in-flight wifi, food and entertainment are additional services. Baggage allowance in economy class is often limited. The target market for economy class seats is usually leisure travellers who want to get to their destination economically.

There is a segmentation difference between airlines. Low-cost airlines usually only have economy class seats with a pitch between 28 and 30 inches . Mainstream airlines like KLM offer multi-class layouts with economy seat pitches ranging from 28-34 (KLM, 2021). Next to this, specialized Comfort airlines like Luebeck air provide increased comfort (35-inch pitch) by using less dense seat layouts (aeronauticsonline, 2020).

Economy comfort or plus

One level up in the airline classes is

"economy comfort" or sometimes called "economy plus". This class sits between economy class and business class and uses the same seats as economy class, but the space between the seats is slightly larger, with usually a few inches of extra legroom (30-32inch pitch). Sometimes the seats are are also adjusted to offer a slightly larger recline angle (KLM, 2021b).

This class is for travellers who want more comfort without immediately paying the price of business class.

Business-class

Business-class is the highest class on short-haul flights, a class intended for business travellers who need to travel frequently and wish to experience greater comfort and increased privacy.

This increased personal space and comfort is to allow the passenger to work undisturbed or rest comfortably.

In most markets, including the United States and Asia, Business Class on domestic or short-haul flights offers more independent and comfortable seats. It features deep backrests, calf support, storage compartments for small items, a power supply, a large centre console and IFE screen, a wide armrest, and a tray table independent of the seat in front. Some business class seat can be laid completely flat and turned into a bed for sleeping in some cases.

This type of seating takes up more than two times the space of regular seats, and its weight ranges around 100 kg (Rizzo, 2018), which can be more than ten times as much as an economy class seat

EU-Business-class

The business class experience in Europe offers a very different level of comfort than in the United States. In Europe, the business class usually utilizes the same seats as the economy class. However, the middle seat is blocked and left empty to increase the traveller's personal space in a three-seat configuration. Besides this, a few inches of legroom (pitch) is added, in addition to a slightly larger recline angle .

The reason for equipping the whole aircraft with economy seats is that it gives airlines flexibility in using their fleet at total capacity. When there are not enough passengers that bought a business class ticket and seats remain empty, the airline can remove the blocking devices and sell them as extra economy class seats (Ewen, 2015).

In addition to greater personal space and comfort, the business class aims to justify its higher price by offering services such as additional baggage allowance, priority check-in and boarding, and access to lounges and drink and meals.

Fig. 4. Regular economy class KLM

Fig. 5. Economy comfort with increased pitch

Fig. 6. Recaro CL4400 business class seat

Fig. 7. EU-business class with empty middle seat

Conclusion:

In Europe, airlines have become inventive in their differentiation of seat classes on short-haul flights. So much so that the added value besides extra services is quite low. One type of economy seat is used throughout the aircraft for both business class and economy. The benefit is that it allows airlines to maximize efficiency and convert business class seats into last-minute economy seats. However, the slight differences in recline angles and seat pitch don't seem to facilitate the differences in activities between business and leisure travellers.

1.3 Sustainability of flying

The aviation sector is responsible for 2-3% of global CO_2 emissions and is one of the fastest rising sources of pollution, with a CO_2 increase of 2.5 times between 2000 and 2019 (IEA, 2020). According to Manchester Metropolitan University, emissions could double by 2050 even if aircraft become more efficient in fuel usage (Kommenda, 2019).

There have been significant improvements since the first commercial aircraft were introduced in the 1960s. Since then, commercial aircraft have become about 85% more efficient, and emissions per seat-km have fallen by more than 70%. However, more is needed to compensate for the rising demand. The IEA (2020) identifies three key factors that make reducing emissions in the aviation sector difficult:

Growth in demand

Over the past ten years, passenger growth has averaged 6.2% per year, and over the next 20 years, an increase of 4.3% (Airbus, 2019) or 4.6% (Boeing, 2019) is expected. Although the covid pandemic will affect this figure negatively in some way, the aviation sector is predicted to continue to grow in the coming years.

Industry Structure

The commercial aviation industry is highly competitive with tight margins and an average profit of only 6-8% per year. At the same time, aircraft manufacturers are on the safe side with only incremental changes rather than revolutionary new designs as there are many risks associated with commercial air transportation. Low profits and high risks work to the disadvantage of the radical innovation needed.

Physics

Flying a commercial aircraft demands high power, which is currently provided by high-energy-density fuels such as kerosene. Switching to renewable sources, such as electric propulsion or hydrogen is not feasible today and uncertain for the future.

As environmental awareness has heightened in recent years, the airline industry has been increasingly confronted with its effect on the environment.

As a result environmental groups are advocating a reduction in the number of flights and want to limit further airport expansion. One proposal to limit flying behavior is the "Frequent Flyer Levy", a tax that would be increased by every flight a person makes per year. This would avoid penalizing hard-working families who only go on vacation once a year.

Taxing everyone the same is considered socially regressive, which is why environmental groups believe that a kerosene tax is long overdue, as this would make flying more expensive for everyone. Rich people who can afford it will continue to fly, while poorer people will have fewer opportunities to fly (Murray, 2019).

At the same time, airlines hope to offset their carbon emissions. The International Civil Aviation Organization (ICAO), the UN body accountable for reducing the carbon footprint of international aviation, has introduced a regulation that allows airlines to purchase carbon credits instead of cutting their own carbon footprint by, for example, reducing the amount of fuel they consume (IATA, 2020).

A German company named atmosfair hopes to bring light to airlines' climate impact by ranking their carbon efficiency using data from the Civil Aviation Organization and the International Air Transport Association. Points from 1 to 100 are calculated by looking at aircraft type, seat and cargo capacity, load factor, engines type and aerodynamic features like winglets.The main goal of atmosfair's Airline Index is to make climate efficiency a key competitive issue for airlines. Airlines that score high in the Index often fly at full capacity and choose modern aircraft that consume less fuel, such as the Airbus A320neo and the boeing 737max (Atmosfair, 2020).

Climate impact of a short-haul flight

From	To	Distance (round trip)	Aircraft type	Class	Flight type	Climate impact
Amsterdam (schiphol)	Stockholm Metropolitan Area	2404 km	Airbus A320 Neo	Economy	scheduled	337 kg CO_2
Amsterdam (schiphol)	Stockholm Metropolitan Area	Stockholm Metropolita n Area	Airbus A320 Neo	Business	scheduled	632 kg CO_2

Fig. 8. Table showing the climate impact of a round trip short-haul flight for Business and economy class (Data retrieved from Atmosfair.de)

Using atmosfair's climate impact calculator, which uses data verified by the German Federal Environment Agency and takes into account the flight altitude, the aircraft type, the number of seats onboard, the extent to which they are occupied, as well as the flight class, the climate impact of a short-haul flight was calculated. (atmosfair, 2020)

For a short flight, such as a return trip from Amsterdam to Stockholm airport, the climate impact is 337 kg CO_2 in economy class, while this 2 times 2 hour flight accounts for 632 kg CO_2 in business class. 632 kg CO_2 is more than ¼ of the emissions for one car per year (12,000 km; middle class model) and more than ⅓ of the climate-compatible annual emissions budget for one person, which is 1500 kg CO_2. (atmosfair, 2021)

To better understand this difference in climate impact between business class and economy class, the occupancy rate (fig.9) and weight of each type of seat in the aircraft was analyzed. To calculate the occupancy percentage per seat class, the floor plan of the airbus A320 neo was used.

Seat occupancy rate Business & Economy class

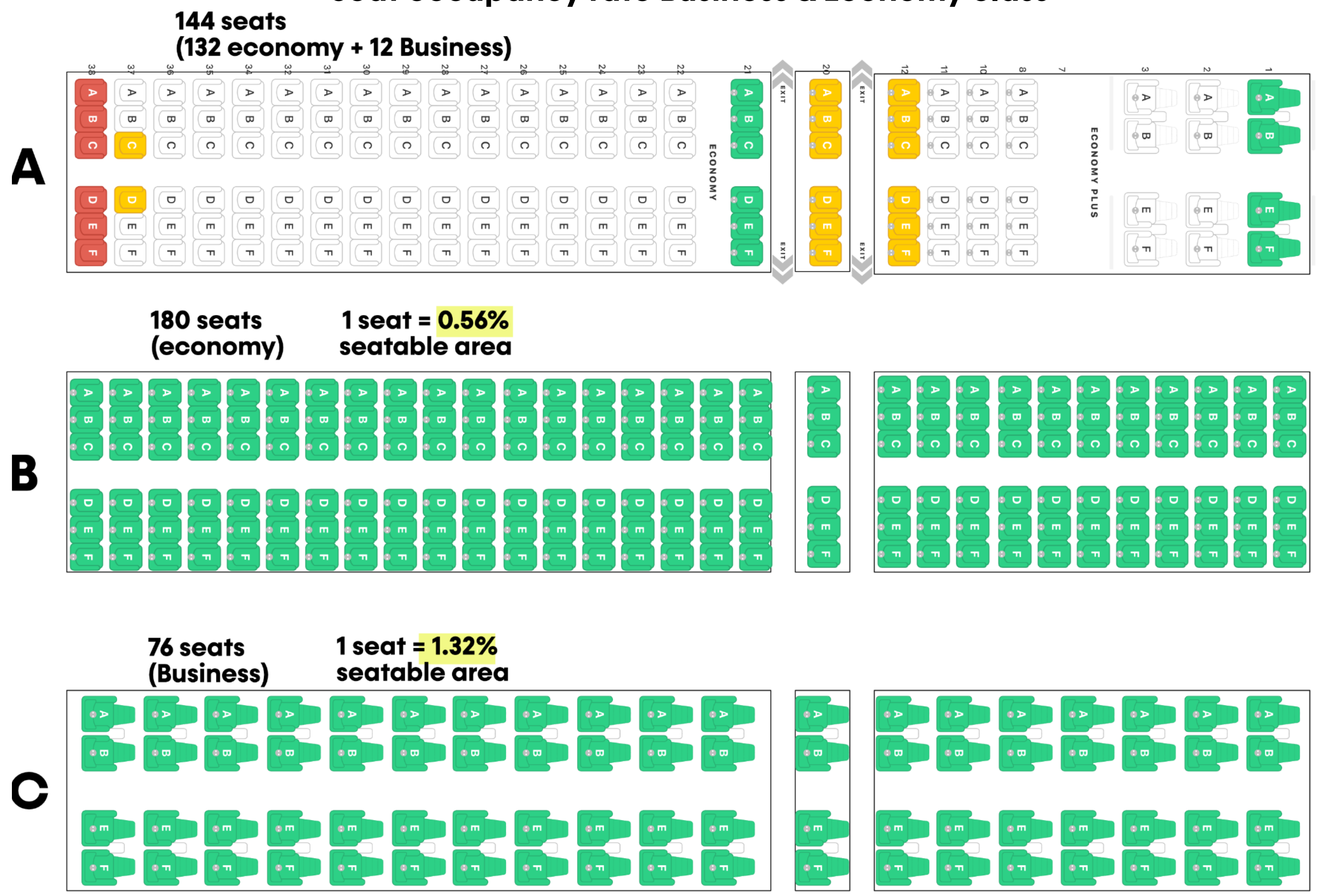


Fig. 9. Table showing the occupancy rate with economy class vs Business class seats

At the top of Fig. 9, A standard 2-class layout of the Airbus A320 is seen with 132 seats in economy class and 12 seats in business class. B shows that an economy class seat in an Airbus A320Neo occupies 0.56% of the total seating area, which corresponds to a total capacity of 180 seats. If we compare this to the area occupied by a Business Class, it is 1.32% per seat, which is 2.3 times more than the economy seat. By comparison, only 76 Business Class seats fit in the same type of aircraft.

Cost of weight

Another way different seat classes have a negative effect on environmental impact is by looking at the differences in weight, as we saw in chapter 1.2. Business-class in Europe leaves one seat free in the middle, so this seat's weight is split between the two other seats in the row, making a European business seat 1.5 times the weight of an economy class seat. If we look at the weight of the 'real' business class seats it is even worse as these seats weigh on average 100kg (Rizzo, 2018) while most economy seats weigh in around 10kg with lightweight seats nearing 5kg.

To assess the environmental effect that weight can have during a flight, it is relevant to look at the cost of weight.The cost of weight measures the extra amount of fuel in kg required to carry 1 kg of extra weight and can be expressed as a percentage.

As a rough estimate, the COW is estimated at 3.5% per hour of flying (on a two-hour trip, the COW would be 2 x 3.5 = 7%, meaning that transporting 1 kg requires 70 grams of fuel. (openairlines,2019).

Figure 10 shows 1.4 kg of fuel with a cost of 0.56 euro is needed for a 2 hour flight and 0.84 for european business class. The fuel cost for a 4 hour flight might look small. However based on the number of seats, fly hours per aircraft and fleet size, a small weight saving can make up a significant yearly cost saving.
See figure 11.

To calculate the annual impact of seat weight on an airline, we used data from KLM's 2019 annual report and looked at the operation of their low-cost carrier Transavia since Transavia only operates short- and medium-haul flights.

According to the report, Transavia's annual seat kilometres in 2019 were 19256 million. (The seat kilometres are the total number of seats multiplied by the total distance travelled).

Transavia uses two versions of the Boeing 737 for short-haul flights, with cruising speeds of 820 to 802. For the calculations, the average of 811 km/h is used. For the COW (cost of weight), we used the same 3.5 per cent as before. To know the total flight hours per year, the total seat miles were divided by the cruising speed, resulting in about 24 million flight hours. For the full calculations, see Appendix.

Transavia's annual operating cost based on the COW was 3.32 million for the year 2019 (see fig.11). Dividing this number by the total number of seats in their fleet (7658, see fig.12), we can assume that Transavia had an operating cost of approximately 434 euros per economy seat for the year 2019. Meanwhile the cost of a new economy seat starts around 3000 euros (Thepointsguy, 2019).

Conclusion:

As airlines struggle with narrow margins but strive to continue to grow, the pressure of their environmental impact is increasing. However Instead of investing in innovative new solutions or rethinking existing structures, airlines are trying to offset their emissions by buying carbon credits.

Reducing their carbon footprint seems to be primarily a matter of economic advantage, as the trend to make economy seats lighter makes little sense when existing business class seats outside Europe are 10 times heavier and in Europe the current Business class offering doesn't add much extra value to justify the use of 1.5 seats. As shown in the calculations, The weight of one seat can cost an airline as much as 434 euro a year, if this seat is in use for 7 years, this means over its life the seats cost around the same on operating cost as its purchasing cost so combined this is a cost of 6000 euro per seat. Meanwhile if the same calculations are done for seats of 5kg, yearly operating cost would drop to 1519 euro over 7 years. This shows that considering the lifetime of aircraft seats, the investment towards lighter seats can save significant amounts of operating cost long term.

Seat COW of a short-haul flight (4h)

Seat type	approximate weight (kg)	Flight duration (h)	Fuel needed to transport weight (kg)	Fuel cost (euro)
Economy	10	4	1.4	0.56
European business	15	4	2.1	0.84
Business	100	4	14	5.6

Fig. 10. COW of an airline seats
*average kerosine cost 0.4 euro/kg (flightdeckfriend,2021)

Yearly COW all ecomomy seats Transavia (2019)

Seat type	approximate weight (kg)	yearly Seat kilometers in million	Fuel consumption in million (kg)	Fuel cost in million (euro)
Economy	10	19256	8.31	**3.32**

Fig. 11. Yearly cost of weight of all Transavia economy seats

Transavia Fleet & seats

plane type	amount	Seat capacity	Total seats
737-700	7	149	1043
737-800	34	189	6615
Total	42		**7658**

Fig. 12. Transavia total seat number

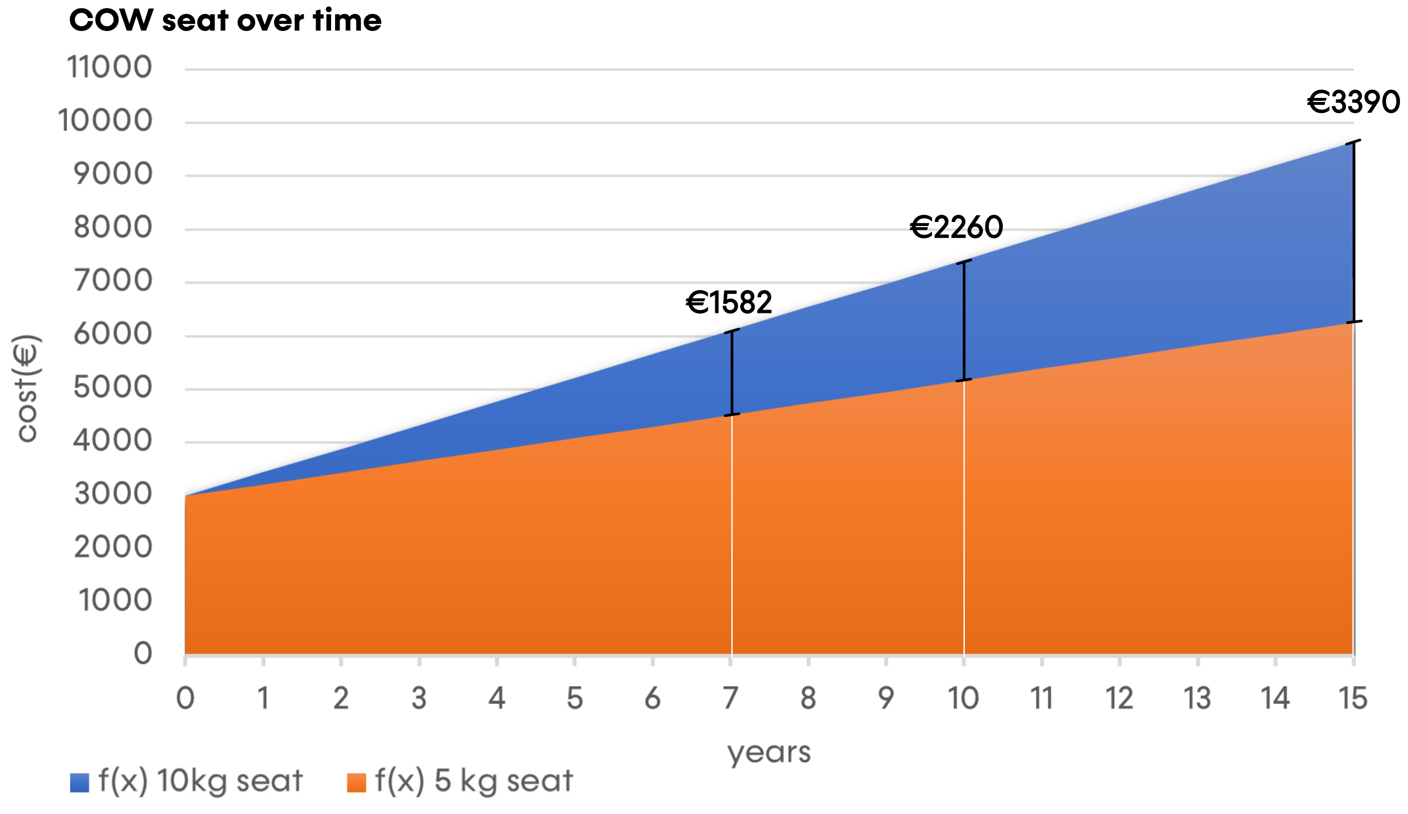


Fig. 13. Cost of weight of 1 seat of 5kg and 10kg over time

1.4 Seating layouts

Standard 6 abreast configuration

This is one of the most commonly used configurations on narrow-body commercial aircraft, such as the Airbus A320 and the Boeing 737 max. The "6 abreast" configuration is a configuration with rows of 3 seats on either side of the aisle. The seats are directly behind each other, and the most important factor for the space of the passengers is the seat pitch and the recline of the seat in front of them. The rows of seats are bolted on rails in the aircraft, and the airline can adjust the seat pitch to find a compromise between personal space and the number of seats that can fit in the aircraft.

Rearward-facing seats

Rear-facing seats are not that common on aircraft; they do occur in business class seats, but there it is a rarity. Since rear-facing seats absorb more impact during a collision, they require better structural integrity and are often more heavily reinforced where they are bolted to the floor. Mounting the seats usually requires the floor to be reinforced as well, making installation even more of a challenge. (simpleflying,2020)

However, rear-facing seats do offer advantages. A 2007 University of Virginia study found that kids below 2 years old in rearward-facing seats are 75% less likely to be seriously injured in a crash. The main reason for this is that rear-facing seats provide better body support, putting less pressure on the neck and head. (Henary et al. 2007)

Another benefit is that rear-facing seats allow for more creative seating configurations, which can lead to space savings that allow for more seating or increased personal space. Over the years, there have been numerous concepts exploring the implementation of rear-facing seating. One of them is from Zodiac aerospace, now part of Safran seats. In 2015 they showcased a concept based on a honeycomb structure that allowed for a configuration with an additional row of seats on one side of the aisle. Instead of the usual six-abreast configuration, there was now room for seven. The extra space was achieved by switching between backward and forward facing seats. (See fig.14) A number of comments in a media article by business insider in 2015 mention concerns about privacy and the awkwardness of facing other passengers, while others are mentioning as advantages that it allows parents to watch over their children and friends to have conversations during the flight.

Another concept using rear-facing seating is by Avio interiors, an Italian design firm (see fig.15). The Janus concept was developed in response to the COVID-19 pandemic. The configuration consists of a rearward and forward seats and has an S-shape similar to the Zodiac concept. To provide social distance, a large transparent screen follows the s-shape of the seats, protecting passengers from neighbors and people walking through the aisle. Aviointeriors claims it has the same footprint as the standard 6-abreast configuration (simpleflying, 2020b).

This concept also raised some questions from online readers. For example, it is not clear exactly how in-flight meals would be served, and this configuration could impede evacuation time. Furthermore, there were concerns about privacy and the effectiveness of the shield, as from the top view in fig. 15, you can still see the middle person looking at other passengers. Another reader mentioned that this seating arrangement is unsuitable for families with young children as the parent doesn't have direct access to the other seats. (Simpleflying,2020b)

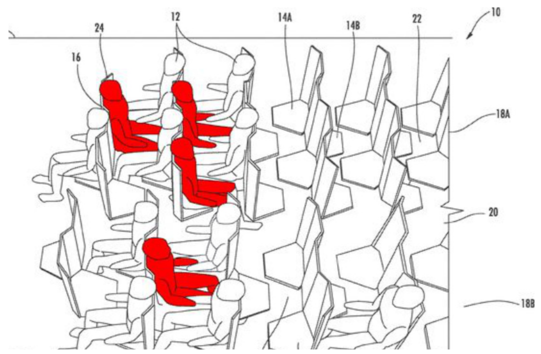


Fig. 14. Zodiac aerospace concept

Staggered airline seats

Another variation to the standard configuration is a concept by Molon Labe (fig.16) which shows a staggered seat configuration, which offsets the middle seat by a few centimeters to increase the amount of hip and shoulder space of each passenger, while also giving more room for the armrest. (simpleflying,2019)

Like Molon Labe's concept, Thompson Aero's Cozy Suite attempts to achieve the same benefits by placing the seats in a stepped configuration (fig.18).
This stepped configuration also improves privacy by adding headrests on the sides and by sitting slightly in front of or behind your neighbouring passenger.

Fig. 15. The janus seat concept by avio interiors

Fig. 16. Molon Labe's concept

Conclusion:

Minor modifications to the existing 6-seat side-by-side configuration, such as staggered seats, seem to be the most progressive but acceptable solution to increase passenger space and improve privacy. Passengers are accustomed to looking forward while traveling, and the benefits offered by these rearward configurations seem to create more uncertainties than solutions. According to the FAA safety regulations, single aisle aircraft may only have rows of 3 seats on either side, which already rules out the zodiac concept and raises the question of how much rear-facing seats can really increase passenger capacity. Additionally, placing the seats more densely together will compromise safety during evacuation.

Chaise longue concept

The Chaise longue, a concept by TU-Delft designed for long-haul flights, creates more space by implementing a height difference between rows of seats. The same amount of seating is retained, but passengers gain more personal space and freedom when reclining. Because it was difficult to assess the concept from existing renderings, a full-size mockup was created to experience this type of configuration. Testing this configuration revealed that the seats would require a complex and easy to use mechanism to move comfortably in and out of the chair. In addition, the support structure that would also replace the overhead bins would have to carry more weight than the current overhead bins, making it likely that this seat design could be significantly heavier.

Fig. 17. Mockup of chaise longue concept

Fig. 18. Thomson Aero Cozy suite seat

2 Aircraft seats

2.1 Construction

An existing airplane of B/E Aerospace with a manufacturing date of May 2000 and seat cushions from 2017 was taken apart to discover how the different seat elements affect the overall weight, what materials they are made of and how they are constructed.

The full seat disassemblycan be found on the following pages.

Next to this an exploded view of a contemporary economy slimline seat by Recaro was analyzed. In fig. 20, we see that there are some differences between the old and new seat. The most obvious change is the addition of a shroud. This is the back part that is made of a plastic shell that covers the frame structure. Another obvious change is that this seat pan is made of plastic or composite material, so the passenger does not feel the parts under the seat when sitting on the thinner seat cushion, allowing for a thinner seat foam. Likewise a suspension fabric is placed behind the backrest to allow for a thinner Foam layer for the backrest. The seat look more lightweight, with holes an thinner sidewalls.

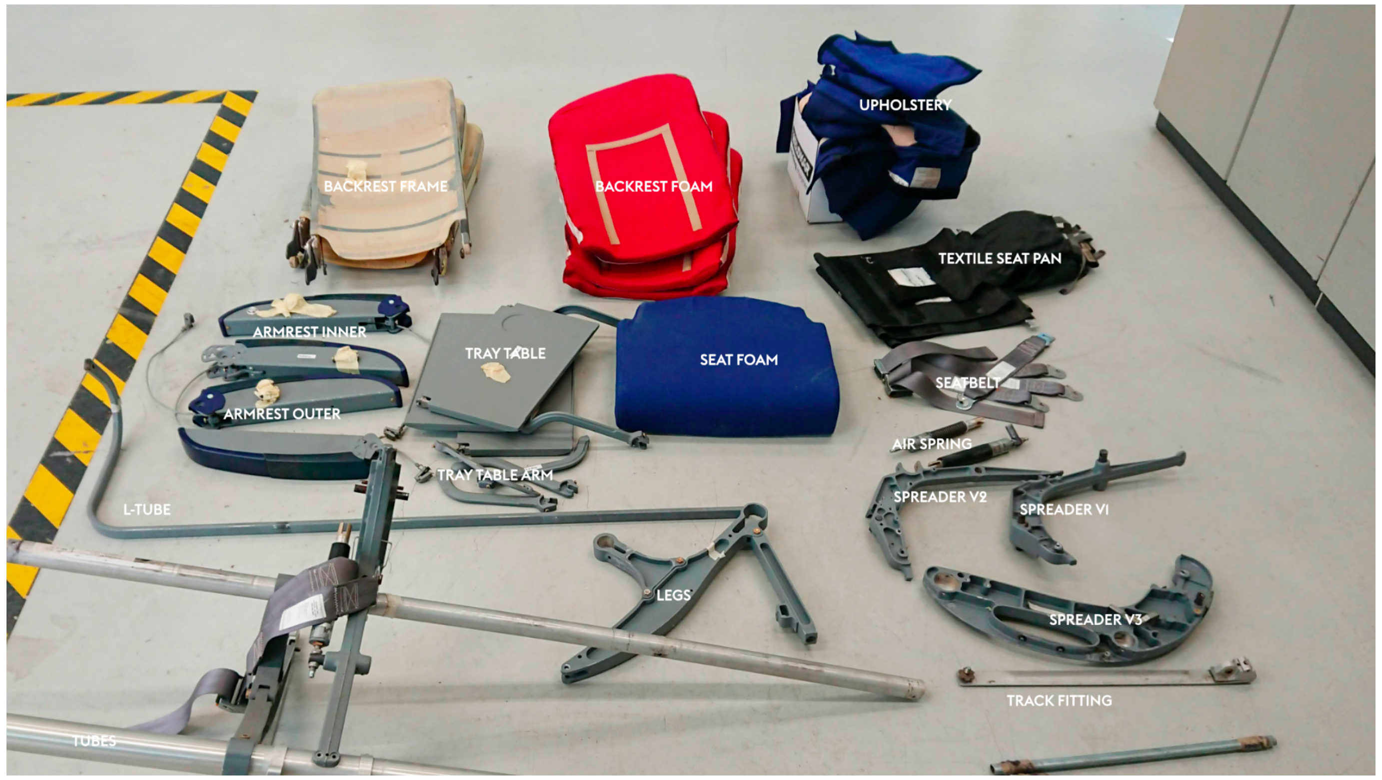


Fig. 19. Seat disassembly

Fig. 20. Exploded view Recaro slimline seat

2.1.2 Structural parts assembly

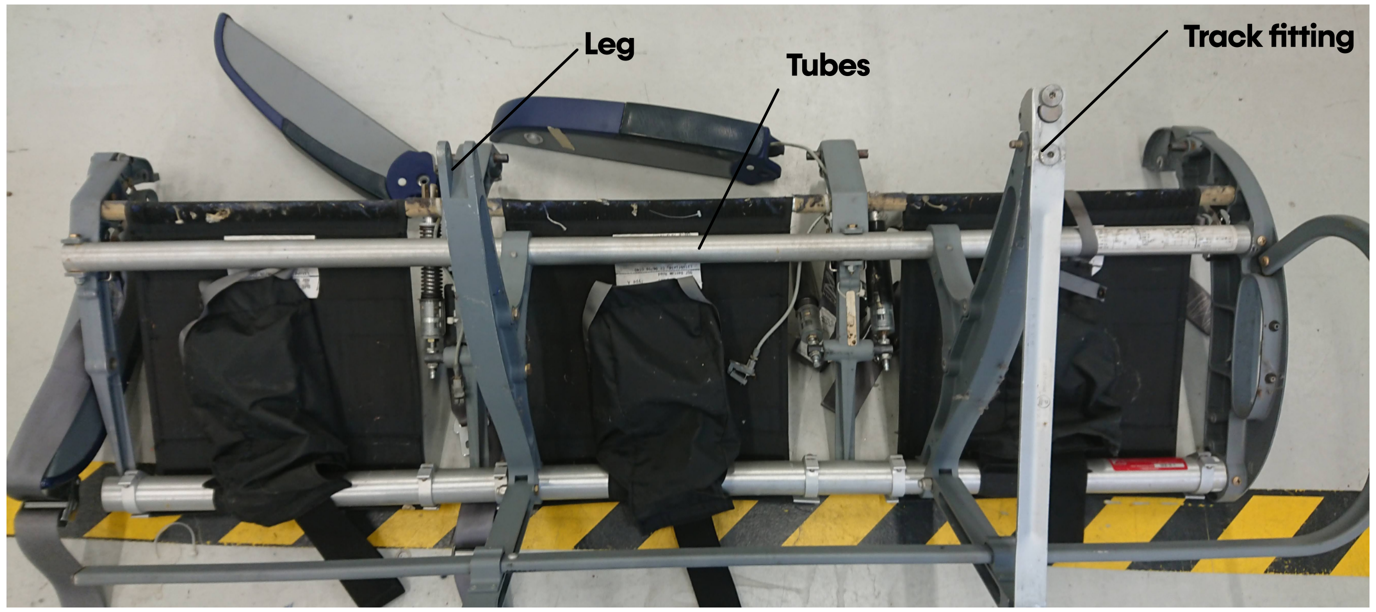


Fig. 21. Structural part assembly 1

Two aluminium legs are positioned under the middle seat and shared among the 3 seats in the row, attached with the track fitting; they are the only attachment points to the floor-rails and carry the weight of the seat and the occupants.

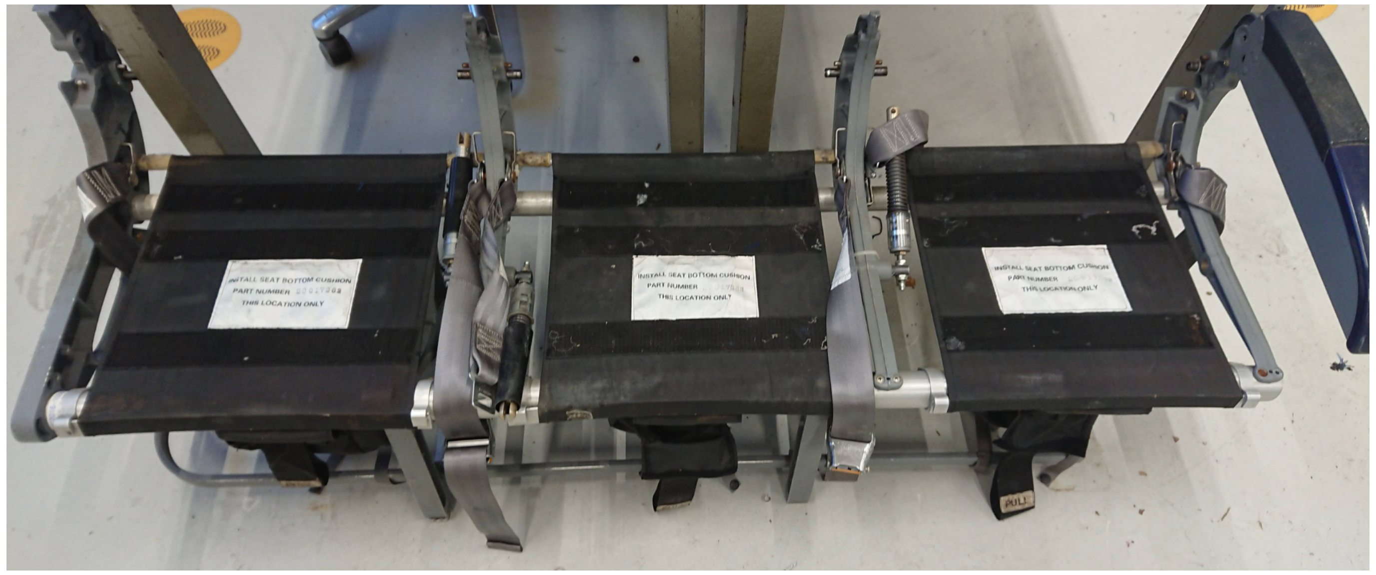


Fig. 22. Structural part assembly 2

Through 2 holes in the legs run 2 aluminium tubes which are the main attachment point for the rest of the seat construction. The tubes support the whole seat structure, The tubes have a circular profile to withstand high torque forces.
Attached to the tubes are the spreaders. The spreaders are the attachment points for the backrest, the armrests,the seatbelt as well as the hydraulic recline mechanisms. The spreader is bolted on the tube in front and through the tube in the back.

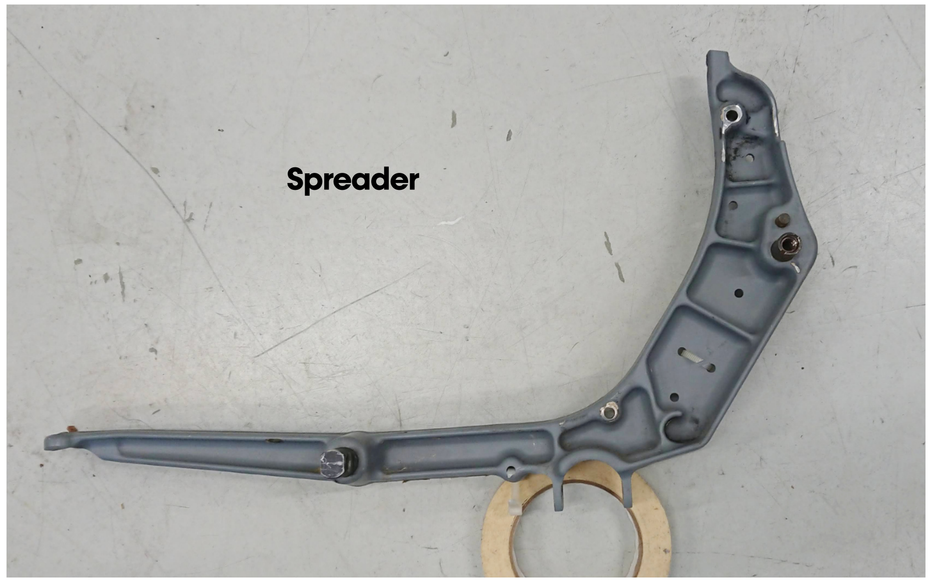


Fig. 23. Structural part assembly 3


Fig. 26. Structural part assembly 4

The spreader is made from die cast aluminium and has numerous screw holes for the different parts it supports. Throughout the assembly there are 4 spreaders and 3 different types. The outer ones have different attachment points and the two middle ones are the same.

Fig. 24. Structural part assembly 5

The backrest is made from plywood, glass fiber and reinforced with carbon fiber. It is attached to the spreaders with bolts.

Fig. 25. Structural part assembly 6

The above mechanism limits the recline angle and is attached to the hydraulic spring on the right.

Fig. 26. Structural part assembly 7

The armrests are bolted at the top of the spreaders and house the button that controls the hydraulic spring of the recline mechanism.
Both English and metric bolts were used in the seat construction. Many bolts also had varying sizes. This required several different tools to disassemble the seat.
Apart from a few oxidized bolts, however, everything was relatively easy to disassemble without having to destroy any part of the seat.

2.1.3 Non-structural parts assembly

Fig. 27. Non-structural part assembly 8

Almost no tools were needed to disassemble the non-structural parts. The seat cushions and upholstery were all attached with Velcro, making disassembly very simple. This is probably for ease of maintenance as there was a label on the upholstery to indicate when the fabric was last cleaned.

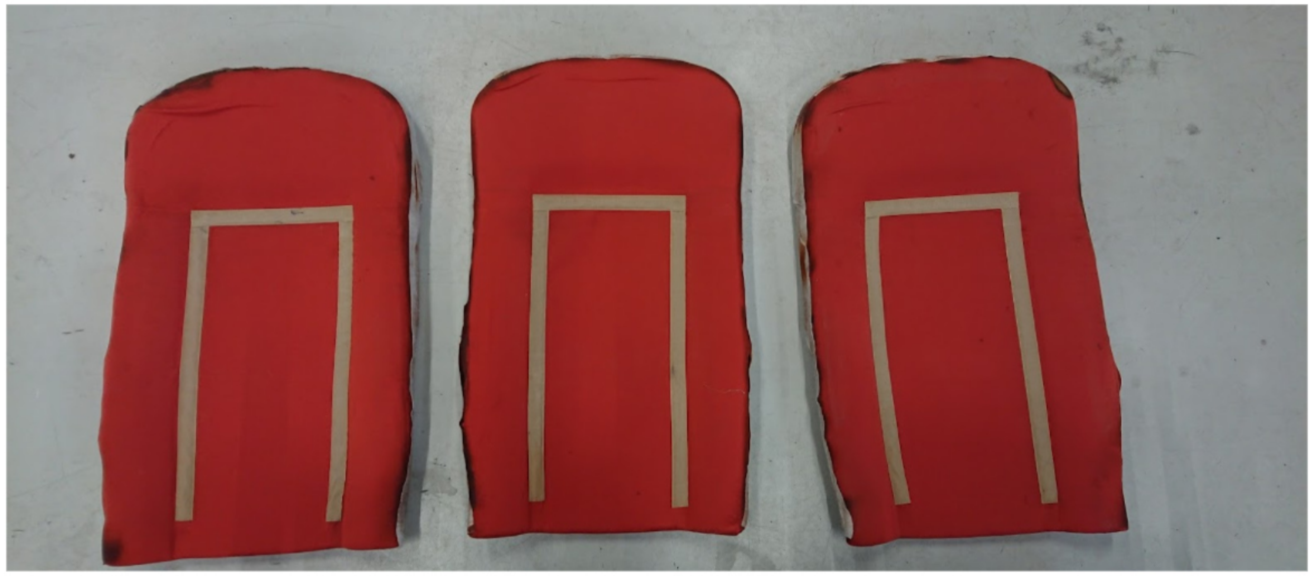


Fig. 28. Non-structural part assembly 9 (backrest cushions)

Fig. 29. Non-structural part assembly 10 (seat pan)

The seat pan itself was made from a nylon fabric material and had two slits stitched so it could slide over the tubes. A small rod with additional slit was attached to the opposing spreaders and used to put extra tension on the seat pan.

Fig. 30. Non-structural part assembly 11 (tray table arm)

Fig. 33. Non-structural part assembly 12

The tray table arms are attached with a form lock which when disassembled could be detached without any tools , the table itself was attached to the table with some screws.

Conclusion:

The construction of aeroplane seats is relatively simple, with no complex sub-assemblies and everything constructed relatively straightforward. The non-structural parts are attached with velcro so that they can be disassembled without any tools. However, the amount of equipment required for structural assembling of the dissambled seat was significant, with both metric and EU sizes of fasteners. These fasteners decrease ease of maintenance, increase assembly time and overall weight.

2.1.1 Seat mechanisms

Most recline systems work with hydraulic recline systems also called Hydrolok. By pressing a button in the armrest the passenger activates a hydraulic piston and is able to tilt the backrest backwards, when releasing the button, the recline angle stays in position. (craneae, n.d.)

The disadvantage of these mechanisms is that the passenger often has to put a significant force on the backrest before it starts tilting.

Fig. 31. Hydrolok recline system

Cradle recline

Another recline mechanism used in aircraft seats is the cradle seat mechanism. This mechanism also uses a hydraulic piston, but the movements are different in that when the backrest reclines, the seat moves forward and up, putting the passenger in a cradle position and preventing them from sliding out of their seat. This enables passengers to move back a bit instead of just reclining.

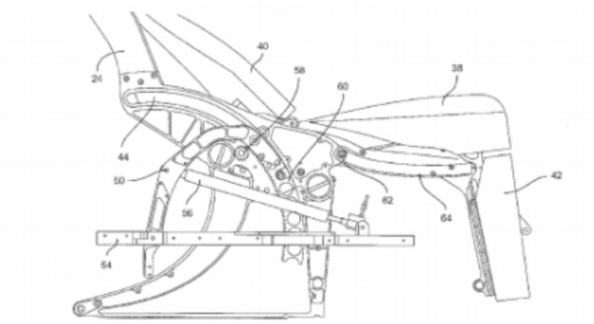


Fig. 32. Cradle recline patent

2.3 Weight

This deconstruction of the B/E aerospace seat provided insight into where there is the most room for potential weight savings. Interestingly, 48% of the total weight is made up of the non-structural parts, of which 27% is the combined weight of the seat cushion, backrest cushion and upholstery. For one seat, this accounts for a mass of more than 3 kg. Other non-structural parts with significant weight percentages are the tray table (8%) and the armrests, 5% each.

The 3 seats combined weigh around 35 kilograms with a single seat weighing almost 12kg.

Of the structural parts, the backrest frame makes up the most weight (14%), the legs 10%. For the full breakdown of weight. The 3 seats combined weigh around 35 kilograms with a single seat weighing almost 12kg.

Conclusion:

With non-structural components accounting for 48% of the total weight, it is clear that there is still room for significant weight savings.

Without even having to redesign the structural components, considerable weight can already be saved, for example, by replacing the foam and upholstery of the seats with more modern alternatives or by using a sandwich structure to make the drawer table or armrests lighter.

Surprisingly the recline mechanism, which consists mainly of the hydraulic spring and a small amount to the backrest, doesn't add much to the overall weight. However, having the backrest fixed does save on some large fasteners, which can add up in weight.

With always having three identical seats next to each other, part consolidation could be an easy way to save a significant amount of weight, as this would require fewer fasteners.

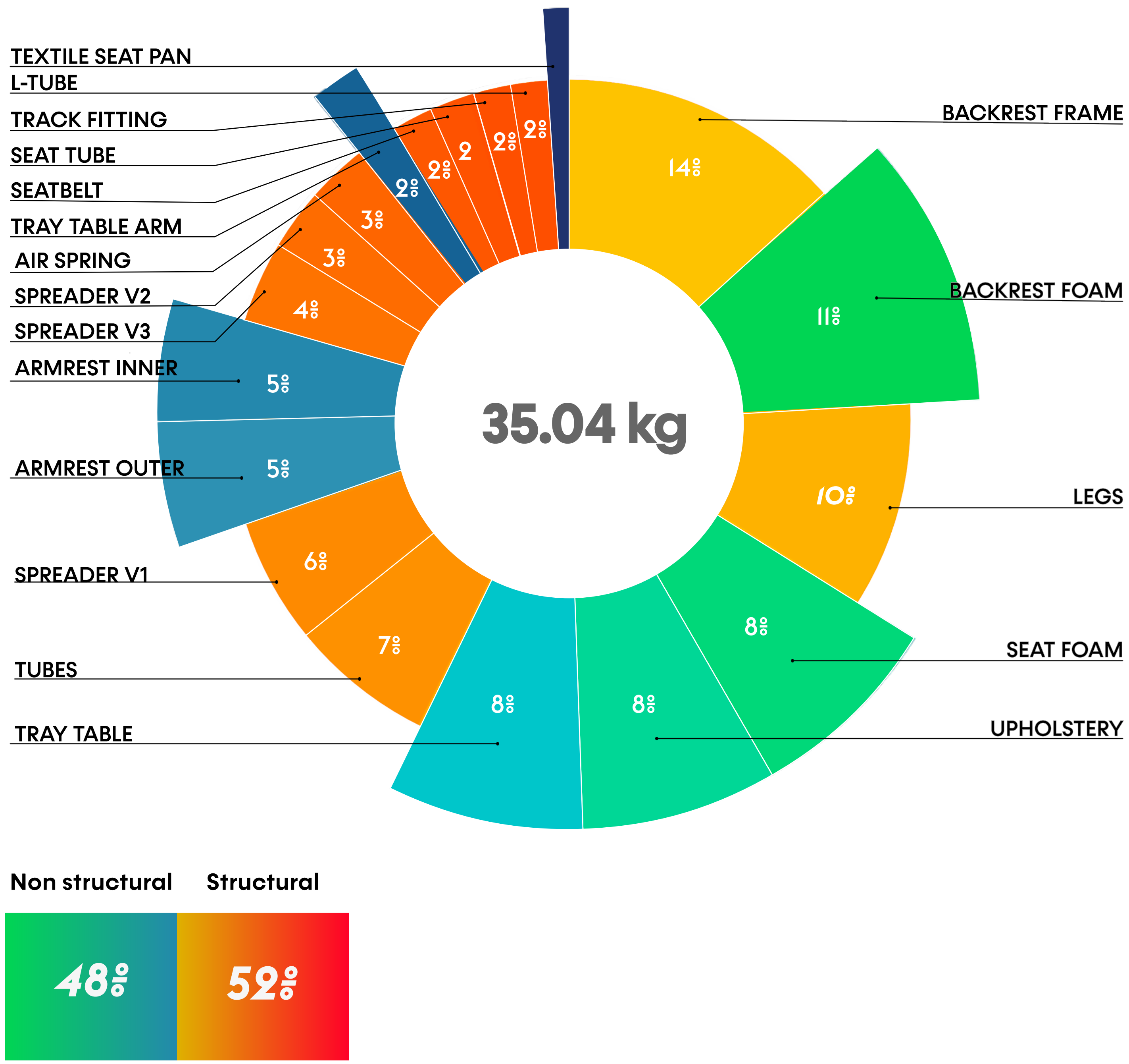


Fig. 33. Overview of weight assesment

2.4 Materials

Four important characteristics determine the materials used in aircraft seats.
The materials must be light to save fuel. They must be strong to protect the passenger in emergency situations such as an emergency landing (16g test).
They should be fire retardant to prevent the spread of fire and at last they should be durable as an airline seat is a high use product and is used between 7 to 10 years.

It was concluded from the disassembly in chapter 2.3 that the structural parts of the disassembled seat were largely made of aluminium, with the exception of the backrest with a plywood frame and fiberglass shell reinforced with carbon fiber.

The disassembled seat is from 2000 with the cushions from 2006. Since then, there have been advances in lightening the weight of airplane seats and increasing comfort. The following is an overview of all the current materials used in aircraft seats , divided into the categories of structural and nonstructural materials

Structural materials

Aluminium

Aluminium is the most commonly used material in aircraft seat construction due to its fairly low cost, lightweight and high versatility. The negative aspect of aluminium is corrosion. Therefore, the aerospace industry often uses a special high-strength aluminium alloy called AL7075, an aluminium alloy with zinc that has significantly better corrosion resistance than the aluminium 2000 series. AL7075 is one of the most frequently used aluminium alloys for highly stressed structural parts in aircraft components. (Granta Edupack, 2020)

Titanium

Titanium is another lightweight alloy used in aircraft seats. The aircraft seat maker Expliseat currently has the lightest seat on the market and has its seat structure made from a combination of titanium and carbon fibre. Recaro uses titanium for the fittings(runwaygirlnetwork, 2017).

Compared to aluminium Titanium has a superior strength to weight ratio and better resistance against corrosion (Granta Edupack, 2020). Titanium's disadvantage is that it is hard to machine as it is brittle and susceptible to fretting damage, which can reduce the structure's fatigue strength. Titanium is also more expensive.

Magnesium

Magnesium is significantly lighter, stiffer and more ductile compared to aluminum and titanium.(Granta Edupack, 2020)
Magnesium was banned by the FAA prior to 2015 due to its characteristics of high flammability. However, it has recently found its way into aircraft seats, with the introduction of an alloy called Elektron® 43. This alloy is in compliance with FAA flammability requirements and made by a company called magnesium elektron. (investingnews, 2015)

Composites

Another important material category used in making lightweight structures are composites. Composites are structural materials made from a combination of different materials such as, for example, a continuous fiber (glass, carbon, aramid) and A thermosetting resin (polyester, epoxy). The fiber dissipates mechanical loads, while the matrix material (resin) transfers the loads to the fiber and also provides toughness and ductility. as protection from the environment.
A major advantage of fiber reinforced structures is that they are customizable to specific requirements. (Granta Edupack, 2020)

Polyester glass composites (GFRP)

Polyester-glass composites or also called fibreglass, are the combination of glass fibres hardened by a thermoset.
They are the cheapest and most widely used fibre composite. Fibreglass is stronger than many metals by weight, is non-magnetic, non-conductive and can be formed into complex shapes.
The disadvantage of fibre composites is that you could not recycle them because of their thermosetting matrix material. Recently, however, high-performance plastics such as PEEK have been used as resins, eliminating this problem and making them more environmentally friendly.

Carbon fiber reinforced composites (CFRP)

Carbon fiber is probably the most well-known composite. Where fiberglass uses glass fibers, carbon fiber uses fibers made of graphite. Compared to fiberglass, carbon fiber offers greater stiffness and strength. Where carbon fiber is strong in tensile and compressive strength, it is brittle and can crack under high pressure. It is also more expensive than fiberglass and, as with other fiber composites, making complex shapes is labor intensive, making it expensive and often unsuitable for mass production

However, with the introduction of thermoplastic resins, more manufacturing techniques have become available, such as thermoforming and 3D printing. Additionally the ability to melt the composite also reduces the need for fasteners. (toraytac, n.d.)

One company specialized in thermoplastic composites is tencate. Which Delivers thermoplastic composites for the aviation industry and car companies.

Aramid fiber

Aramid also known as kevlar is another fibre used in fiber reinforced composites.

Compared to carbon aramid it is tougher and more flexible it has a high resistance to impact and doesn't crack under pressure as it is tougher and allows significant energy absorption. Aramid composites are for example used in bulletproof vests. Another benefit is that aramid composites do not conduct electricity, where carbon can interrupt phone signals aramid doesn't (dexcraft, 2020).

Plywood

Plywood are laminated sheets of light wood that are bonded together to make a stronger material. It was often used during World War II in periods of material scarcity as an alternative to the scarce aluminium in aircraft construction.
Nowadays as shown in the disassembly of the seat in chapter 2, plywood can still be a viable material to create lightweight structures as it is lighter than aluminium and combined with resin can be stronger. (Hinte & Beukers, 2020)

Short Fibre reinforced plastics

Whereas fiber composites such as glass fiber and carbon fiber use continuous strands, fiber-reinforced composites use chopped pieces of fibers bonded together in a matrix material such as epoxy. The mechanical strength of the plastics is improved by the addition of fiber materials. The reason for adding fiers is to prevent creep, wear, improve fracture toughness or thermal stability. (Masuelli, 2013)

Non-structural (comfort) materials

For the non-structural parts, weight, fire retardancy, and durability are the essential characteristics. The non-structural materials or comfort materials mainly include cushions materials and upholstery fabrics.

Cushions

The foam of most cushions is PU foam. PU foam of different densities is assembled in a seat upholstery to provide ideal pressure distribution.

Seat cover

All textiles used in aircraft cabins must be flame retardant, durable, non-toxic and light (Dilba, 2018). Therefore, most seat covers are made from a blend of 89-95% wool and polyamide(Nylon™). Wool is the most fire-retardant natural fibre and is difficult to ignite.

Polyester is also sometimes used in airline-seat textiles, but then it is blended with fire blocking materials such as Kynol®. Kynol fibres are highly flame resistant and often used in electronics as electrical insulation (Dilba, 2018).

LOI

The Limit Oxygen Index or LOI is the material property that determines the fire resistance of a material. LOI indicates the minimum oxygen level required to sustain a fire. The LOI of wool is 25%, which means that wool will not begin to burn at an average air-oxygen concentration of 21%(Dilba, 2018).

Next to choosing materials with a high LOI, there are different ways to engineer the material to be more fire-resistant. For example, the higher the density of the weave of the fabric, the less oxygen can reach the surface. Flame retardant coatings are also sometimes used on seat fabrics(Dilba, 2018).

Material trends & developments

Structural cushions

To further reduce the weight of aeroplane seats, Greiner, a manufacturer of cushions for the airline industry, is now making structural cushions that eliminate the need for a seat pan since the cushion has its own structural integrity it can support the weight of the passenger. Although it is unclear exactly how much the seat weighs, Greinier states on its website that this saves about 600 grams per seat (Greiner, 2020).

Antibacterial fabrics

The covid-19 pandemic has led to increased hygiene awareness among airlines and Passengers. Seat cushion manufacturer Greiner, therefore, developed a new line of products under the name ''Germ sentinel'' offering airline seat covers, foams and fabrics, with antibacterial additives that destroys 99.9% of all bacteria after 24 hours, neutralizes odours and ensures that the foam remains free of a bacteria breeding ground that can lead to degradation of the cushions (Greiner, 2020).

Smart textiles

In the challenge to further reduce the weight in the airline seat and the cabin interior, textile manufacturing is exploring ways to add more functionality within textiles. One of the ways textiles could reduce weight in the cabin is by being self-illuminating. The metal fibres in these textiles illuminate when electrified and could replace cabin lighting.

Spacer Fabric

As seen in chapter 2.3, the weight of the seat cushion and the foam of the backrest makes up 19 % of the total weight. In newer lightweight seats spacer fabrics are often used in combination with thinner PU foam for the backrest (Kokorikou et al., 2016). Spacer fabric is a hollow fibreglass structure held apart by piles. The spacer fabrics' unique woven structure provides more breathability and water permeability than polyurethane foam, making spacer fabrics more thermally comfortable. In addition, the structure has good recovery when compressed, so it keeps its shape without losing thickness, and finally, it is also recyclable (Hinte & Beukers, 2020).

3d/4d knitting

3D knitting or technical knitting offers many advantages because it has no excess material in production. The properties can be constructed so that the fabric can have a combination of different fibre materials, patterns and densities. In-office chairs, 3D knitting is already being used as a replacement for foam cushions, and aircraft seat cushion expert Greiner recently experimented with a 3D knitted seat for passenger drones that can adapt to the passenger's unique body because of its different knitting properties.

Artificial leather (E leather)

Another material used to cut weight from airline seats is the substitution of genuine leather for artificial leather; this is a favoured choice among airlines because it is lighter and requires less maintenance (Aviation Business News, 2020).

Air cushion

Using air to create cushioning structures is another alternative for creating lightweight comfort. The advantage of a pneumatic air cushion system is that the amount of air can be controlled to adjust the comfort of each passenger. The company Lantal already does this by replacing the usual PU cushion foam with air-filled chambers controlled by powerful lightweight flat motors. The motors of only 75 grams allow adjustments to changing cabin pressure and automatically adapt to the shape of the passenger's body. The firmness of the cushion can also be adjusted individually. This system has been used on all Swiss International long-haul aircraft since 2009. According to Lantal, replacing the foam with this system saves 1.5 to 3 kg per Business Class seat. (Maxongroup, n.d.)

Aramid fibers textiles

Another interesting fibre for comfort applications in aerospace is the meta-aramid fibre Nomex. Nomex is used in seat covers to help meet the flammability requirements of aircraft interiors (Dupont, 2021). Its advantages are that it feels like a typical textile but is exceptionally durable with hard-wearing properties over its lifetime. It also has low flammability and is self-extinguishing as it hardens, begins to melt, discolour and char on contact with fire. (Sabir, 2018).

2.5 Safety regulations

Structural test

Safety is one of the most important factors when designing a new aircraft seat. The design of the seat has a significant impact on the chances of survival during a crash scenario. The more a seat is able to absorb energy during a collision, the more likely a passenger is to survive. In addition, the design of the seat's back plays a significant role in preventing head injuries (Boeing, 2011).

Over the years, structural tests have become more stringent to improve passenger safety. Today, new seats must pass the 16g test. The 16g test simulates the loading scenario in an accident where a collision can be survived and consists of two main dynamic tests simulating two separate impact scenarios.

One test with a dynamic forward force of 16 g and the other with a dynamic downward force of 14 g. Fig. 34 describes the loading scenario.

In addition to the 16 g dynamic test, aeroplane seats must also meet the head injury criterion (HIC), which measures the likelihood of head injury in a collision. This is tested during a dynamic sledge test where a seated 50p male dummy can be struck by the aircraft structure (EASA, 2011) .

When simulating the tests, the structural capacity of the seat should be designed for the 50 percentile (77 kg), as this protects the broadest range of occupants, Aircraft seats optimized for extremes such as p95 or p5 would have stiffness characteristics incompatible with the other extreme. They would be too stiff to absorb energy for lighter occupants or too flexible to protect heavier occupants (EASA, 2011).

CS 25.561 EMERGENCY LANDING CONDITIONS (EASA, 2011)

The occupant undergoes the following inertial forces separately.

Upward: 3·0g
Forward: 9·0g
Side: 4·0g on the seats and attachments (3·0g on the airframe)
Downward: 6·0g
Rearward: 1·5g

The structural calculation and testing of seats and their supporting structures may be determined by assuming that the critical load acts in the forward, lateral, downward, upward, and backward directions of the emergency landing conditions act separately or by using selected combinations of loads if the required strength is demonstrated in each specified direction.

The seats and supporting structure must not deform under these forces to the extent that rapid evacuation of the occupants is impeded.

Additional safety measures related to the seat (EASA, 2011)

- Each seat belt must have a metal-to-metal locking mechanism.
- If seat backs do not provide a handhold, a handle or handrail shall be provided along each aisle to allow persons to stand during use of the aisles.
- Each occupant of a seat that makes more than an 18-degree angle with the vertical plane containing the aeroplane centreline must be protected from head injury by a safety belt and an energy absorbing rest (airbag)
- No seat part must touch the sidewall of the cabin

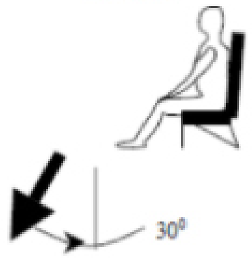
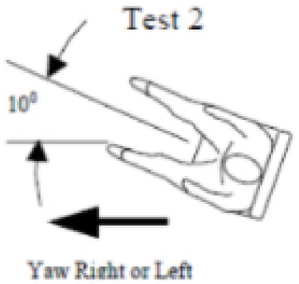
	Test 1	Test 2
Illustration shows a forward facing seat Inertial load shown by arrow	 30°	 10° Yaw Right or Left
Min V_1 m/s (ft./s)	10.67 (35)	13.41 (44)
Max t, s	0.08	0.09
Min G	14	16
Deform Floor		
Degrees Roll	0	10
Degrees pitch	0	10

Fig. 34. Dynamic test, loading scenario

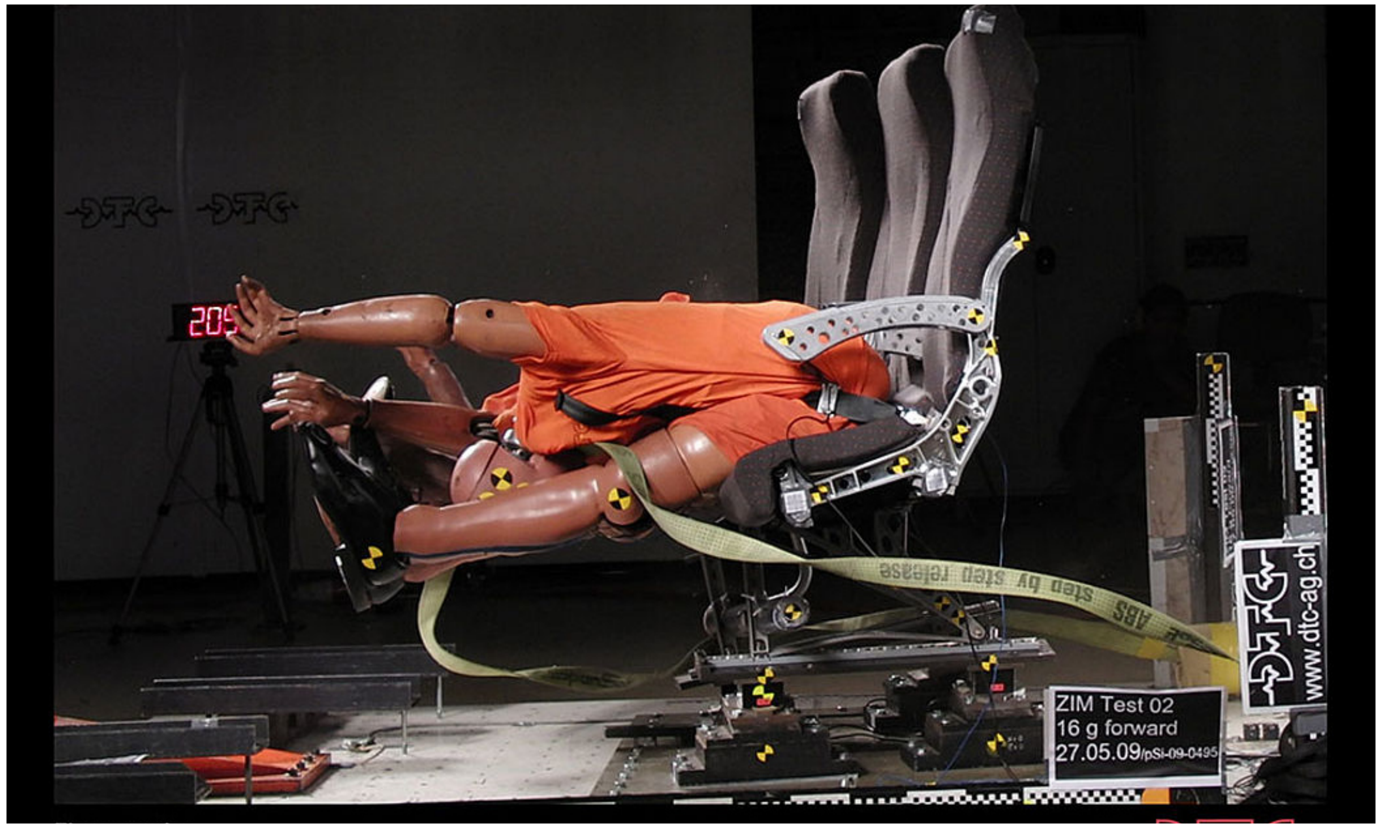


Fig. 35. 16 g test

Fire safety

In terms of fire safety airplanes have to comply with a maximum peak heat release rate of 65 kilowatts per square meter and specific optical smoke density of 200 (Boeing, 2011b). Most cabin materials are therefore required by the FAA to be self-extinguishing.

Aircraft cushion material plays a large role in a cabin fire. Thermal radiation can intrude into the outer lining of the seat and cause ignition of the foam core. With the amount of foam material used in aircraft, this potential fuel source can lead to a fire spreading throughout the cabin and producing significant amounts of smoke and toxic gases. (FAA, 86AD)

One way to delay the involvement of seat foam in a cabin fire is to add a layer of fire-resistant material. This means using a thin layer of highly fire resistant material to envelop the foam mass and protect it from external fire sources. (FAA, 86AD)

CS 25.815 Width of aisle (EASA, 2011)

The minimum aisle width is described by the figure below

Passenger seating capacity	Minimum passenger aisle width (cm (inches))	
	Less than 64 cm (25 inches) from floor	64 cm (25 inches) and more from floor
10 or less	30 (12)*	38 (15)
11 to 19	30 (12)	51 (20)
20 or more	38 (15)	51 (20)

Fig. 36. Minimum aisle width requirements

CS 25.817 Maximum number of seats abreast

no more than three seats may be placed side by side on one side of the aisle In aircraft with only one aisle.

Evacuation

The FAA requirements say that all passengers should be able to evacuate the plane in under 90 seconds. During an emergency, situation smoke can enter the cabin obscuring overhead lighting. Evacuation is therefore improved with floor proximity lighting, reflectors and escape slides to facilitate this process. (Boeing, 2011b)

2.6 Trends and developments in airline seats

Weight saving

Airlines are equipping their new aircraft seats with lighter seats to reduce fuel consumption and improve their margins by saving on fuel costs. Seat manufacturers have achieved weight savings reducing the foam thickness, swapping out real leather for more lightweight synthetic leather and applying more composites such as carbon fibre in the seat's construction (Aviation Business News, 2020b).

Fig. 37. Recaro slimline seat

More legroom

New lightweight airline seats provide more legroom. The thinner foam allows the same seat spacing to be maintained and gives passengers more legroom as the backrest becomes thinner. Seat manufacturers' efforts to further improve legroom also include literature pockets placed above the knees. Similarly, the Recaro CL3710 has the IFE box set directly below the screen to further reduce the knee area's backrest thickness.

Fig. 38. Recaro CL3710

BYOD

More airlines support the BYOD model, which stands for "bring your own device." and means that passengers bring their tablet and entertainment devices (PED's) and allow for streaming media from the aeroplane server.

From a seat design perspective, new seats have been equipped with all sorts of tablet stands and holders to support the use of passengers' own media devices. While it doesn't always replace the implemented IFE screens in the backrest, many seat makers believe it can also complement the current experience. It supports the double-screen trend of using multiple media devices at once at home. Such as watching a movie on tv while browsing through social media on your smartphone.

Fig. 39. BYOD

In-flight internet & real-time entertainment

To further reflect our entertainment level to which we are accustomed on the ground, airlines are working to introduce streaming of real-time entertainment, such as live sporting events.

Micro-nesting

In line with the trend to reflect our comforts of home, new seats often support the concept of micro-nesting. Micro nesting encourages personalizing your personal space during a flight. It allows the passenger to make the small space they have their own by supporting storing personal items such as glasses, bottles, appliances, etc.

Adjustable headrest

To prepare for long flights, passengers often bring neck supports to achieve a comfortable sleeping position with the ability to rest the neck in place. Recent seat designs, especially in the higher comfort segment, have implemented these features with highly adjustable headrests.

COVID-19

When COVID-19 hit the world, airlines reacted rapidly to operate while maintaining passengers' safety on board. In the past year, numerous aircraft interiors concepts were proposed that allow for social distance and minimize touchpoints. Some of the solutions in these concepts were quickly adopted by certain airlines. For example, spacers that keep the middle seat empty in a three-seat configuration and zero-touch that IFE allows you to watch movies and order meals and drinks onboard using your smartphone so that passengers don't have to touch the IFE screen. (Future Travel Experience, 2021)


Fig. 39. Micro nesting in seat


Fig. 40. Recaro adjustable headrest

Fig. 41. Touchless IFE

Improving the middle seat

Another trend in improving passenger comfort in the economy segments is making the middle seat a more attractive position. The middle seat was often seen as the worst seat in a plane as it provides the least personal space since the person in the middle often finds himself being shoulder to shoulder with his surrounding passengers (smartertravel, 2019).

Seat makers are aware of this problem and are making design changes accordingly. Bombardier, for example, has equipped their C series aircraft with a seat configuration where the middle seat is half an inch wider. The startup Molon Labe Seating has also shifted the middle seat a little backwards and downwards, so the seat configuration is staggered, and the person in the middle doesn't have to fight for his shoulder space anymore (Airlinetrends, n.d.).


Fig. 42. Wider middle seat

Empty Seat Option

As airline companies constantly hope to fly their planes at maximum capacity and strive to maximize their revenue, some low-cost airlines have adopted creative solutions to fill their empty seats. Many airlines now allow passengers to buy the remaining open seats next to them. When a passenger has one row of seats, they can sleep across the three seats.

Some seat manufacturers have already responded to this trend by supporting sleeping across the three seats by modifying the seats to turn them into a bed. By fully retracting the armrests and being able to position the calf rest horizontally parallel to the bed they are able to a bed-like structure (simpleflying, 2020c).


Fig. 43. ANA couch-seats

Modularity

The current economy Recaro seats and the Safran modulair S concept both have a modular architecture allowing the airline to customize the economy class for a particular route. By using a plug and play system add ons such as an adjustable 8 way headrest, double deck tables and tablet holders can be interchanged (Safran, 2021).

2.7 Benchmarking existing lightweight seats

Economy seats (short- and long-haul) for which weight data is publicly available were benchmarked for their comfort characteristics* and weight. Fig. 44 shows a market gap for a seat with medium (yellow) to high comfort (green) and a weight between 4 and 8 kg.

*Since it is not possible to compare the seats actual comfort, comfort levels are based on features attributed to higher comfort. The lowest two comfort levels are distinguished by either a fixed backrest or an adjustable backrest; the higher comfort level has additional comfort features such as an adjustable headrest, a calf rest, or a cradle recline. (See appendix for specific seat characteristics)

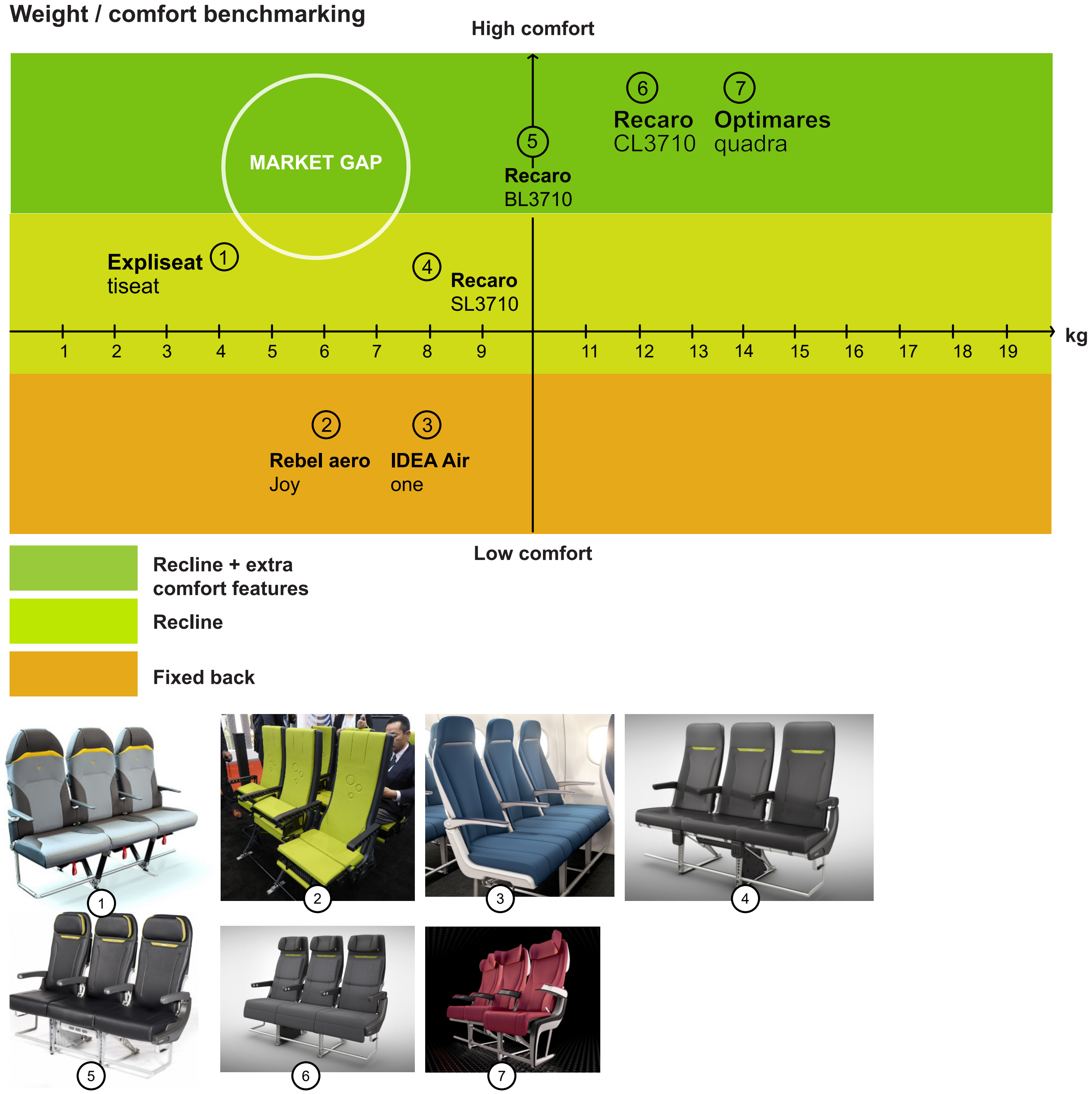


Fig. 44.

3 Comfort

3.1 What is comfort?

To understand what comfort is, we need to look at the relationship between discomfort and comfort. A study by Zhang (1996) mentions that comfort and discomfort are not opposites of each other, and a lack of one doesn't necessarily mean the other's presence. Both can even exist simultaneously. Zhang(1996) describes that discomfort is caused by biomechanical factors such as pressure distribution, joint angles, and other attributes that cause stiffness, pain, numbness, etc. These feelings of discomfort increase over an extended period and with fatigue.

Comfort is associated with relaxation and well-being.

Therefore, when designing a new seat, it is more meaningful to measure discomfort because it is directly related to physical attributes.

Why is comfort essential?

Besides connectivity, time, price and marketing, comfort is an essential deciding factor in choosing a flight. (Brauer,2004). According to Richards (1980), comfort is related to passenger satisfaction and the tendency to reuse a transportation system.

Comfort may lead to customer loyalty and, thus, a competitive advantage.

However, the aeroplane seat is only part of what leads to the passenger's overall comfort experience. The context also affects comfort, as it informs the human-product interaction. (Desmet and Hekkert, 2007)

How to design for comfort?

In 2015 Hiemstra- van Mastrigt developed a model to guide the design of comfortable vehicle seats. The model is divided into three areas from left to right within blue the inputs, consisting of the user seat and context activities. In grey, the interaction and to the left in orange the perception. The interaction leads to levels of discomfort and comfort. The arrow from discomfort to comfort indicates the finding of the model by Zhang that to perceive comfort, the level of discomfort cant be too high. See Fig.45

To further analyse what factors lead to comfort, we will use this model's categorisation, distinguishing between human factors, context factors, and seat factors.

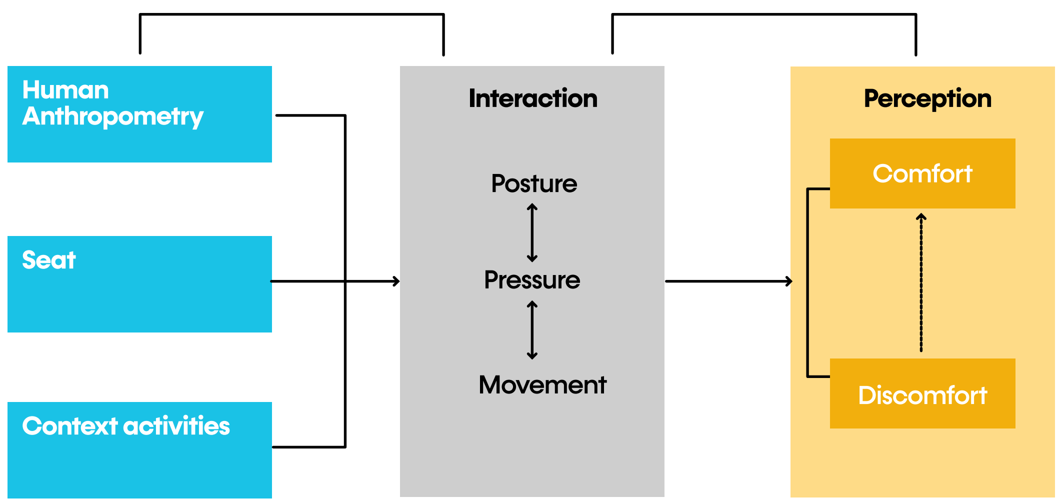


Fig. 45. Hiemstra- van Mastrigt, How to design for comfort?

3.2 Human comfort

Variation in sizes

An aeroplane seat must accommodate many passengers and, therefore, consider the size differences of different people from different demographic groups. For example, tall people tend to experience more discomfort in the neck due to a headrest that is too low. In contrast, smaller people are more likely to experience discomfort in their lower legs, where they come into contact with the seat's edge. Even between demographic groups, there are marked differences in size. Japanese, for example, anatomically have a longer chest than most other humans. (Kennedy, 1978). Gender plays a role in differences in proportions too, the difference in hip-width and shoulder-width is only 20 mm for Dutch women while it is 82 mm for Dutch men (Hiemstra-van Mastrigt 2015)

Variation in posture

Research by Dieën(2001) suggests that there is not one perfect seating position, rather it is that a seat should enable a posture variation. According to (Rosmalen et al.2009), every seat will cause discomfort over time and adopting different postures is essential to reduce discomfort. Seat adjustability is, therefore, one of the crucial factors in the design of a comfortable seat.

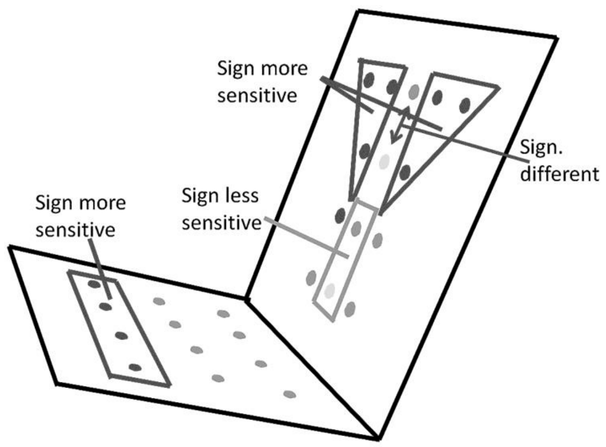


Fig. 45. P.Vink, Areas of varying sensitivity

Sensitive areas & pressure distribution

Appropriate pressure distribution is important for sitting comfort, according to Grandjean et al.,(1974). High surfacing pressures can constrict the blood vessels in the underlying tissues, restricting blood flow and causing discomfort.

For this reason it is essential to know what an ideal pressure distribution when making a seat and to understand what areas of the body are more sensitive than others. A study by (Vink et al.) researched what the sensitive areas are when seated. In this study, they found that the parts of the body touching with the seat pan's front are more sensitive. For the backrest, the shoulder level's point proved to be more sensitive, and the area in the middle, lower back was less sensitive. See fig. 45.

Zenk et al. (2008) studied the ideal pressure distribution when seated. Fig 46. The findings from this study also reflect the sensitive areas as there should be the least pressure where the legs touch the seats pans front.

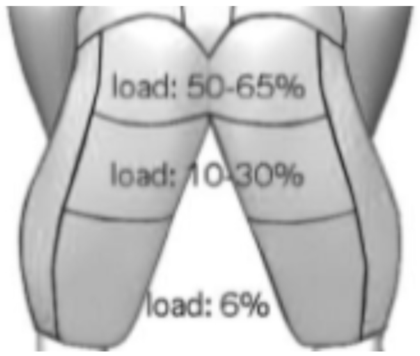


Fig. 46. Zenk, ideal pressure distribution

Mergl (2006) discovered that the distribution of pressure on the back of the seat area influenced the perceived discomfort in the lower rear of the spine. He found that the seat foam under the ischial tubercle (fig.47) must be denser to prevent discomfort in the lower back. A study by Herman Miller concluded similar observations, stating that correct pressure distribution in a seat concentrates the maximum pressure under the sit bones in straight up positions but adding that for reclining postures, it should be in the lumbar and thoracic regions.

Another study related to pressure sensitivity is by Franz et al.(2012). They investigated the effect the headrest has over the pressure in the neck and trunk and concluded that the neck rest should be softer than the foam in contact with the head.

For seat cushions, Ragan R, Kernozek et al. (2002) examined that pressures of compression reduce with increasing cushion height.

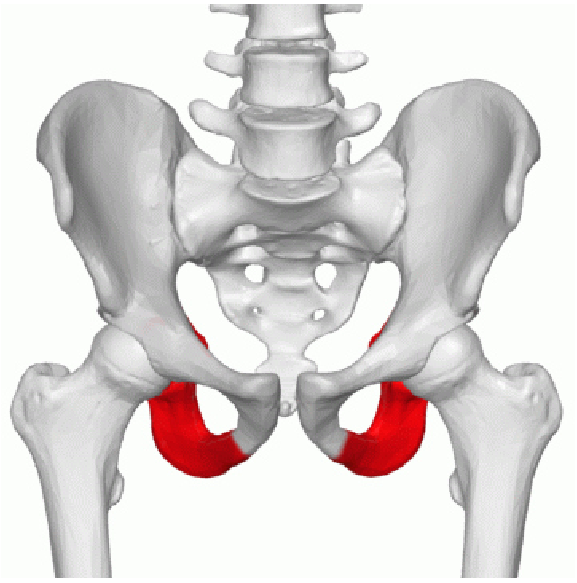


Fig. 47. Ischial tubercle

Regardless, there is a certain height to which an increase does no longer reduce the pressure more. In this study, this thickness was 8 cm; however, this result is not applicable to a wide demographic as the study was conducted with only one 70 kg participant.

The thickness and density of foam that provides optimal comfort for one person may be uncomfortable for another as a perfect softer seat for a lighter person can be too soft and compress too much under a more heavyset individual. According to (Zacharkow 1988; Hertzberg), a seat that is too soft exerts pressure on the gluteus maximus muscles on the side of the buttocks causing the type of unease that you can feel when you are sitting on director's chair for too long.

Ideally a chair should adapt equally to all the different human dimensions and apply little to no pressure, so circulation can't be impeded. (Herman Miller, 2013)

3.3 Seat comfort

In order to get an idea of how airline seats are currently perceived in terms of comfort Vink et al. (2011) studied the passengers comfort experience during flight by analysing 10.000 internet reports and taking 150 interviews of arriving passengers.

When asked about their seat's positive aspects, passengers often mentioned personal space, bright colours, adjustability of the headrest and the legroom under the armrest. Negative aspects were armrests being too bulky, hindering the ability to rest the leg under them, the seat width being too small, and the lumbar support too excessive.

The study results also showed that legroom significantly leads to lower comfort ratings, especially with taller people. In recent years this problem has been addressed by airlines, by further reducing the backrest's width.

Related to this personal space was also considered as one of the important factors leading to perceived seat comfort.

Seat dimensions

Based on literature research and the anthropometric database Dined, the optimal dimensions and foam pressures(headrest) required for an aircraft seat design were determined.

seat dimension	value	source
Seat angle	15 degrees	Goossens en Snijders 1995
Backrest angle	110 degrees	Goossens en Snijders 1995
Seat width	457 mm (18 inch)	Anjani et al. 2021
Lumbar support portrusion	max 30mm	carcone & Keir, 2007
Lumbar support height	120-280mm above seat pan	Korte,2013
Seat depth	457-553mm (p5-p95)	Dined dutch 2004 20-60 years (buttock-popliteal depth)
Headrest height	523-664mm (p5-p95)	Dined dutch 2004 20-60 Years (shoulder height sitting)
Headrest foam at neck level	<1Kpa (soft)	Franz et al.(2012)
Headrest foam at head level	5,6 Kpa	Franz et al.(2012)
armrest height (elbow height)	203-301mm (p5-p95), p50 = 252mm	Dined dutch 2004 20-60 years (Elbow height)
armrest width inbetween (hip width)	447 mm	Dined dutch 2004 20-60 years
Buttock-knee space	min 686 mm	Dined dutch 2004 20-60 years (Buttock-knee space p95)
Table height from seat	min 174mm	Dined dutch 2004 20-60 years (Thigh clearance seating p95)
Seat height	397-529mm (p5-p95), p50=463mm	Dined dutch 2004 20-60 years (popliteal height sitting)
Table - body distance	min 347 mm (p95)	Dined dutch 2004 20-60 years (abdominal depth)

Fig. 48. Ideal seat dimensions

Future proof sizing

Airplane seats are used on average between 7 and 10 years, but demographic anthropometrics change over time. Thus, to design an airplane seat that can provide long-term comfort to a broad demographic, it is essential to consider the sizes that may change over time.

From 1980 to 2014, obesity in the U.S. increased from about 10 per cent to more than 30 per cent. See fig.x (NCHS,2014). These lifestyle changes can lead to significant changes in body dimensions. For example, The hip width, which is an important measurement for the space between the armrest, increased from 408 mm to 440 mm in the 22 years from 1982 to 2004 for Dutch men of P95 (DINED 2004). See figure 49.

Ideal seat-backrest shape:

Hiemstra et al. (2015) conducted a case study to see If you can design an aircraft-seat based on peoples body outlines. In this experiment, 16 participants between p5 to 95 had their sitting-imprints 3d scanned to extract their own unique contour shapes.

The combined outside and inside shape then led to the ideal outside and inside contours. The outside contour would be used to create a composite shell that was then filled with spacer fabric to cover the differences between the contours. (Fig.50)

Aesthetics

Aesthetics influence the comfort experience, especially on short flights, as the first aesthetic impression plays a significant role in the first 40 minutes of sitting. After 40 minutes, the physical contact takes over (Vink,2014). Also, the feeling of comfort can be enhanced by an aesthetically pleasing design of the seat. However, the lack of an aesthetically pleasing design will not result in discomfort, because this requires unfavorable seating circumstances perceived by the body(Helander et al. (1987)).

According to Nigel Goode, head of design at Priestmangoode, patterned fabrics are also preferred over plain ones for seat covers since they effectively mask wear that has accumulated over the years. And Bronkhorst (2001) found that Bright coloured seats are perceived as more comfortable on the first impression than darker colours.

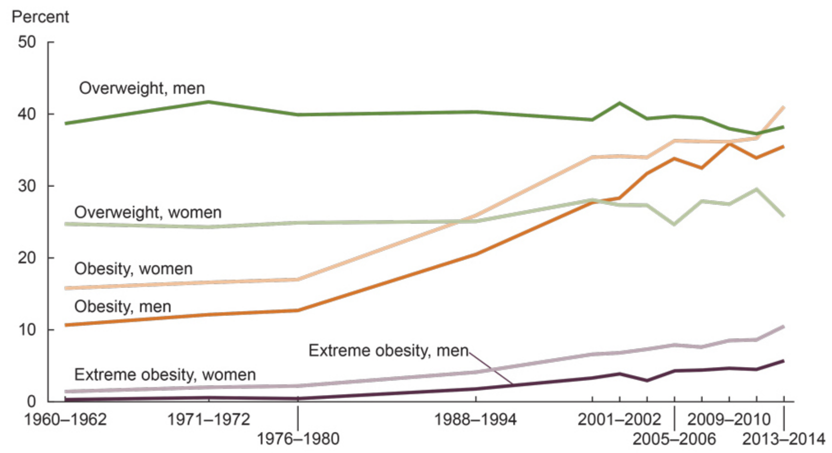


Fig. 49. Trends in adult overweight obesity, man and women 20-74,

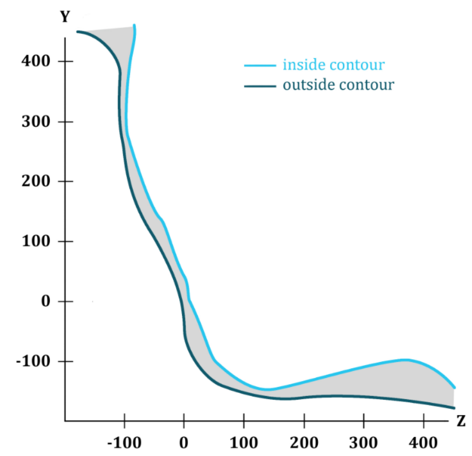


Fig. 50. Ideal backrest contours

3.4 Context comfort

In addition to the seat and the Anthropometry there are also context-related factors from the cabin environment that influence a passenger's perceived comfort during a flight. Bouwens et al.(2017) ranked the senses that relate to discomfort in the interior of an airplane.
After anthropometry, the biggest influences on in-flight discomfort are smell, noise and climate, followed by vibrations and light having the lowest impact. Below an overview of how these factors can affect discomfort.

Noise and vibrations
at cruise flight altitude the average noise level in aircraft is 75 dB. This noise is caused mostly by the engines. Mellert (2008) investigated The effect of sound and vibrations on the health of passengers on longhaul and shorthaul flying trips. In his study he discovered that under noisy conditions passengers where more aware of pain and discomfort.

Similarly Münzel et al. (2010) conducted a study that concluded that dying of a heart failure occurred at a higher rate in individuals who had increased levels of noise exposure from airplanes.

Smell
In a passenger aircraft with many people close together, bad odours can occur.

The effect of these bad smells can have a significant negative impact on perceived comfort. Similar to Mellert (2008), who examined that the effect of airplane sound and vibrations can heighten the awareness of discomfort. Martin G., (2006) found that individuals who were exposed to an unpleasant odour experienced more pain than those who were not.

Climate
Cabin temperature varies widely with values between 21 and 32 degrees celcius on mainland flights. A study by Pasut et al. shows that maintaining a neutral thermal sensation between 16°C and 29°C by heating and cooling of the seats leads to improved comfort. However there is a diminishing return at temperatures of 25°C. Besides the enhanced thermal experience, air quality is better perceived by participants who used the thermal control system.

Light

Light can influence people's mood.

According to Sokolova & Fernández-Caballero, the colours green, yellow and blue elicit the most positive emotions, although it should be noted that this depends greatly on the mood and personality, demographics and age of the person.

Boeing uses the colour blue in their sky interior through Led mood lighting in the cabin. McMullin (2013) examined that the sky interior contributed positively to the perceived comfort of the seats, as his study showed that 78 percent of travelers felt that the seat in the sky interior was perceived better in terms of comfort compared to the older interior. However, the same seats were used.

Additional comfort factors:

Other than smell, noise and climate and vibrations there are additional factors contributing to the perceived comfort such as aesthetics, time and the overall service.

Time

According to several studies there is a decrease in discomfort over-time and it takes about 30 to 45 minutes for discomfort to occur.(Porter. 2003; Jackson 2009). For seat pressure for example Noro. (2005) found a that the greater the period of time, the more pronounced the sitting discomfort was.

4. Designing lightness

As we concluded in chapter 1.3, an airline seat's lightweight design plays a vital role for an airline. Weight leads to better fuel efficiency, which then leads to economic benefits and a reduced carbon footprint. Tempelman(2014) came up with eight rules for guiding designers in making their products more lightweight.

1. Do not over specify

The designer should strive to ensure that the product does exactly what it is supposed to do and nothing more than that. Don't overspecify.

2. Do not use factors of ignorance

Use a safety factor in the design. For aircraft, this is 1.5. This means the product must be stronger than its load limit. In other words, an aircraft will fail if the limit load is exceeded by 50% or more. This narrow margin is large enough to prevent almost all over load scenarios, but small enough for economic use.

3. Avoid bending and torsion

Bending causes both tension and compression and is therefore not an efficient way of dealing with force, which is why a beam under bending and torsion is often heavier. A hollow beam can bear about 40 times the same load in tension as in bending.

If bending cannot be avoided, consider increasing the width and height of the cross section, which determine the moment of inertia. If we double the cross section, the moment of inertia becomes 16 times larger, while the area and therefore the weight becomes only 4 times larger.

4. Do not select materials independent of shape and manufacturing

When products and parts need to be stiff and light, one might think of making them from materials with a high ratio between their elastic modulus E and their density r. But this only applies to things that are loaded purely by tensile or compressive forces. For bending and torsion of beams, different criteria are applicable.

Furthermore, Not all materials are suitable for every manufacturing technique and different shapes such as plates, shells. beams handle the loads in different ways. Thus, the shape of a part can therefore not be chosen independently of the material and the manufacturing process.

5. Only use joints that are absolutely necessary / part consolidation

Fewer joints result in a lower overall weight. Joints often require overlaps in the material, which can result in additional weight, and the weight of the fasteners themselves can also represent a significant weight. Joints also reduce the strength and stiffness of the overall product and they are susceptible to fatigue and corrosion, which could reduce the allowable stress level and the stiffness of the structure.

less parts also will require less fasteners therefore saving weight. Parts of the design that would require an assembly of different subparts are sometimes able to be manufactured as one part when considering different manufacturing techniques.

6. Do not stop optimizing until the product cannot possibly be made any lighter

Continue to optimize the product if it appears to be too strong or stiff and can still lose weight. CAD FEM and Topological optimization can help with this.

7. Do not rule out steel not yet!

light metals and composites are not all there is. Steel offers high-strength plates and shells, and can be attractive for stiffness if you can avoid bending and torsion.

8. Nature

Be inspired by Nature!

4.1 structural lightweighting

Lattice Infills and sandwich structures

Lattices are crossings between solid material and empty space. They are useful in applications such as sandwich structures where they can create significant more strength and stiffness.(Harris, 2020)

Types of lattices:

Honeycombs

Honeycombs present the natural shape of stress in nature. They have a really good stiffness to weight ratio in the direction of their extrusion but about a magnitude less in the other direction.

Auxetic honeycombs

Auxetic honeycombs show a negative poisson ratio and contract inwards when compressed.

Octet lattices
Stiff in 3 dimensions but hard to manufacture (3d printing).

Gyroids
Gyroids are also interisting for lightweight applications, they are three-dimensional porous structures that can give a product high strenght and stifness along with good energy absorbption. (Monkova et al, 2017)

They always have two sides to them with a large surface area making them also interesting for heat exchange applications. (Harris, 2020)

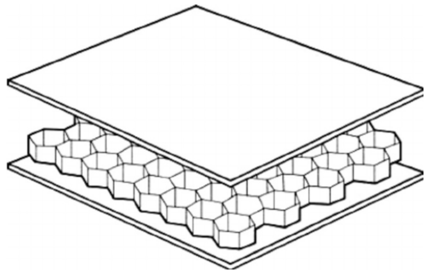


Fig. 51. Sandwich structure

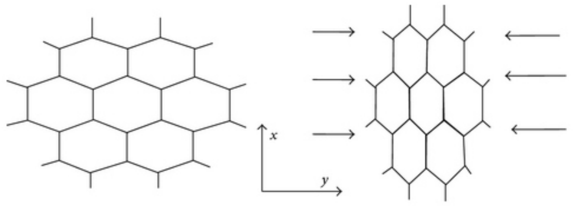


Fig. 52. Honeycomb structure

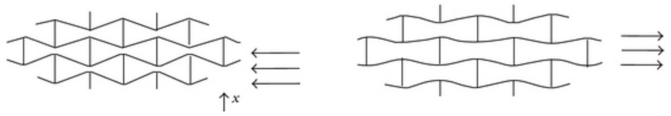


Fig. 53. Auxetic honeycombs

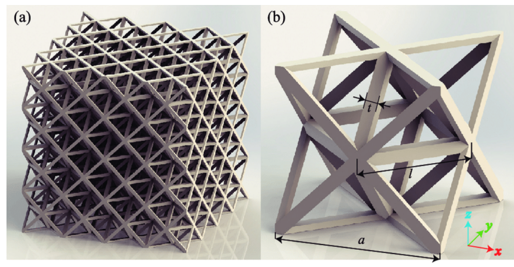


Fig. 54. Octet lattice

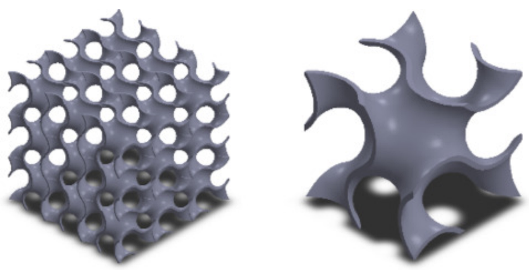


Fig. 55. Gyroid

Part Consolidation
similar to rule 5 less parts will require less fasteners therefore saving weight.With new manufacturing techniques parts of the design that would require an assembly of different subparts are now often able to be manufactured as one part using 3d printing for example. (Harris, 2020)

Topology Optimization

Topological optimization is a technique in which loads and constraints are applied to a specific design area, and then a smart algorithm calculates where the material can be removed until the specified goals are achieved. The drawback is that buckling is sometimes neglected in the algorithms, and a force at a slightly different angle can result in an entirely different design. Apart from these problems, the complexity of the shapes often requires additive manufacturing to fabricate the parts. (ntopology,2019)

Ribbing & conformal ribbing

conformal ribbing enables thinner part walls while improving buckling resistance and can be made used in polymers, metals, or composites. In polymers this technique is affordable and can be mass produced but for metals its more expensive however 3d printing makes this method easier to use.(Harris, 2020)

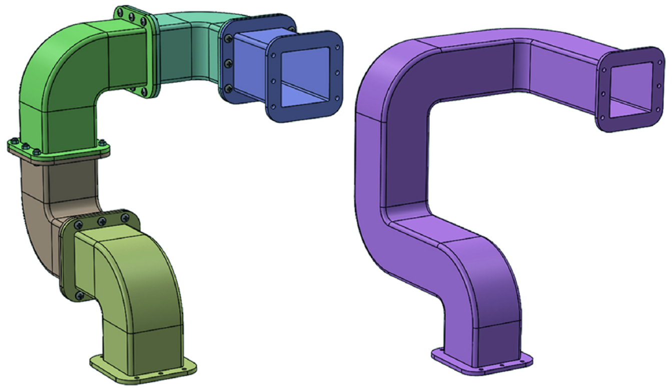


Fig. 56. Example of Part consolidation

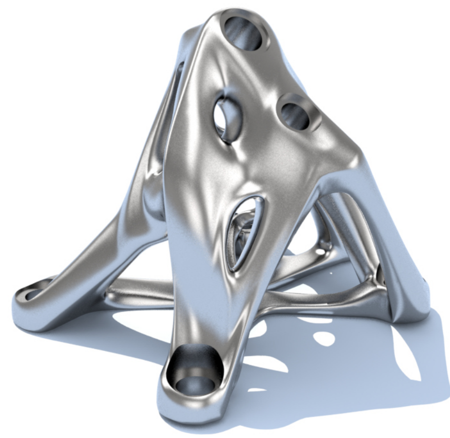


Fig. 57. Example of Topology optimization

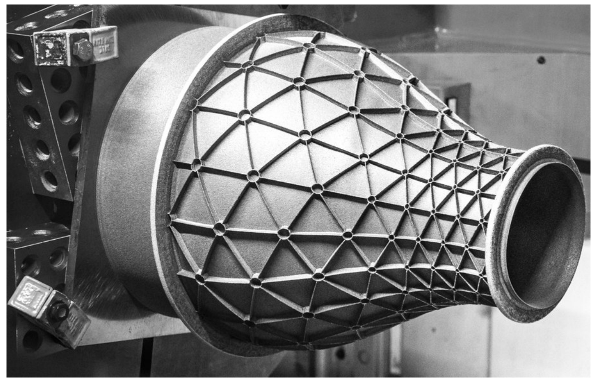


Fig. 58. Example of conformal ribbing

5 Circular design principles

As we saw in chapter 1.3, the biggest environmental impact of an aeroplane seat is due to its own weight. Nevertheless, it is still important to consider the other aspects that can have an influence on the life span and ecological footprint of an aeroplane seat. Below are some circular design principles which can be used as an aid in making the design of an airline seat more circular. (Bakker & Hollander, 2020)

1. Attachment and trust

Products that can create an attachment with their owner are generally less likely to be replaced and thus last longer. A lightweight aircraft seat that lasts longer also saves an airline the investment in new seats. A seat that is perceived positively by passengers and can stand the test of time with both timeless aesthetics and durable materials could help achieve this.

2. Durability

The product should be durable and should not break before the intended lifespan has expired. As a passenger, you would also not like to sit on a seat that shows signs of dirt, wear and age. Therefore, it is important to consider the durability and maintainability of the materials and the seat as a whole.

3. Ease of maintenance

Going hand in hand with durability is ease of maintenance. Designing a product in such a way that it can be maintained easely is important. As we saw in Chapter 2.1 when disassembling the reference seat. Both metric and British Imperial fasteners were used, which makes this more difficult. This could be because different manufacturers are sometimes responsible for different parts of the overall seat assembly.

5. Upgradeability and adaptability

A product that can evolve with its user and adapt to different use cases is less likely to become obsolete quickly. Embedded electronics in a car for example can make the whole product feel outdated after only a few years, it is therefore better to design those parts that will become old quicker in a way that they can be swapped without destroying the rest of the product.

6. Disassembly and reassembly

Easy assembly and disassembly not only reduces assembly time and thus production costs, but also benefits repairability and recyclability at the end of the product's life. The quantity of parts, the tools needed, and the type of fasteners all affect this. The design of an aircraft seat must take into account that passengers should not be able to take the seat apart, so the use of "special" fasteners could be a solution to this.

6 Eco-seat (vision)

While the existing economy class focused on economic flying, this project aims to focus on ecological flying by creating a synergy between airlines, passengers and the environment by creating a desirable eco-seat for a progressive airline committed to sustainability.

This eco-seat for short-haul flights will strive to maximize airline efficiency through low weight, low maintenance and a small footprint. The seat should express this commitment through its design, so that passengers are aware of the airline's commitment and offer a customizable and satisfactory level of comfort that is independent from other passengers.

The concept will further consider current industry values such as hygiene and cleanliness, sustainability, and sufficient space for each passenger.

7 List of requirements

Requirements lightweighting

- The seat should aim for a reduction in 40% of the mass compared to the reference seat.

Requirements comfort

- The seat should offer better passenger comfort to current economy class seating.
- The seat should offer adequate personal space.
- The seat should offer adequate hip and shoulder space from p5 to p95
- The concept should offer comfort to a wide demographic.(P5 to P95)
- Passenger comfort can not be imposed by the surrounding seats.
- The seat must support eating and drinking activities.
- The seat must support storage of personal items.
- Comfort materials should be breathable.
- Seat should support BYOD.
- The seat should have a bright colour.

Requirements hygiene

- The concept should minimize seams and gaps that can accumulate dirt.
- Products should be easily cleanable.

Requirements safety

- Each seat and its supporting structure, and each safety belt or harness and its anchorage must be designed for an occupant weight of 77 kg.
- Structurally the seat and its attachments should comply with CS 25.561 inertial forces and can't deform to the point where it would impede rapid evacuation.
- Aisle width should be minimum 38cm in between seats at points less than 64cm from the floor and minimum 51 from 64cm and above. cleaning) in a quick and easy way without disassembling structural components.
- At least 80% of the seat should be recyclable at its end of life.
- Seat materials should be self-extinguishing.
- Each seat belt must have a metal-to-metal locking mechanism.
- If seat backs do not provide a handhold, a handle or handrail should be provided along each aisle to allow persons to stand during use of the aisles.
- The seat angle cant exceed 18-degree angle with the vertical plane containing the aeroplane centreline so no costly airbags are required.
- No seat part must touch the sidewall of the cabin

Requirements sustainability

- The seat should be designed for durablility.
- Comfort materials should mask wear that has accumulated over the years and high wear components such as ''comfort materials'' should be upgradable.
- Electronics must be able to be swapped without destroying the rest of the product.
- The product should be able to be re- and disambled without destroying any parts or the overall structural integrity of the seat.
- The product should be able to be disassembled to its separate materials components.
- The seat must be disassembled with a maximum of 3 tools.
- All fasteners must be metric.
- For ease of maintenance, seat comfort materials should be able to be dissemblable (for example for cleaning) in a quick and easy way without disassembling structural components.
- All seat materials should be recyclable

8 Ideation

To kick off the ideation phase, a 6-3-5 brainwriting session was done with six fellow students. This group brainstorming technique requires 6 participants to jot down three ideas in 5 minutes and do this five times. In this case, 5 participants generated a total of 75 ideas. The goal of this brainstorming session was to think outside the box on how to make the tray table lighter.

While not all ideas during this session were feasible, the most valuable take-away is that the session demonstrated how important it is to second guess a product on its core functionality, this mindset became essential in the rest of the design process.

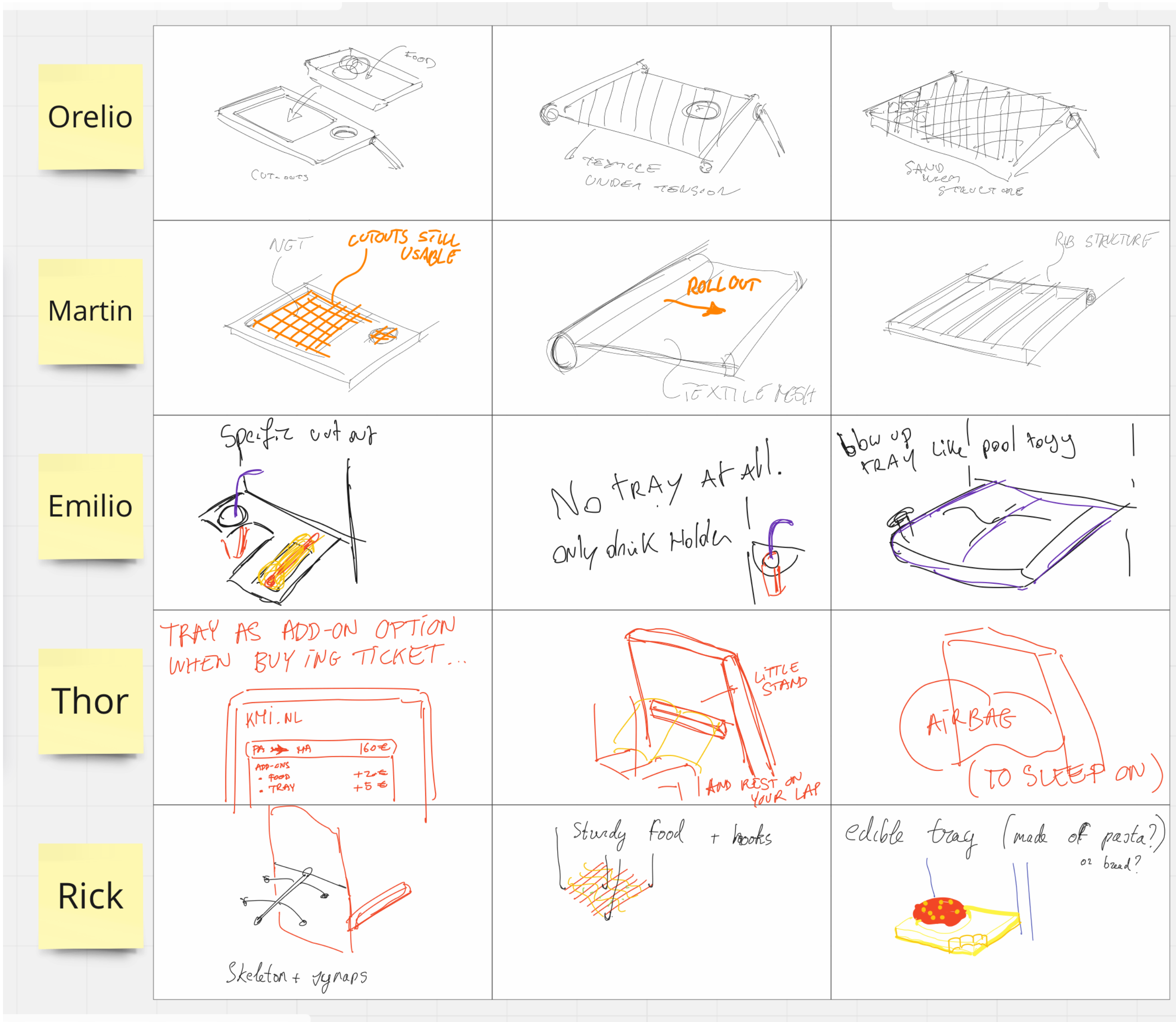


Fig. 54. 6-3-5 brainwriting

Seat layout exploration

Before proceeding with the design, it was necessary to determine what the best seat configuration would be to maximize efficiency, maximize personal space, and minimize weight. Several structures of existing and concept seats have already been examined in Chapter 1.4, but these layouts do not have the critical criterion of reducing weight. As a result, likely, the configuration with the most personal space is not the lightest.

Seat layout exploration

Before proceeding with the design, it was necessary to determine what the best seat configuration would be to maximize efficiency, maximize personal space, and minimize weight. Several structures of existing and concept seats have already been examined in Chapter 1.4, but these layouts do not have the critical criterion of reducing weight. As a result, likely, the configuration with the most personal space is not the lightest.

For example, the staggered seats offer the most personal space but will be heavier than a conventional arrangement because the staggered arrangement requires stronger connections between the individual seats' underlying structure, and the legs may need a larger size to balance the non-symmetrical structure.

Therefore, variants closer to conventional side-by-side configurations were investigated. One such variant is to bend the backrests and seats inward, creating more personal space for the shoulders in exchange for less width for the legs.

With simple 3D mockups, this configuration proved interesting, as the curved shape is more resistant to bending and can be lighter as a result.

However, after exploring this idea further, it became apparent that the tradeoff was becoming too large, whit the seat width being less than acceptable.(<400mm)

It was essential to keep the seat width as large as possible since this left open the possibility of using a textile-based seat structure where the person can sink in a bit. Eventually the conventional layout was chosen as the starting point for the design.

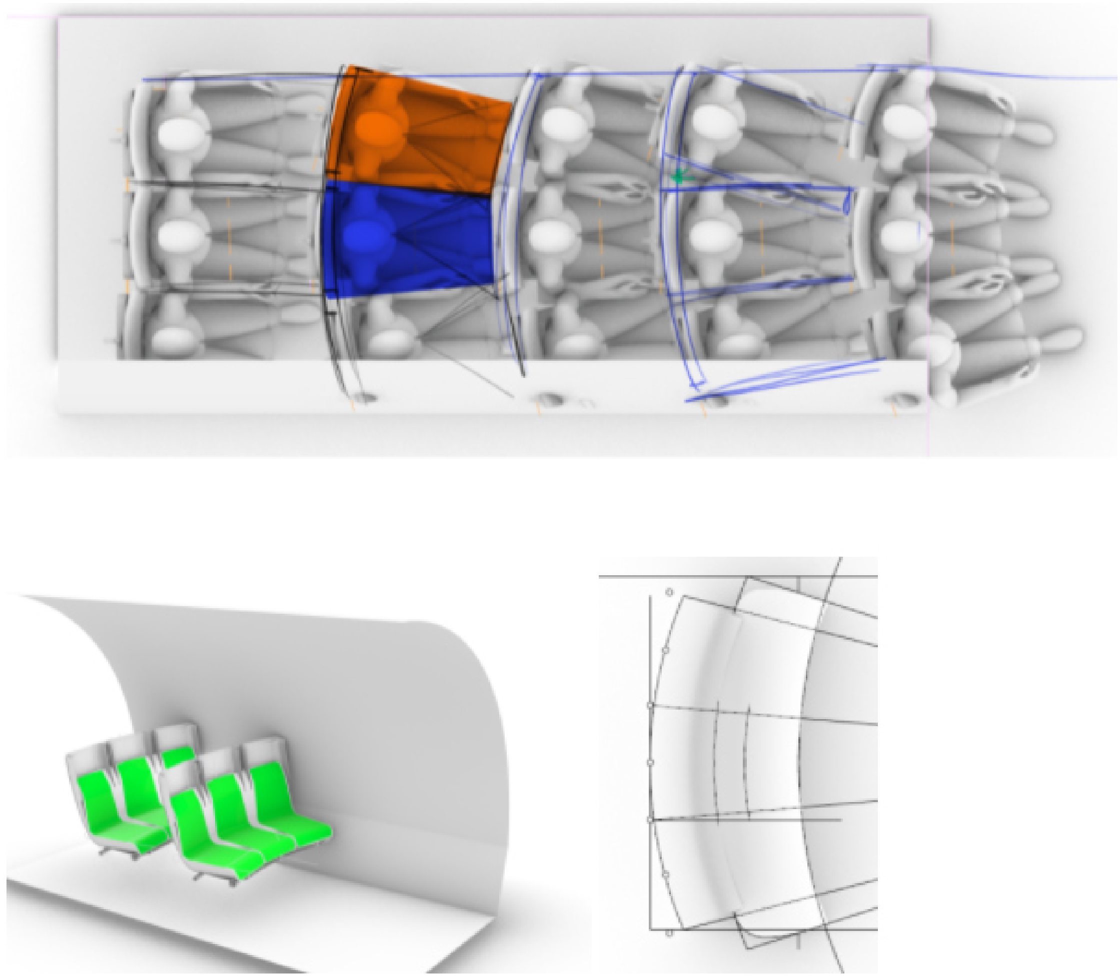


Fig. 56. Seat layout exploration

9 Ideation sketching

Brainstorming with ideation was widely used to think outside the box and avoid premature criticism in the initial idea development. This resulted in many rough ideas that later had to be validated. With the vast amount of dimensional requirements of airline seats, the first phase of this validation and further idea development was often done in 3D with simple mockups. This gave room for more control in working towards feasibility. An overview of some of the rough idea sketches can be seen on the following pages.

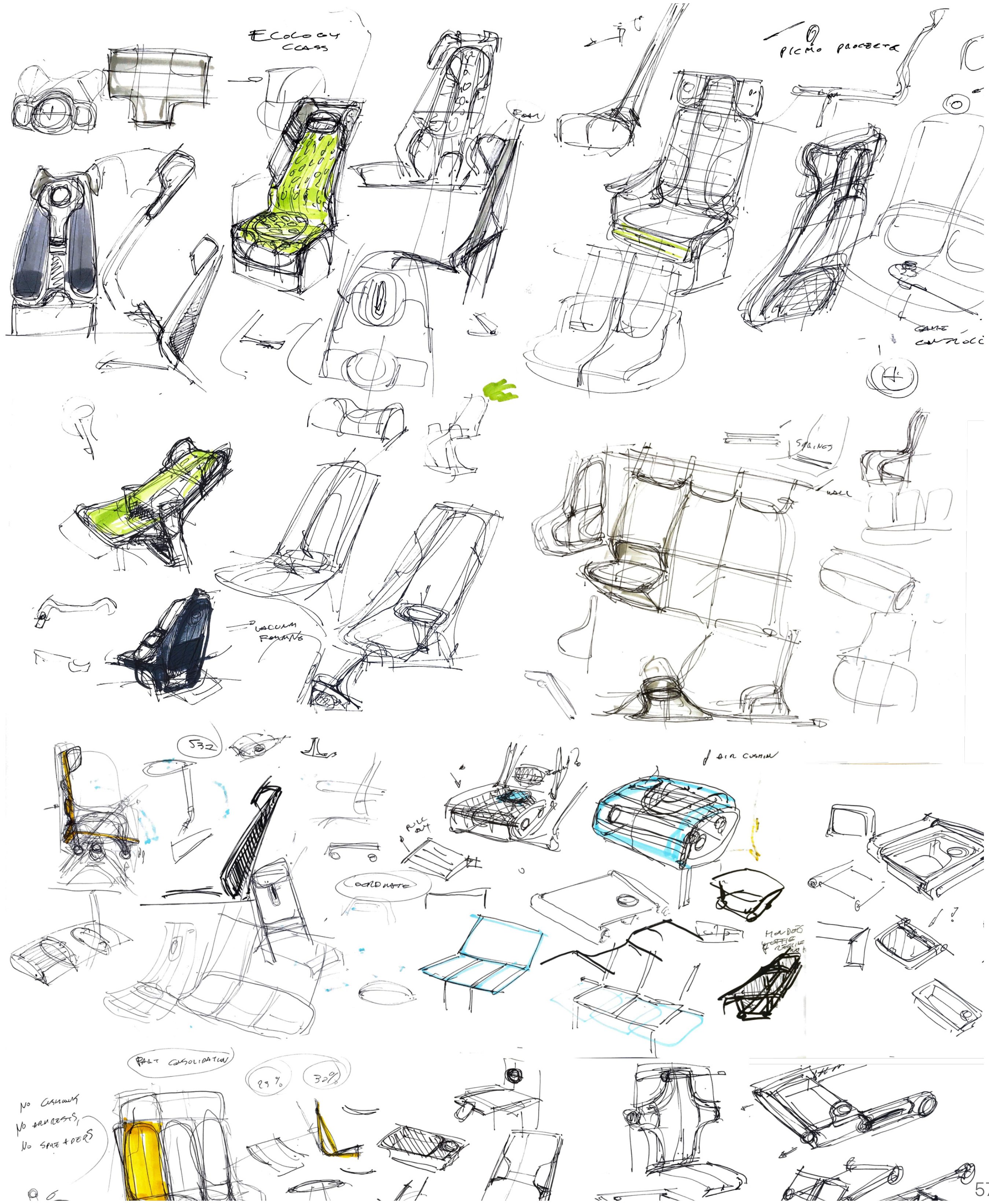


Fig. 57. Ideation sketches

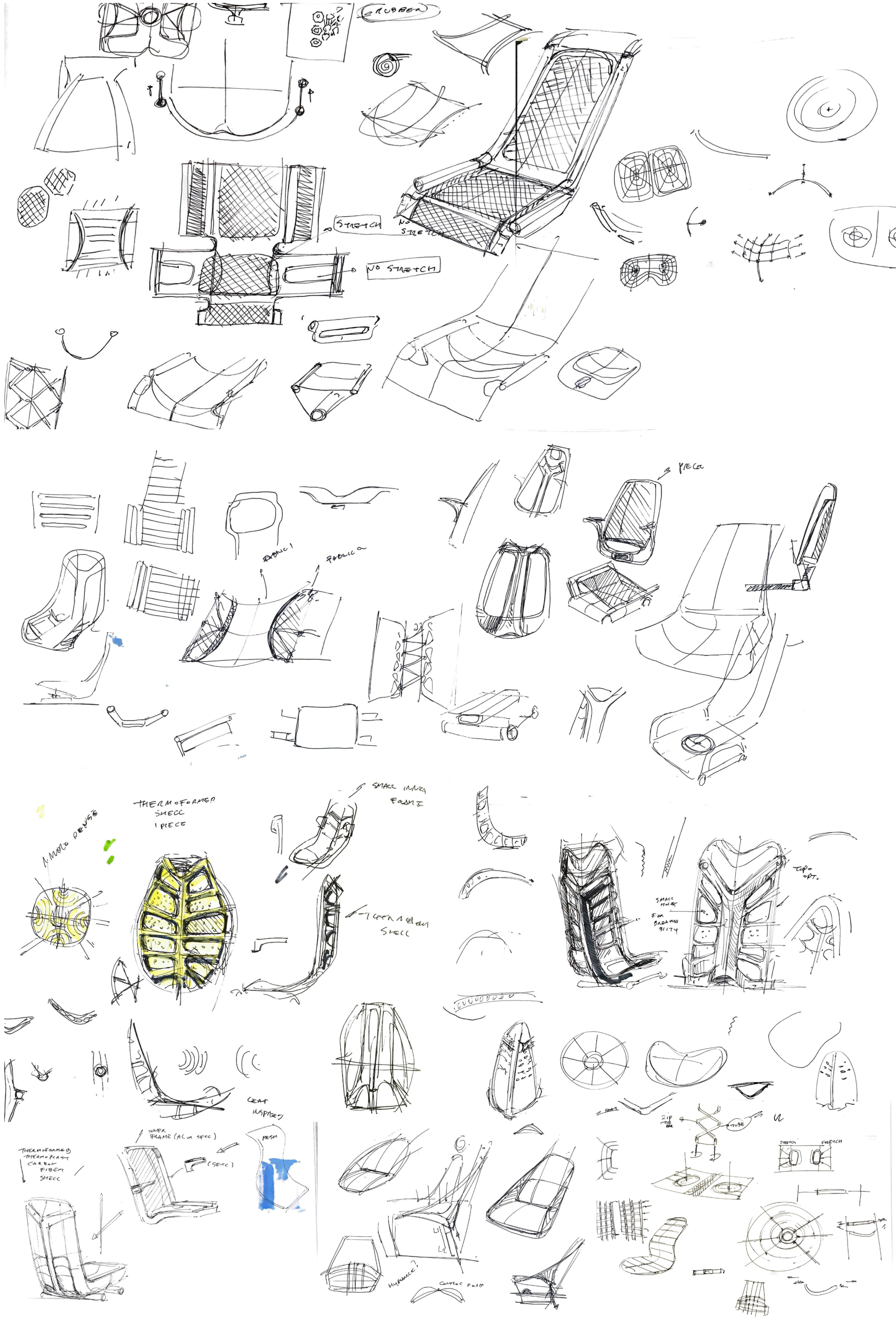


Fig. 58. Ideation sketches

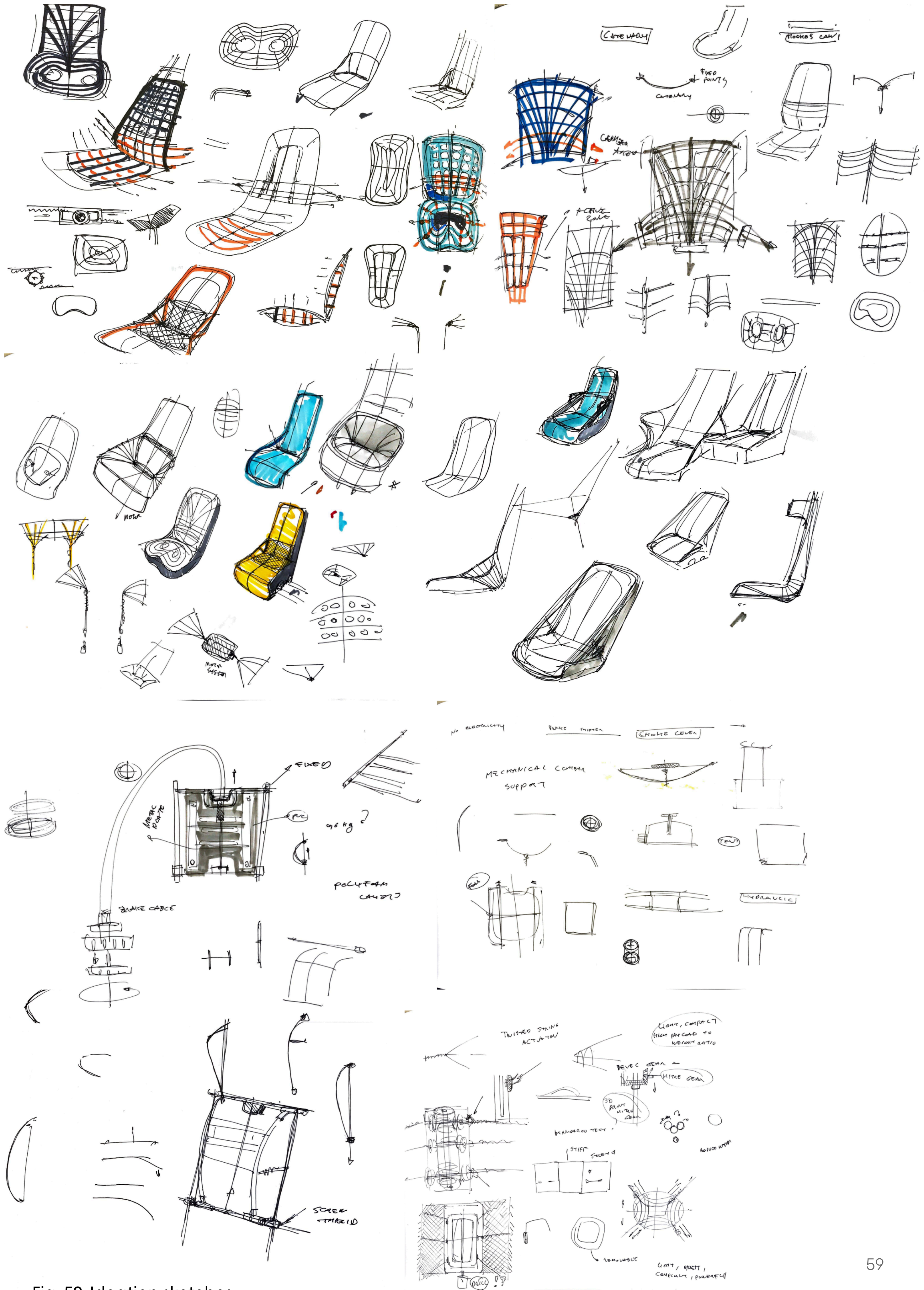


Fig. 59. Ideation sketches

10 Concept development

The ideation process quickly led to initial concepts that initiated an iterative concept development process. The concepts were examined and developed to a level where feasibility and suitability for the project objective could be validated. The concept development process therefore had three main directions. These directions did not emerge simultaneously, but developed mutually on top of each other towards a single feasible outcome most consistent with the project objective.

10.1 Concept direction 1

Description:

Concept 1 has a frame inspired by carbon fibre bicycles. The lightweight frame acts as a structural exoskeleton with an attached, lightweight aluminium frame that only has to carry the passenger weight and suspends the passenger from a suspension fabric

For the kinematics of this concept, the pivot point is placed at the top of the carbon frame; this enables the passenger to tilt forward into a cradle position so that, when the passenger leans back, the rear passenger's personal space is not compromised.

Conceptadvantages VS. disadvantages

+ Because the passengers knees can surround the upward beam to the sides, the seats can be placed closer together with a smaller pitch giving room to placing more seats in the aircraft and thus increasing occupation efficiency.

+ Weight can be saved by integrating the different structural parts and functions into one strong carbon fibre structure. less parts will require less fasteners therefore saving weight

- The production method of carbon fiber bicycle frames is labour intensive and thus not cost- efficient on a large production scale. Furthermore because of the complex geometry the carbon fiber composite has to be made with thermoset resin which is not recyclable and therefore wouldn't fit the ecological aim of the project

- Lifting someone up and forward requires forces higher than current recline mechanisms because the moment of force is higher with the pivot point at the top compared to a pivot point at the position of the lower back. Therefore to make this work the mechanism to enable this would add complexity and weigh more.

Fig. 58. Concept direction 1

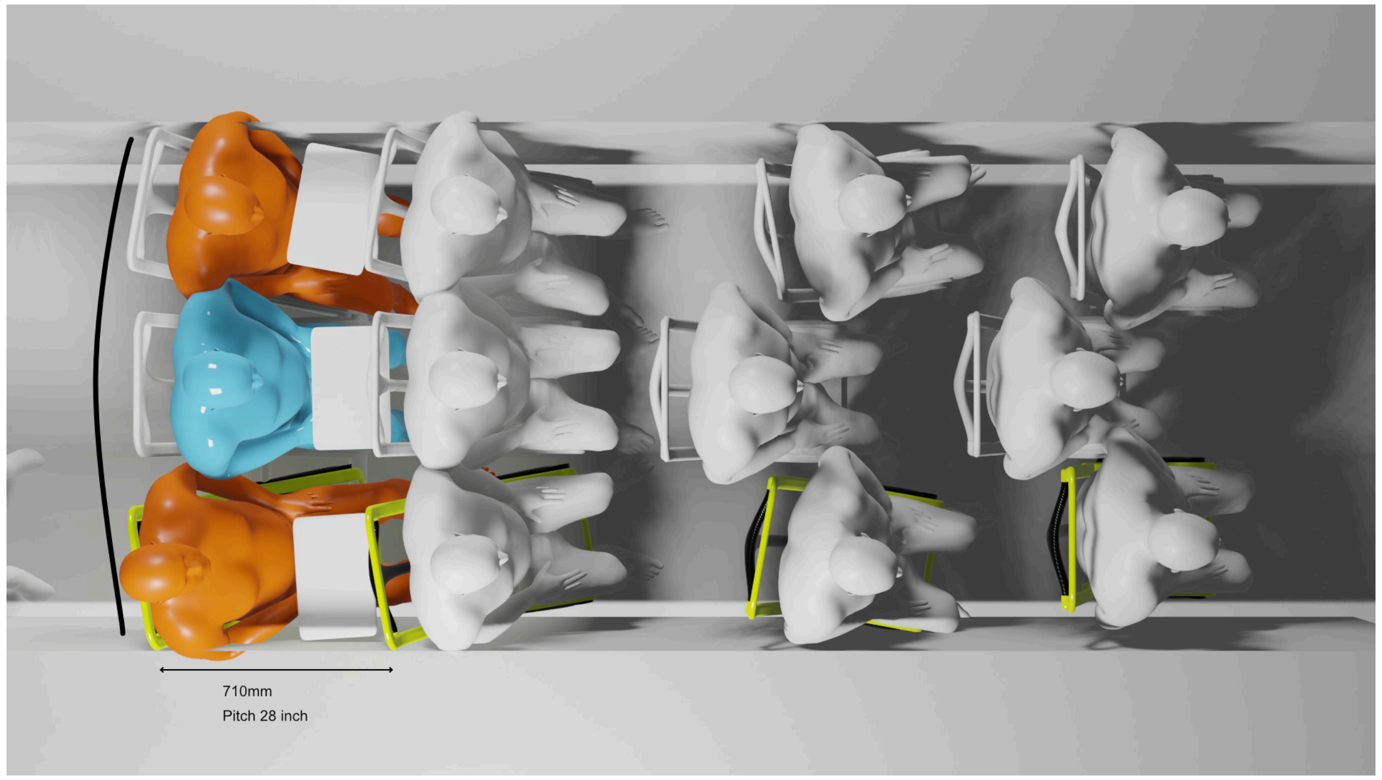


Fig. 59. Direction 1, layout exploration

10.2 Concept direction 2

Description:

Concept 2 moves from a frame with moving parts to a fixed structure with the possibility of changing position by adjusting the tension of the textile mesh using a mechanism. This mechanism allows the passenger to sink into the seat or sit upright, depending on the relaxation of the textile. Numerous mechanisms were explored that could make this possible, however it quickly became apparent that a motorized system would be needed. The disadvantage of this is that this system would require in seat- electricity which on short-haul flights is a rarity because of the extra weight the cabling would require. Also the forces to lift someone up in the seat would require high torque motors making the overall seat heavier.

The different explored systems and mechanisms can be seen in the appendix. While this could have been an interesting direction for other types of seating such as business class it didn't fit with the most important rule of lightweight design which is to not over specify and strive to ensure that the product does exactly what it is supposed to do and nothing more than that.

Conceptadvantage VS. disadvantages

- In- seat electricity will add weight to the aircraft.

+ Fixed frame structure gives opportunity for a strong and lightweight structure

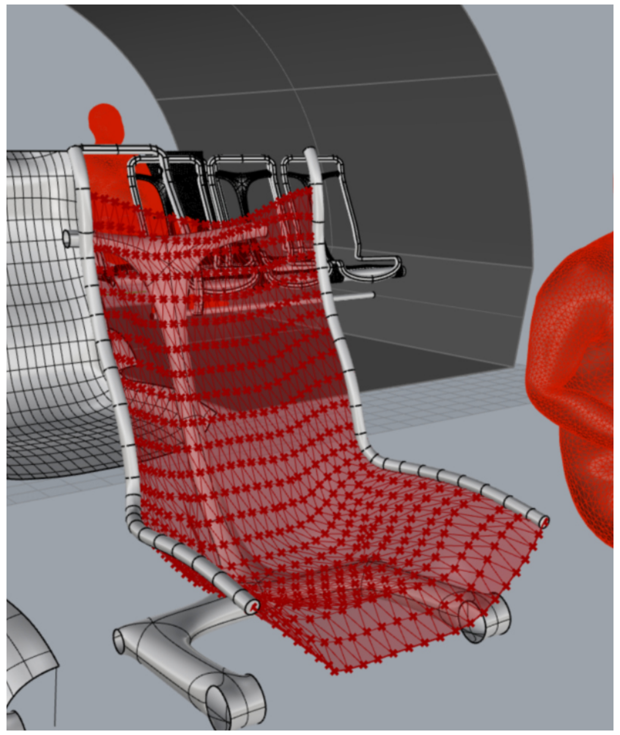


Fig. 60. Grashopper, mesh seat simulation

Fig. 61. ideation sketching concept 2

10.3 Final concept direction

The third and final concept direction addresses the problems of the previous two concepts by finding a solution for a lightweight structure suitable for mass production and seating comfort without complicated mechanisms or electricity necessities.

Since structure and comfort are the main areas addressed in the concept, the concept description will first address these areas.

Seat structure

Frame

At the core of the concept is a rigid frame structure manufactured using CFRTP compression moulding.
This material and manufacturing technique is suitable for large parts and high-volume production, making it an economical way to produce lightweight, high-performance parts.

The frame shell combines three seats into one bench construction, with the two outer seats now enclosing the middle seat. Consequently, the depth of the individual seat shells automatically forms a rib structure between them, replacing the structural spreaders of conventional airline seats and providing an attachment point for the armrests and seat belts.

Several functions are now combined in one multifunctional structural shell. This approach reduces the number of parts and materials required, making the chair as a whole lighter and easier to assemble and recycle.

Fig. 62. CRFTP frame

There are two circular cavities at the bottom of the frame were two tubes can be supported and attached with bolts. The tubes provide additional torsional rigidity to the overall seat structure and provide an attachment point for the legs. The use of the two tubes to connect the three seats is common in seats for economy aircraft because it allows only one pair of legs to be used under the seat, with the tubes distributing the forces of the "shell" to the legs. The tubes have a round profile because this profile shape is the most resistant to torsion.

Fig.63. Render showing leg attachment

Legs

The legs attached to the tubes are made from aluminium and have a gyroid lattice inside. The gyroid inner lattice combined with the outer ribbing creates a lightweight porous sandwich structure that can provide high strength, stiffness and good energy absorption at a reduced weight.

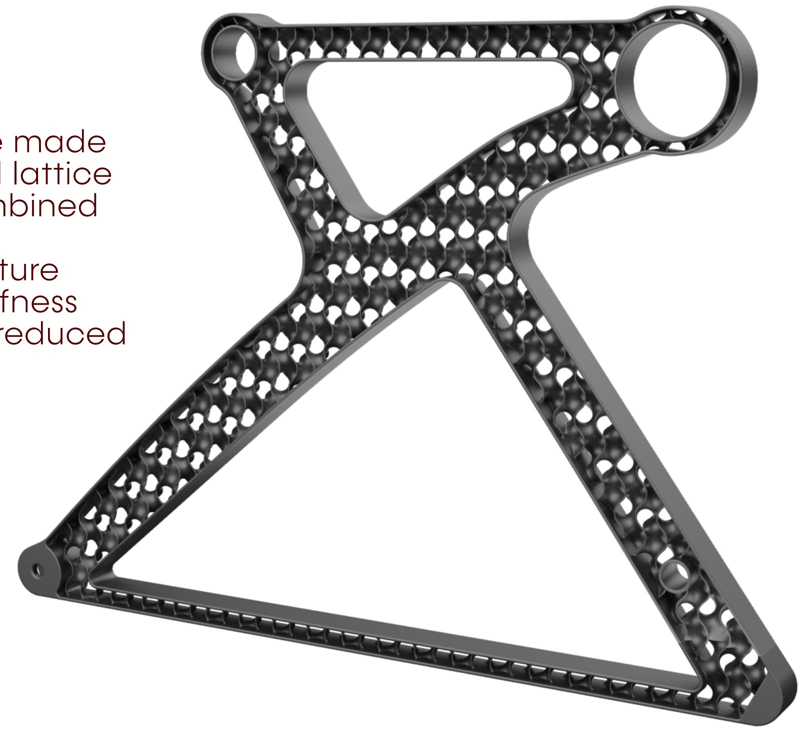


Fig. 64. Investment cast leg

Seat comfort

For seat comfort, the electronic system of concept two is replaced by a fixed suspension, which is lighter, cheaper and easier to maintain.

The fixed back of the seat frame is preset to an angle of 100 degrees, which is slightly more upright than the ideal described by Goossens en Snijders (1995).

A lot of short-haul flight economy seats already have fixed back to save weight and reduce seat pitch. However, having a fixed backrest restrict the freedom for variation in posture. As seen in chapter 3.2, variation in posture is vital in preventing discomfort when seated.

This concept substitutes the seat recline by replacing the conventional foam backrest with a more dynamic suspension system. This suspension system supports the back in the lumbar and thoracic spine area (see fig. 67)
The springy behaviour of this suspension system supports micromovements through which slight variations in posture are still possible.

The suspension frame is made from lightweight bent spring-steel rods, to which a pre-tensioned suspension fabric is attached.

In the same way as the backrest the seat also uses a suspension fabric, creating a similar comfort experience to many mesh office seats.

A stretchable fabric covers the suspension system for the backrest and the seat. This covering should be stretchy to follow the suspension system closely. In addition, the material should be flame retardant, durable, soft to the touch, and breathable.

The cover is attached to a lightweight aluminium frame, making it easy to detach for maintenance.

The same aluminium frame is used to support the headrest. The headrest uses conventional foam and is attached to a lightweight shell made from the same CFRTP material as the frame.


Fig. 65. Render displaying suspension system

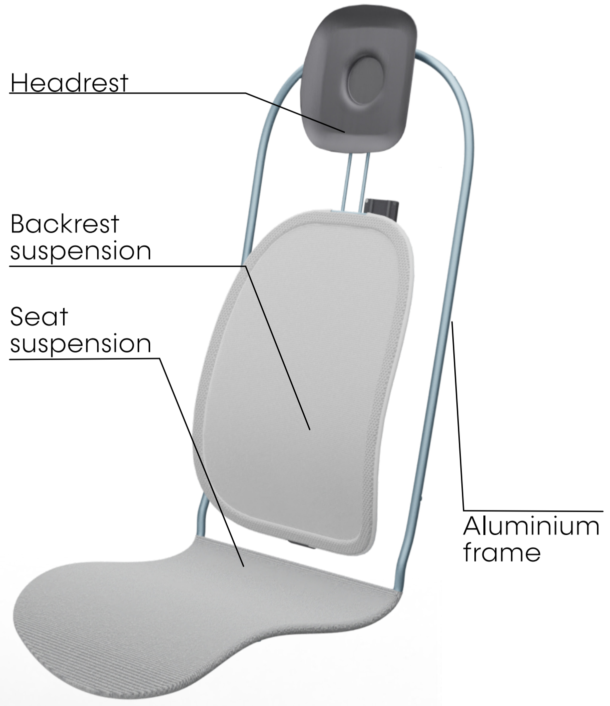


Fig. 66. Suspension system

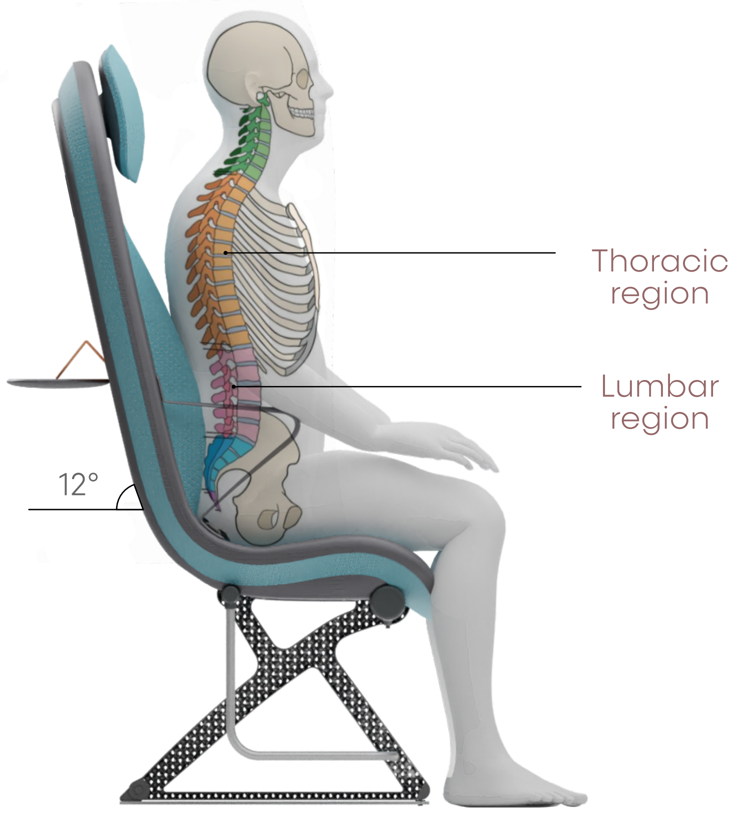


Fig. 67. Visual displaying how the backrest follows the spine

Fig. 68. 3/4 perspective render

Seat dimensions & passenger space

For the general dimensions of the seat design, the values of table x (ideal seat dimensions) in chapter 3.3 were consulted.

The design attempted to stay as close to these ideal dimensions while meeting a small footprint, comfort, and legal size requirements.

Maximizing the seat width was necessary because replacing the conventional foam cushion with a suspension fabric meant that the passenger would have to sink slightly into their seat, reducing the effective width.

On the other hand, the available passenger space is maximized by combining the three seats into a bench since there is no longer empty space between the seats. This allowed a maximum available seat width of 450mm, which is slightly less than the ideal 457mm described by (Anjani 2021).

Fig 69 below shows an overview of the main dimensions of the seat, and fig 70 shows the seat with a pitch spacing of 28 inches displaying how the cavity in the back of the frame shell creates 50mm extra space around the knees.

Fig. 69. Seat plan views

Fig. 69. Section view of seat showing knee-space at 28-inch pitch

Fig. 70.

concept details

BYOD & nesting support

To further enhance the seating experience, the seat is equipped with some features to support the nesting and BYOD trend.

There is a tray table integrated into the cavity of the backrest. Behind this cavity is room to store a bag for personal items and flight information, such as safety instructions.

The lid of this bag closes magnetically and can be folded into an angle so that the passenger can position their phone against it.

Fig. 71. Personal items bag

Fig. 72. Back of seat with QR code

Back cover
Because the use of compression molding creates a shell with a negative, concave side that looks unfinished, the cavities on the back of the frame are sealed with a synthetic leather covering - this leather covering gives the design a more voluminous feel. synthetic leather was chosen to provide ease in maintenance and cleaning.

Fig. 73. Frame with and without back covering

10.4 Concept materials

Structural-materials

CFRTP is chosen as the primary structural material. CFRTP has the advantages in design freedom and mass scalability of thermoplastics, with the performance and durability of carbon fibre composites. The thermoplastic matrix material allows the production of cost-effective composite parts with high yields and low cycle times. This is possible because of its compatibility with automated manufacturing technologies such as compression moulding, automated tape layering, and automated fibre placement as well as weld jointing.

CFRTP are lighter, stronger and stiffer than aluminium and compared to thermoset carbon fibres have a higher durability and impact resistance due to their thermoplastic matrix resin.

The polycarbonate resin based carbon fiber composite Maezio produced by german manufacturer Covestro was chosen due to its class-A surface quality and the high variety in surface finishes. Making it suitable for applications where visual appearance is important. Maezio is a Polycarbonate resin carbon fiber composite.

Table x shows an overview of how Maezio compares to other lightweight structural materials. For more detailed material properties see appendix.

As seen in the table, Maezio has very low density and high tensile strength, making it suitable for lightweight, high performance applications. In addition to this, the direction of the fiber in each layer of the tape lamination can be adjusted to meet specific performance objectives, allowing even more weight to be spared or extra strength to be added in certain areas of the design.

	CFRTP (Maezio) CF FR 1000T	Thermoset carbon fibre composites	aluminum 7075-T6
Density(g/cm^3)	1.5	1.5	2.81
Tensile strength(Mpa)	1500 = 0° 25 = 90°	865	620
Specific strength	1000*	576	199
fatigue strength*	+++	+++	+
corrosion	++	++	-
Fire resistance	++	+	+++

Comparison of mechanical properties of different materials (data from Ces-edupack 2021 and Covestro.com)

Recyclability of CFRTP

The composite matrix resin of CFRTP's is a thermoplastic , which means that it can be recycled by melting the resin and remoulded into other products at the end of the product's life. This is a significant improvement over thermosets composites which are not recyclable due to the thermoset resin (epoxy) which cannot be melted or remoulded.

However due to CFRTP materials being relatively new there are not a lot of recycling facilities in place for it right now, this makes its actual recyclability a lot harder. Now CFRTP are often downcycled by chopping the material's fibers and using it in an injection molding process for chopped fiber composite materials. next to reuse advanced solutions, such as cost-effective fiber extraction, also exist. (Covestro,2021)

The effective recyclability depends on the commitment of the different stakeholders to create a closed loop. Luckily CFRTP is already widely used in the aviation and aerospace industry for structural components in the airplane which makes recycling increasingly valuable for these companies as they can reuse the material for different purposes at its end of life and effectively create a closed loop system.

A recent news publication shows covestro commitment to recycling CFRTP by partnering with recycling specialist carboNXT. CarboNXT developed a process that allows the waste to be processed on an industrial scale and Covestro is seeking to implement this process to eliminate production waste. (Compositeworld,2021)

With the seat's lifetime being around 10 years we can be hopeful that by then recycling of this material has become commonplace in the aviation industry. Especially since its excellent performance and recycling ability could be a gamechanger in working towards a sustainable future.

Fig. 77. Naked frame

Tray Table

The tray table is also made of the CFRTP Maezio. The traytable consists of two thermoformed shells welded together with a honeycomb sandwich structure of polycarbonate on the inside, which is the same material as Maezio's matrix resin, so it does not affect recyclability but ensures additional necessary rigidity. see fig 78.

Legs

The seat legs will be made with investment casting as this allows to produce a complex and detailed topologically optimized metal part without using expensive metal printing. Instead of 3d printing the complex geometry directly in metal a 3d printed wax model is used in the centuries old lost wax technique. This makes it possible to achieve complex geometry in an economical way. Autodesk did a case-study on this in 2017 where they were able to achieve 30% on a seat part that combined the legs and spreaders. (Autodesk,2017)

Fig. 78. Traytable with PC-honeycomb

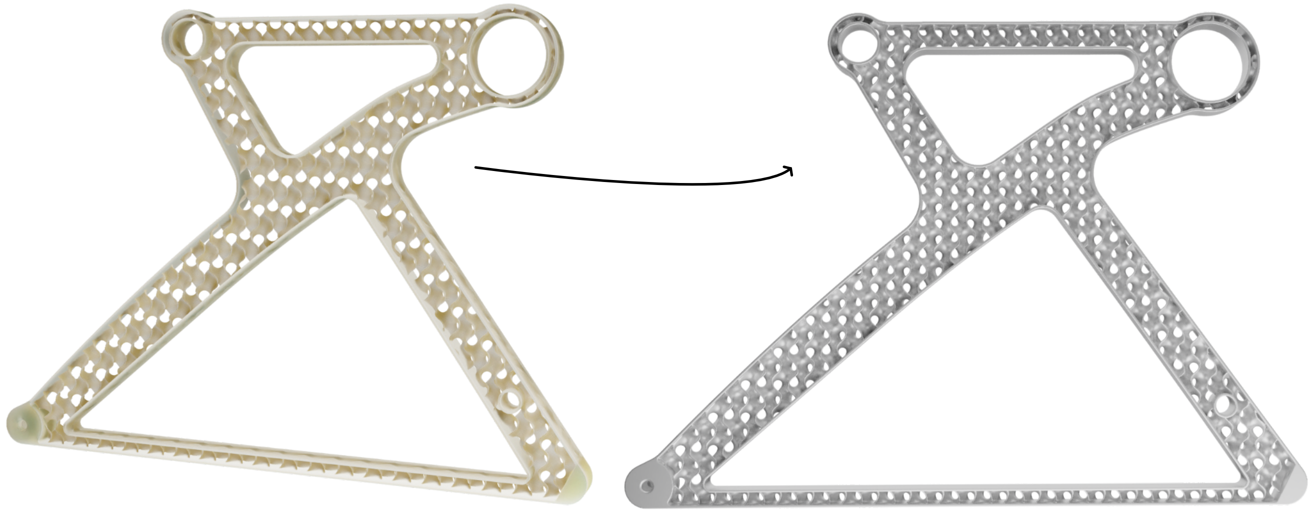


Fig. 79. Wax and casted seat leg

Comfort-materials

Dynaflex is a sustainable suspension fabric made of 100% polyester and specially developed for aircraft seat applications.(acmemills.com,2021)

It was chosen as the seat suspension instead of seat cushions, allowing for a significant weight reduction. As seen in chapter 2.3 with seat cushions weighing around 900 grams using dynaflex can reduce this to just 120 gram as dynaflex weight ranges from 600 to 700g/m2 (innovasio.com,2021)

The yarns of Dynaflex are bonded together so that they act as a spring set and allow for a comfortable yet supportive sitting experience. Current economy slimline seats such as Recaro already use this type of material together with a thin layer of foam to make the backrest less thick. However, Ames, the manufacturer, says it can also be used on its own, just like office chairs such as the Herman Miller Aeron have a suspension mesh.

The material is available with a flame retardant finish and is certified for use in aircraft and passes the dynamic crash test and all smoke, flame and toxicity tests. Next to this being 100% polyester makes it recyclable.

As a cover material Climatex® LifeguardFR™ was chosen, this fabric is the sustainable alternative of Lantals Airworthiness certified wool blend seat cover material. It consists of 50% wool, 50% viscose. The material is fully biodegradable and offers excellent comfort properties such as breatbility, moisture transport and absorption. For added comfort the material can also be outfitted with graphite foam. The fabrics weigh 350 g/m2 (Lantal.com,2021) .

Fig. 80. Seat suspension with dynaflex fabric

Material Look and feel

Frame

For the look and feel of the seat the design aim is to be minimal, approachable and comfortable looking, while also reflecting sustainability through innovation.

With the dark CFRTP frame being one of the main components, the look and feel of this dominant material can play a big role in the overall appearance. The CFRTP Maezio from covestro was chosen for not only its high performance characteristics but also the wide range of surface finishes the material has. Maezio's finishes include fiber color, resin color, in-mold texture, painting, coating and debossing, printing and laser marking.

Changing the polycarbonate resin color to a lighter PC resin than black could be a way to uplift the dark appearance of carbon fiber and create a material appearance unique to the airline brand. The visual fibers give Maezio an organic, wood like appearance while its reflectivity and Class-A surface finish resembles metals. This combination of Modern & high tech with organic fits the vision of the seat which is to create sustainability through innovation. In terms of feel Maezio is cool to the touch like metals giving it a premium feeling. fig x shows an overview of some of the Maezio finishes.

Cover textile

For the cover textile a bright color and pattern is important. Comfort chapter 3.4 showed that Bright coloured seats are perceived as more comfortable on the first impression than darker colours (Bronkhorst (2001)) and Nigel Goode, head of design at Priestmangoode, believes that and that patterned fabrics are also preferred over plain ones for seat covers because they effectively mask wear that has accumulated over the years.

Fig. 81. Maezio material finishes

10.5 Concept evaluation

Structural analysis

The final concept was developed in CAD to a level where its frame could be tested structurally and the weight could be estimated. The focus of the validation lies on the frame as its design is unproven and it is the part with the largest weight influence. .

The structural test is carried out in Solidworks with a static FEA using the static safety requirement from chapter 2.5. No structural tests are made for the rest of the seat parts due to time limitations.

In the structural test the seat and occupant undergo the following forces separately according to

CS 25.561 EMERGENCY LANDING CONDITIONS.

Upward: 3·0g

Forward: 9·0g

Side: 4·0g on the seats and attachments

Downward: 6·0g

Rearward: 1·5g

CS 25.561 states that 'the structural calculation and testing of seats and their supporting structures may be determined by assuming that the critical load acts in the forward, lateral, downward, upward, and backward directions of the emergency landing conditions act separately or by using selected combinations of loads if the required strength is demonstrated in each specified direction.'

'The seats and supporting structure must not deform under these forces to the extent that rapid evacuation of the occupants is impeded.'

Structural analysis 1

For the first test the forward 9g and downward 6g forces were used in combination as a static gravitational force.

A passenger load of 77 kg was applied according to the regulation from chapter 2.5. This is becuase when simulating the tests, the structural capacity of the seat should be designed for the 50 percentile (77 kg), as this protects the broadest range of occupants, Aircraft seats optimized for extremes such as p95 or p5 would have stiffness characteristics incompatible with the other extreme.

Material

The following material properties were used for the FEA simulation, taken from the mechanical properties of Maezio® CF FR 1000T, a yield strength also had to be entered in Solidworks, but Maezio has no yield point, therefore an arbitrary value of 270 Mpa was chosen, which is below the yield point of aluminum.

To verify the structural integrity, the stress simulation was compared to the tensile strength and flexural strenght values of Maezio.

A symmetrical fiber orientation of 16 plies was chosen, with tape plies of 0.17 mm each varying in fiber orientations of 0°, 45° and 90° degrees. The total shell has a thickness of 2.72 mm.

Material	Maezio® CF FR 1000T
Tensile modulus 0° Mpa	108000
Tensile modulus 90° Mpa	6000
Tensile strength 0° Mpa	1500
Tensile strength 90° Mpa	25
Flexural strength 0° Mpa	900
Flexural strenght 90° Mpa	40
Shear strength +/-45° Mpa	40
Shear modulus	2900
Poisson's ratio	0.35
Density g/cm3	1.5

Maezio® CF FR 1000T mechanical properties (thermoplasticcomposites.de,2021)

Stress (fig.82)

The maximum stress value is 60.7 Mpa, which is below the tensile strength of 1500 Mpa in the 0° direction, but above the tensile strength of 25 Mpa in the 90° direction. However, by using a multiply arrangement with different fiber orientation angles, there is effectively no area only in the 90° direction. Thus it can be assumed that the seat will still be more than stiff enough

For the flexural strength, the value is just above the 40 Mpa of the 90° direction and far below the flexural strength in the 0° direction of 2900 Mpa. From this we can assume that it should be structurally possible to make an airline seat frame with this material.

Displacement (fig.83)

The displacement results show no excessive displacement that would prevent rapid evacuation. In the image, it is clear that the top half of the frame deflects to absorb the energy, the sides at the edge deflect the most and can be reinforced with ribs or additional layers of Maezio through an automated tape-laying process.

In appendix an extra simulations can be found, with the 9.0g forward force and the 4.0 g sideway force.

Conclusion:

All FEA analysis gave results with no exsesive stresses or deformation. From these results we can assume that it should be possible to make an airline seat-shell frame with this CFRTP material. However dynamic testing is necessary to further validate this and see where design changes or structural reinforcements are necessary.

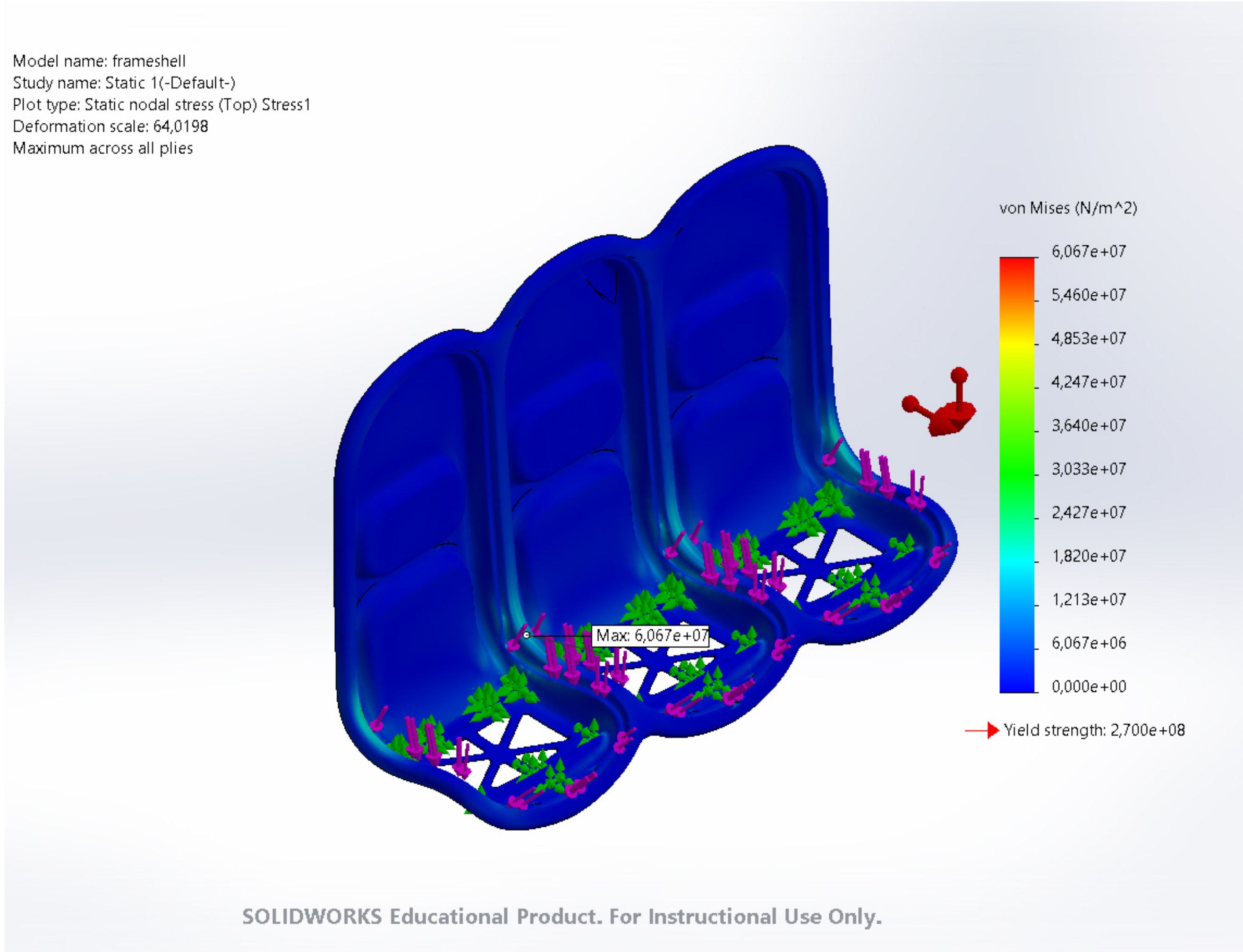


Fig. 82. Stress result

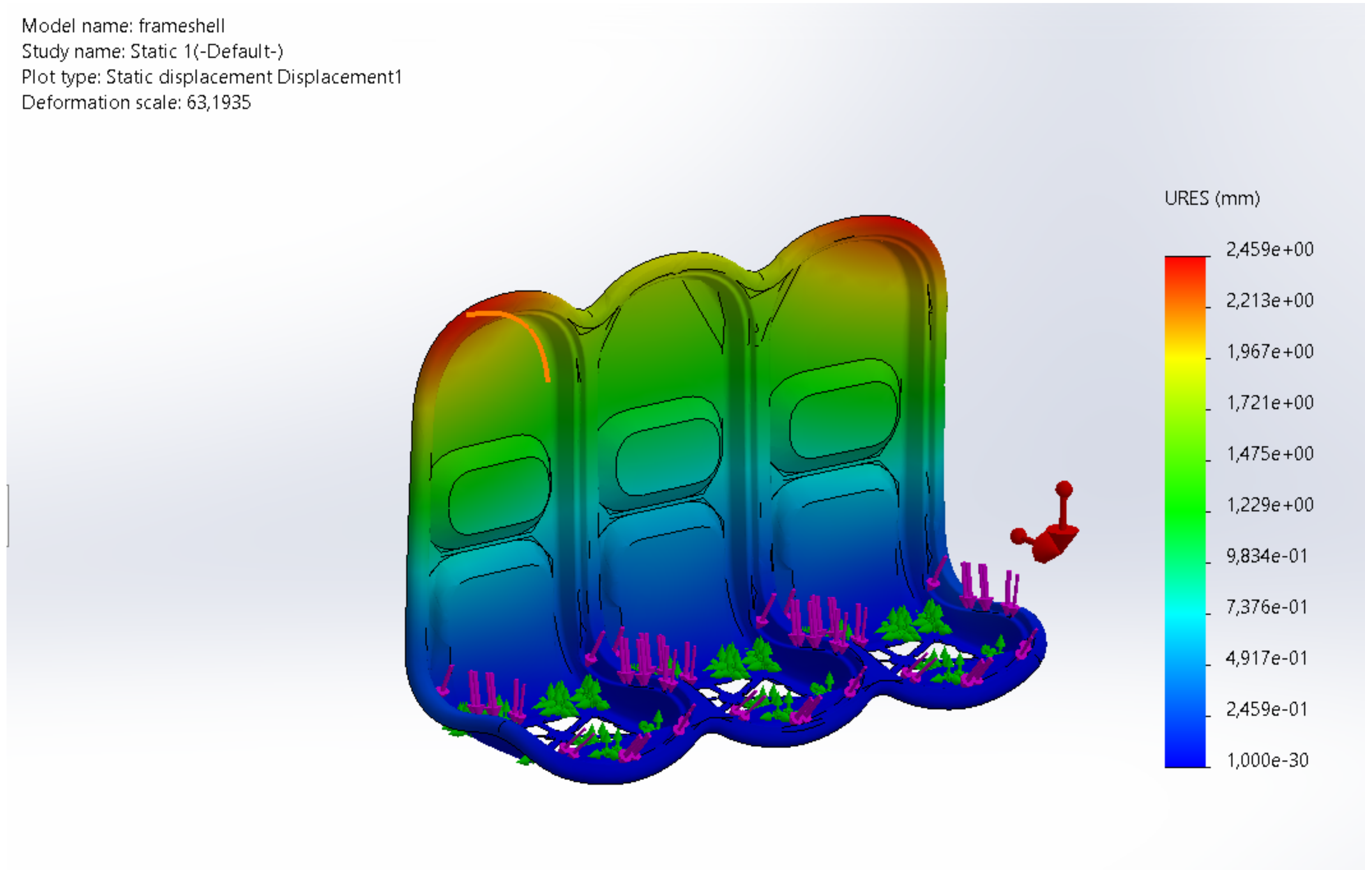


Fig. 83. Displacement result

10.6 Weight estimate

Based on the CAD design, the volume of the parts and the material density, the weight of the complete bench seat was estimated to be 20.22 kg.

One seat has an estimated weight of 6.7 kg. This weight includes the tray table and the storage bag for personal items. If the chair is stripped down to its essentials and these parts are removed, we end up with a starting weight of 6.3 kg.

With this weight of about 6.5 kg, the seat falls between 4 and 8 kg, as established by the benchmarking of Chapter 2.7. Fig 84 and table x give an overview of the complete breakdown. And show that optimization of the frame, which accounts for 55% of the total weight, has the most potential for further weight reduction.

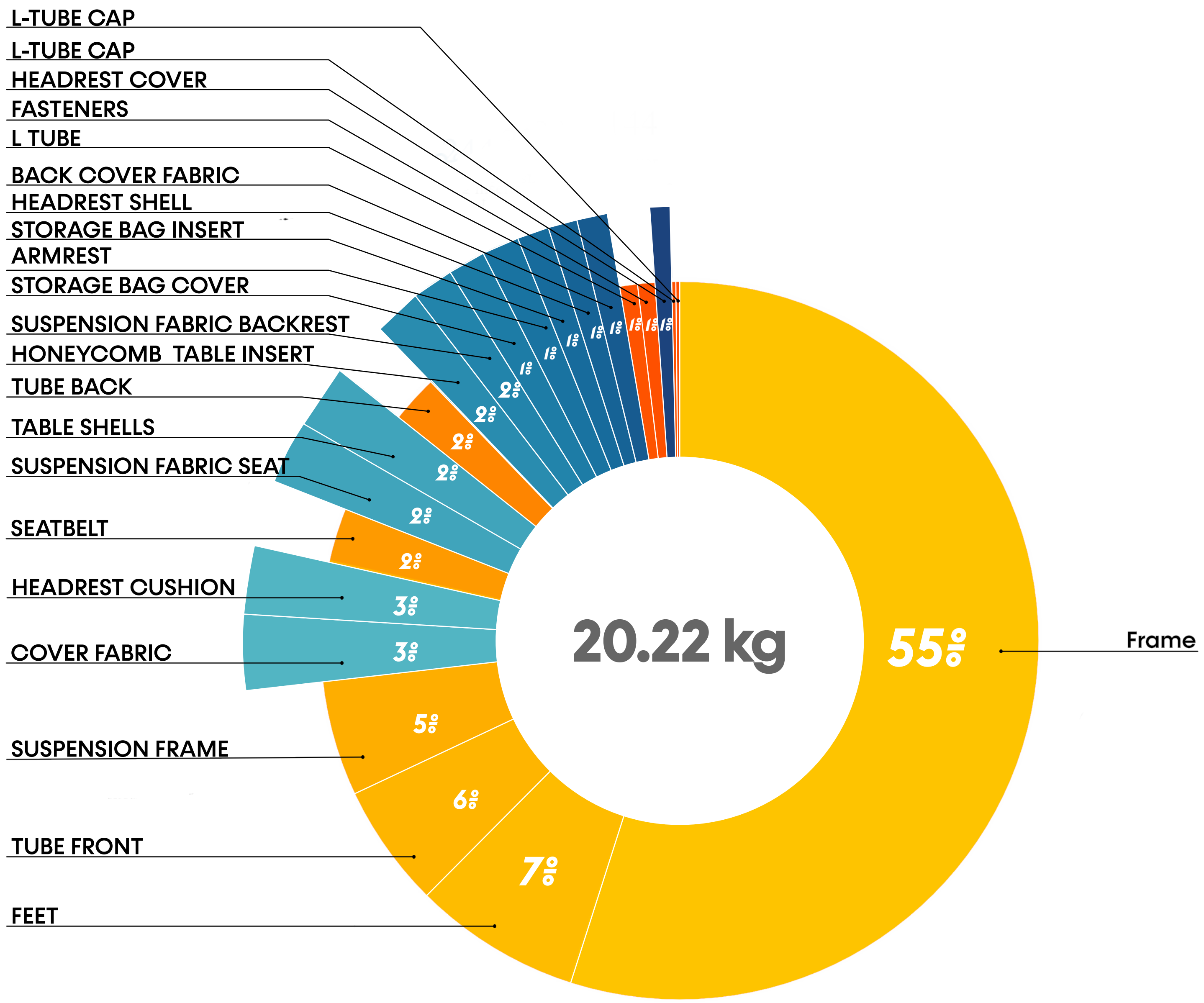


Fig. 84. Pie chart with weight breakdown of final concept

Part	material	Weight (g)	number	Tot. Weight (g)	% of tot. weight
Frame	Maezio (CFRTP)	11118	1	11118	55%
suspension headrest frame	Aluminium	353,7	3	1061,1	5%
Suspension fabric backrest	polyster	104	3	312	2%
Suspension fabric seat	polyster	156	3	468	2%
cover fabric	Wool Blend	189	3	567	3%
Back cover fabric	E-leather	220	1	220	1%
Headrest shell	Maezio (CFRTP)	75	3	225	1%
Headrest cushion	Polyurethane foam	170	3	510	3%
Headrest cover	E-leather	48	3	144	1%
Table shells	Maezio (CFRTP)	154,5	3	463,5	2%
Honeycomb	PC	117,6	3	352,8	2%
armrest	Maezio (CFRTP)	70,5	4	282	1%
seatbelt	stainless steel	167	3	501	2%
Personal items storage bag cover	E-leather	96	3	288	1%
Personal items storage bag inserts	PC	81,6	3	244,8	1%
feet	Cast Aluminium	756	2	1512	7%
L tube	CFRTP	159	1	159	1%
Ltube cap back	ABS	23	2	46	0%
Ltube cap front	ABS	15	2	30	0%
Tube back	CFRTP	439,5	1	439,5	2%
Tube front	CFRTP	1114,5	1	1114,5	6%
Fasteners	stainless steel	158	1	158	1%
Total 3 seats				20216,2	
weight 1 seat				6739	

Structural parts

Non-structural parts

Fig. 85. Table with weight breakdown of final concept

11. Ergonomic mockup

A simplified ergonomic model was made to evaluate the main dimensions and suspension backrest position, size, and overall feel. A lightweight spring steel frame was made as a prototype of this suspension system, and a net was stretched over it as a replacement for the Dynaflex suspension fabric.

The main concept attribute to evaluate with this mockup was if the seat-back suspension could be a valid alternative to the replacement for foam backrests of conventional airline seats.

Five adults with different heights and body size tested the model; Their feedback provided valuable insight on the sitting experience of the concept in its current state.

Conclusion

The outcome of this small-scale test was that the backrest suspension was perceived as pleasant by all participants. They noted the supportive feeling and the suspending, springy feel. No excessive pressure points were observed, and the back did not notice the edge of the frame.

A point of improvement that came from this evaluation is the seat depth being too short. The seat depth now is 450 mm. However, since the backrest puts the passenger slightly more forward, the actual usable seat depth is less; therefore, the lower part of the upper legs stay unsupported.

The armrests in the concept are shorter than conventional armrests, so it was essential to see where they were too short. In most cases, the armrest was long enough; however, one participant said that the armrests could be about an inch longer.

This was a small ergonomic evaluation, and The armrest length should also be tested further with neighbouring passengers. This could require the armrests of the middle seats to be longer since they are shared.

Furthermore, a test with the Dynaflex fabric material and the suspension of the seat bottom is necessary to test the comfort over an extended period.

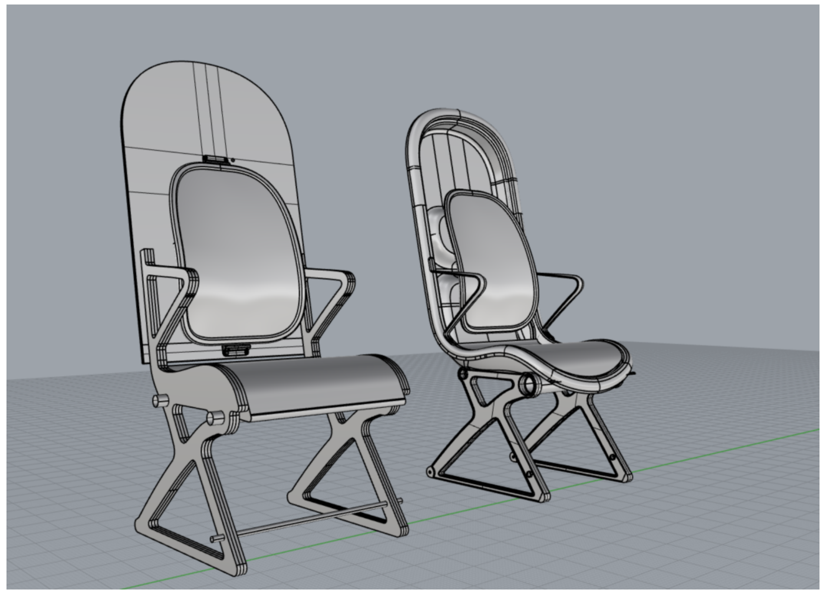


Fig. 86. Cad simplification of Mockup model

Fig. 87. Ergonomic test model

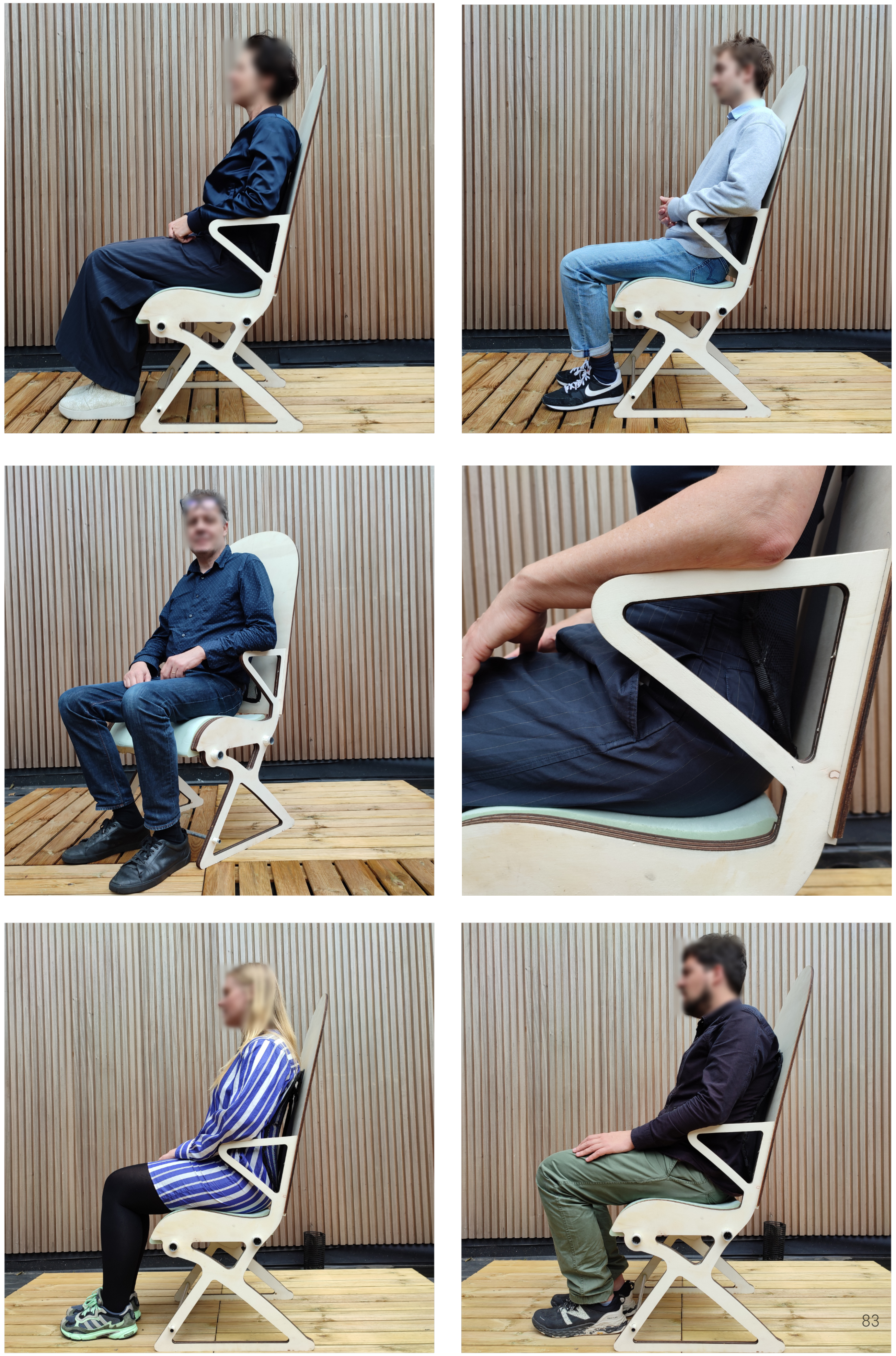


Fig. 87. Different test subjects sitting on the ergonomic model

12. Evaluation LOR

Requirements lightweighting

Requirement	Evaluation
The seat should aim for a reduction in 40% of the mass compared to the reference seat.	✔ yes ,seat weight is reduced by 43%.

Requirements comfort

Requirement	Evaluation
The seat should offer better passenger comfort to current economy class seating.	✔ The suspension follows the shape of the back and allows micro movements. Potentially offering improved comfort.
The seat should offer adequate personal space.	✔ Yes, see chapter 10.3
The seat should offer adequate hip and shoulder space from p5 to p95	✔ Yes, see chapter 10.3
The concept should offer comfort to a wide demographic.(P5 to P95)	✔ Yes, the concept was eevaluated with P5,P50,P95.
Passenger comfort can not be imposed by the surrounding seats.	✔ The seat has a fixed imposing on others passengers is not possible.
The seat must support eating and drinking activities.	✔ There is a traytable.
The seat must support storage of personal items.	✔ There is a cavity in the frame which holds a bag for personal items.
Comfort materials should be breathable.	✔
Seat should support BYOD.	✔ There is the possible to prop up a phone
The seat should have a bright colour.	✔ The fabric is customizable to the airlines wish.

Requirements hygiene

Requirement	Evaluation
The concept should minimize seams and gaps that can accumulate dirt.	✔ Seams and gaps are minimzed
Products should be easily cleanable.	✔ Fabrics are detachable and CFRTP frame is easely cleanable.

Requirements safety

Requirement	Evaluation
Each seat and its supporting structure, and each safety belt or harness and its anchorage must be designed for an occupant weight of 77 kg.	✔ Frame was tested with FEA with an added occupant weight of 77 kg per passenger.
Structurally the seat and its attachments should comply with CS 25.561 inertial forces and can't deform to the point where it would impede rapid evacuation.	✔ The deformations of the frame was tested in chapter 10.5 with FEA. Seat attachments are not tested becuase of time limitations.
Aisle width should be minimum 38cm in between seats at points less than 64cm from the floor and minimum 51 from 64cm and above.	✔ These seats dimensions comply with these constraints.
Seat materials should be self-extinguishing.	✔ yes, only regulatory approved materials are used.
Each seat belt must have a metal-to-metal locking mechanism.	✔ yes
If seat backs do not provide a handhold, a handle or handrail should be provided along each aisle to allow persons to stand during use of the aisles.	✔ The seat back rounded top provides a handhold.
The seat angle cant exceed 18-degree angle with the vertical plane containing the aeroplane centreline so no costly airbags are required.	✔ Seat angle is 0-degree
No seat part must touch the sidewall of the cabin	✔ Dimensions fit within cabin size of Boeing 737 and Airbus A320 neo and dont touch side walls.

Requirements sustainability

Requirement	Evaluation
The seat should be designed for durablility.	✔
Comfort materials should mask wear that has accumulated over the years and high wear components such as "comfort materials" should be upgradable.	✔
Electronics must be able to be swapped without destroying the rest of the product.	✔ The seat has no electronics.
The product should be able to be re- and disaambled without destroying any parts or the overall structural integrity of the seat.	✔
The product should be able to be disassembled to its separate materials components.	✔ Only 3 different type of fasteners are used throughout the design.
The seat must be disassembled with a maximum of 3 tools.	✔
All fasteners must be metric.	✔
For ease of maintenance, seat comfort materials should be able to be dissemblable (for example for cleaning) in a quick and easy way without disassembling structural components.	✔ By detaching the alluminium inner frame which houses the cover fabric this is possible.
All seat materials should be recyclable	✔ All materials are materials used are recylable.

13. Industry feedback

Industry feedback and recommendations

Since the project was conducted without a company's involvement, it was essential to validate the final design by approaching the aviation industry and presenting the result. A presentation was held for representatives from Airbus, Collins Aerospace and Jetaviation.
The overall reaction to the concept was positive and feasible.

The following is a summary of the main feedback points:

Positives

- The functional flexibility of the frame, which acts as a modular platform with many variations that can be made by the airlines.
- The ability of the design to weigh only about 6.5 kg with a fresh perspective on structure and comfort.
- Having a structural frame that can be made from a single component with potentional for economic benefits in production.

Points of improvement.

- The manufacturing method of the seat legs is not allowed by regulation. It was mentioned that seat-manufacturers are not allowed to use investment casting for structural parts because this manufacturing method could lead to irregularities that could compromise structural integrity. Therefore, it was recommended that the seatl egs be redesigned to a design suitable for CNC milling, or metal extrusion.
- A tray table lock and stronger hinge mechanism were recommended because aircraft turbulence could cause the hinge to loosen and the table to open unintentionally.
- Folding armrests were recommended. While the current armrests are very light, concerns were raised about lateral accessibility for the disabled.
- From an aesthetic standpoint, different cultures and airlines might prefer different styles and find the top of the frame too round. This could be a potential design recommendation depending on the target airline.
- The seat should have an alocated space for a life vest.
- An eye-level phone holder was recommended, but it should be designed so that it does not interfere with head impact during emergency situations.
- The front of the seat frame should curve slightly downward and backward to make it easier for people to place angle their towards the seat.
- Flax composite was recommended as a more durable alternative to the current CFRTP frame material.

Project reflection & recommendations

In addition to the industry recommendations, some recommendations were derived from reflecting on the concept evaluation in chapter 10.5. These are necessary design iterations, for which there was no time left in this project to explore them further.

The following summarises the next steps needed to move this project forward, arranged by thematic area.:

Sustainability
Although recyclability, ease of maintenance, and disassembly and reassembly have been considered in the design, a thorough sustainability evaluation of the seat should be conducted - for example, a life cycle analysis to see where sustainability can be further improved.

Comfort
The findings from testing the ergonomic mock-up provided the valuable insight that the seat depth is not deep enough and the armrests are too short. This is a necessary design change, along with the change proposed in the feedback meeting to a more curved frame at the legs. In addition, lightweight folding armrests that can be operated sideways should be developed and a secure phone holder at eye level that is safe with any head impact during emergency conditions.

Following these modifications, ideally, a prototype should be created that represents a complete bench. This ergonomic prototype should have a complete suspension system and upholstery fabric and check whether 450 mm is sufficient for the width of the seat. In addition, this prototype should also be used to assess discomfort over extended periods of time and analyze the use of the seat with surrounding passengers, especially at the level of the armrests.

Lightweighting
There is still room for more weight savings. The aluminium inner frame is relatively heavy in contrast to its limited functionality. The attachment of the upholstery fabric suspension and the seat suspension is something that the composite structure could consolidate. Furthermore, the legs of modern seats should be studied and benchmarked to find a light and economical alternative to cast legs, which are not allowed by regulation. Finally, the seat frame, which accounts for 55% of the weight, is the most amenable to design optimization. The incorporation of tape layering could further reduce the mass of this large component.

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- **Fig.50**: Vink, P. (n.d.-b). Ideal backrest contour [illustration]. Retrieved from https://www.tudelft.nl/io/onderzoek/research-labs/aviation/research/designing-comfortable-passenger-seats
- **Fig.51**: [Illustration]. (n.d.). Honeycomb sandwich. Retrieved from https://www.researchgate.net/figure/Schematic-of-sandwich-panel-with-honeycomb-core_fig2_275378358
- **Fig.52**: [Illustration]. (n.d.). honeycomb. Retrieved from http://staff.um.edu.mt/jgri1/auxetic/auxetic_f2.html
- **Fig.53**: [Illustration]. (n.d.). auxetic honeycomb. Retrieved from http://staff.um.edu.mt/jgri1/auxetic/auxetic_f2.html
- **Fig.54**: [Photo]. (n.d.). octet lattice. Retrieved from https://www.migueloptimization.com/posts/lattice-design/
- **Fig.55**: [Image]. (n.d.). Gyroid. Retrieved from https://www.sciencedirect.com/
- **Fig.56**: [Illustration]. (n.d.). part consoldiation. Retrieved from https://link.springer.com/chapter/10.1007/978-981-13-8281-9_5
- **Fig.57**: [Photo]. (n.d.). Toplogy optimization. Retrieved from https://www.materialise.com/en/software/solutions-for-design/post-topology-optimization
- **Fig.58**:[Photo]. (n.d.). isogrid tank. Retrieved from https://medium.com/@matmatch/elon-musk-revolutionising-space-transportation-with-stainless-steel-120514bed8b0

COW calculation

```
> restart;
> COW := 0.035;
  mass_economy_seat := 10;
  yearly_seat_kilometers := 19256·10^6;
  Cruisingspeed := 811;
  Fuel_cost := 0.4;
  Total_seats := 7658;
  Total_narrowbody_aircraft := 42;
  Average_amount_seats := Total_seats / Total_narrowbody_aircraft;
```

$$COW := 0.035$$
$$mass\_economy\_seat := 10$$
$$yearly\_seat\_kilometers := 19256000000$$
$$Cruisingspeed := 811$$
$$Fuel\_cost := 0.4$$
$$Total\_seats := 7658$$
$$Total\_narrowbody\_aircraft := 42$$
$$Average\_amount\_seats := \frac{547}{3}$$

> $yearly\_fly\_hours := evalf\left(\frac{yearly\_seat\_kilometers}{Cruisingspeed}\right);$

$$yearly\_fly\_hours := 2.374352651\ 10^{7}$$

> $Totalfuel\_seats := yearly\_fly\_hours \cdot COW \cdot mass\_economy\_seat;$

$$Totalfuel\_seats := 8.310234278\ 10^{6}$$

> $Totalfuelcost\_seats := Totalfuel\_seats \cdot 0.4;$

$$Totalfuelcost\_seats := 3.324093711\ 10^{6}$$

> $single\_Fuel\_seatcost := \frac{Totalfuelcost\_seats}{Total\_seats};$

$$single\_Fuel\_seatcost := 434.0681263$$

Weight calculation Reference seat

Seat foam	PU Foam	912	3	2736	8%
Upholstery	Textile	949	3	2847	8%
Table	Plastic	912	3	2736	8%
Table arm	Plastic	125	6	750	2%
armrest outer	Aluminium	886	2	1772	5%
armrest inner	Aluminium	800	2	1600	5%
seatbelt	steel	279	3	837	2%
Bracket v1	Aluminium	885	1	885	3%
Bracket v2	Aluminium	989	2	1978	6%
Bracket v3	Aluminium	1249	1	1249	4%
Seat tube	Aluminium	229	3	687	2%
Seat fabric spanner	Nylon	121	3	363	1%
Air spring	mostly steel	325	3	975	3%
Feet bar	Aluminium	298	2	596	2%
Frame (feet)	Aluminium	1665	2	3330	10%
L tube	Aluminium	550	1	550	2%
Tubes	Aluminium	2444	1	2444	7%
Total 3 seats				35035	
weight 1 seat				11678	

Weight calculation final design

Part	Part Volume cm3	material	material density g/cm3	weight	number	Tot. weight	% of weight
Frame	7412	Maezio (CFRTP)	1,5	11118	1	11118	55%
suspension/headrest frame	131	Aluminium	2,7	353,7	3	1061,1	5%
Suspension fabric backrest	0,16	polyster	650	104	3	312	2%
Suspension fabric seat	0,24	polyster	650	156	3	468	2%
cover fabric	0,54	Wool Blend	350	189	3	567	3%
Back cover fabric	0,55	E-leather	400	220	1	220	1%
Headrest shell	50	Maezio (CFRTP)	1,5	75	3	225	1%
Headrest cushion	2125	Polyurethane foam	0,08	170	3	510	3%
Headrest cover	0,12	E-leather	400	48	3	144	1%
Table shells	103	Maezio (CFRTP)	1,5	154,5	3	463,5	2%
Honeycomb	98	Polycarbonate	1,2	117,6	3	352,8	2%
armrest	47	Maezio (CFRTP)	1,5	70,5	4	282	1%
seatbelt		stainless steel	7,9	167	3	501	2%
Personal items storage bag cover	0,24	E-leather	400	96	3	288	1%
Personal items storage bag inserts	68	Polycarbonate	1,2	81,6	3	244,8	1%
Frame (feet)	280	Cast Aluminium	2,7	756	2	1512	7%
L tube	106	CFRTP	1,5	159	1	159	1%
Ltube cap back	23	ABS	1	23	2	46	0%
Ltube cap front	15	ABS	1	15	2	30	0%
Tube back	293	CFRTP	1,5	439,5	1	439,5	2%
Tube front	743	CFRTP	1,5	1114,5	1	1114,5	6%
Fasteners	20	stainless steel	7,9	158	1	158	1%
Total 3 seats						20216,2	
weight 1 seat						6739	

Seat benchmarking

Recaro
SL3710

Class: Economy
Duration: Short & medium haul
Weight: 8 kg
Recline: Fixed at 15°
IFE: No
Usb-charging: No
Headrest: No

Traytable: yes
Calf rest: no
Footrest: no
Literature pocket: no
Micro-nest: no
Extra: Modular

Recaro
BL3710

Class: Economy
Duration: Short & medium haul
Weight: 10 kg
Recline: yes
IFE: optional
Usb-charging: No
Headrest: 6-way adjustable

Traytable: yes
Calf rest: no
Footrest: no
Literature pocket: no
Micro-nest: no
Extra: Modular

Recaro
BL3530

Class: Economy
Duration: Short & medium haul
Weight: 10 kg
Recline: yes
IFE: optional
Usb-charging: No
Headrest: 6-way adjustable

Traytable: yes
Calf rest: no
Footrest: no
Literature pocket: no
Micro-nest: no
Extra:

Recaro
CL3710

Class: Economy
Duration: Long-haul
Weight: 12 kg
Recline: yes
IFE: yes
Usb-charging: yes
Headrest: Six-way adjustable

Traytable: yes
Calf rest: yes
Footrest: yes
Literature pocket: High
Micro-nest: yes
Extra:

Recaro
PL3530

Class: Economy premium
Duration: Long haul
Weight: /
Recline: yes
IFE: yes
Usb-charging: yes
Headrest: 6-way adjustable

Traytable: yes
Calf rest: yes
Footrest: yes
Literature pocket: High
Micro-nest: yes
Extra:

Expliseat
tiseat

Class: Economy
Duration: Short & medium haul
Weight: 4 kg
Recline: yes
IFE: no
Usb-charging: no
Headrest: mo

Traytable: yes
Calf rest: no
Footrest: no
Literature pocket: no
Micro-nest: no
Extra: only 30 parts

Ideation sketches

Optimares
quadra

Class: Economy
Duration: Long-haul
Weight: 14 kg
Recline: Cradle recline 19°
IFE: yes
Usb-charging: yes
Headrest: adjustable

Traytable: yes
Calf rest: no
Footrest: yes
Literature pocket: low
Micro-nest: no
Extra:

IDEA AIR
one

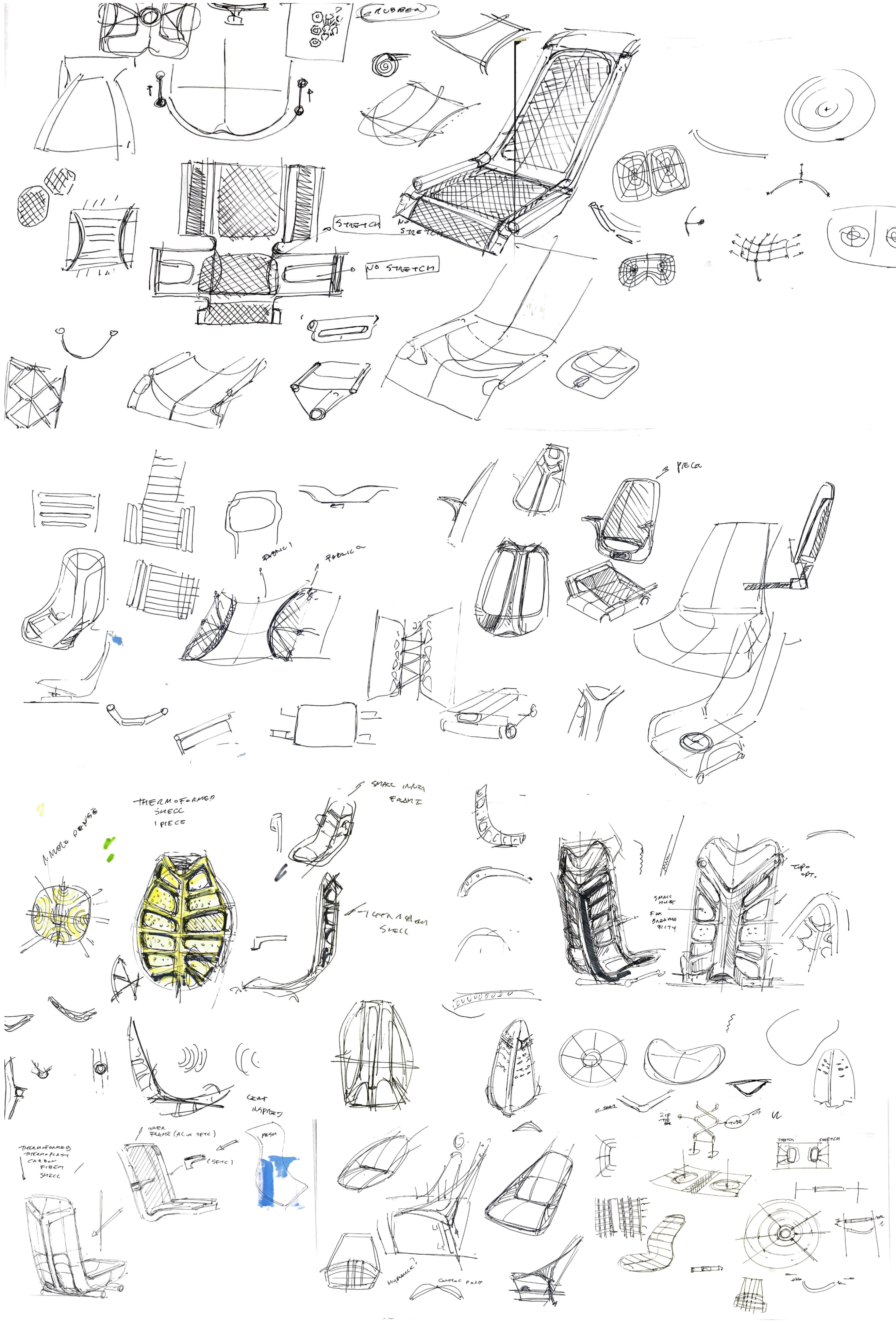
Class: Economy
Duration: short haul
Weight: 8kg
Recline: no
IFE: no
Usb-charging: no
Headrest: no

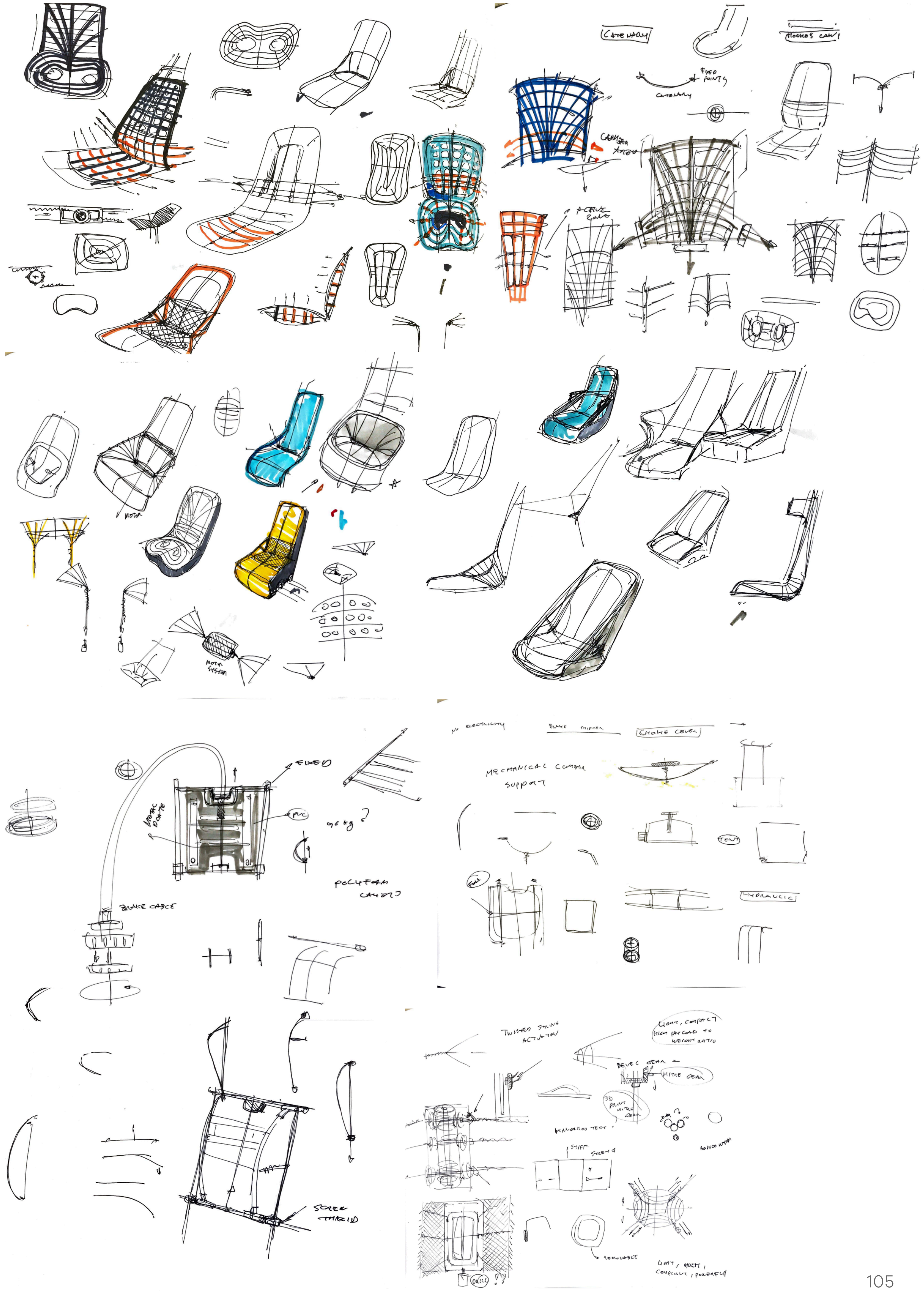
Traytable: yes
Calf rest: no
Footrest: no
Literature pocket: low
Micro-nest: no
Extra:

Mirus
Hawk

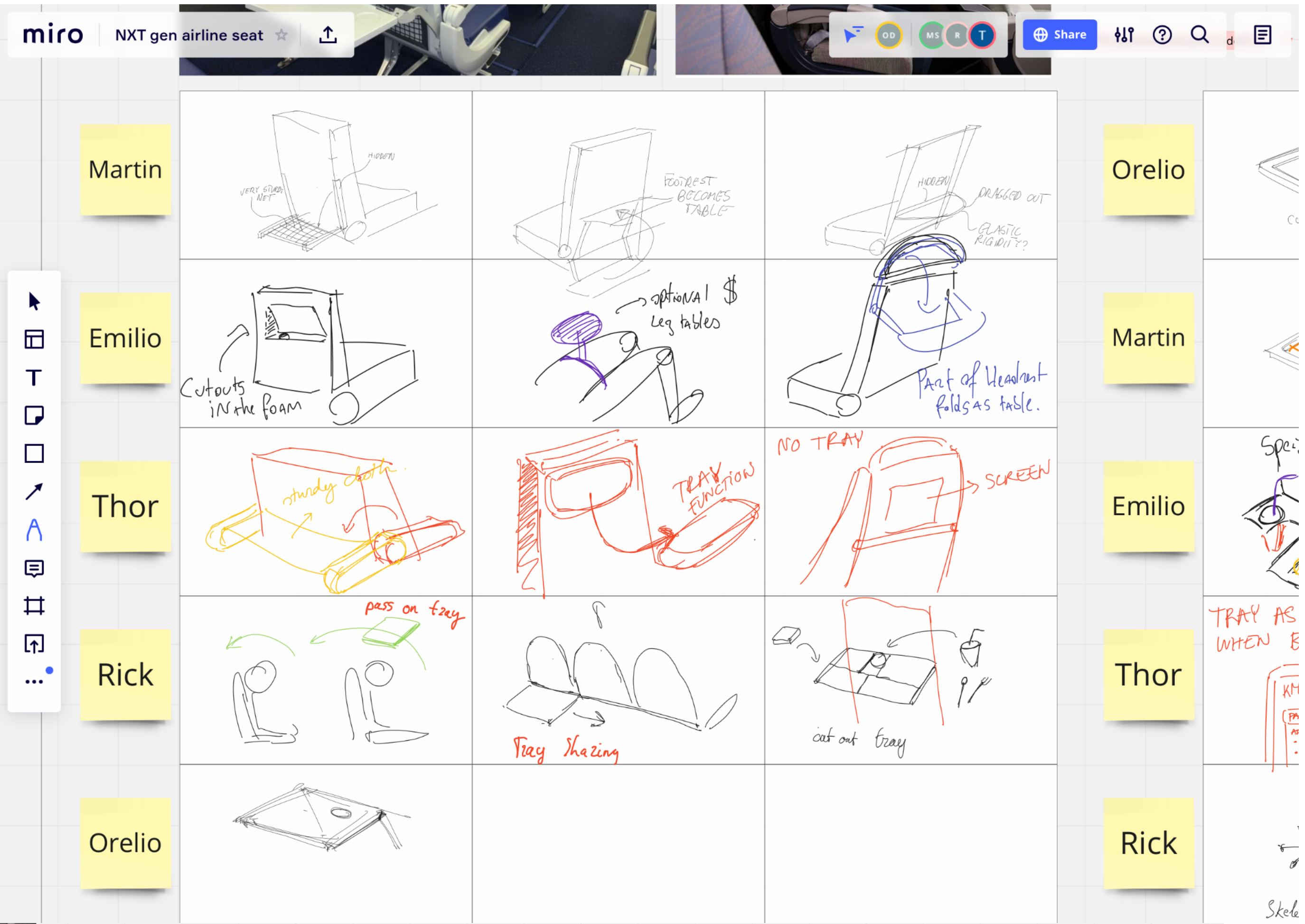
Class: Economy
Duration: Short & medium haul
Weight: /
Recline: 5.7" recline
IFE: no
Usb-charging: option
Headrest: Option,4-way adjustable

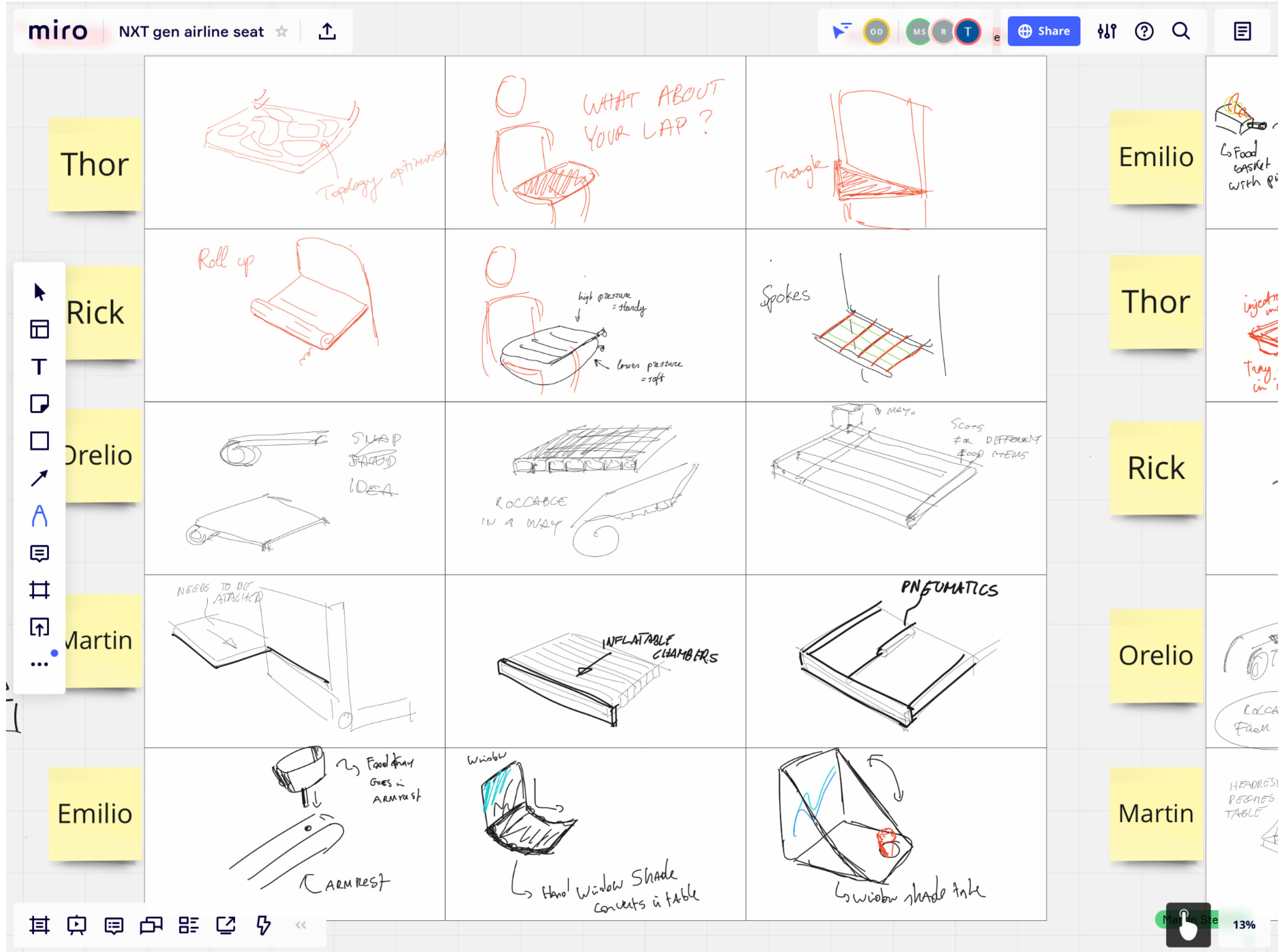
Traytable: yes
Calf rest: no
Footrest: option
Literature pocket: yes, low and high optional
Micro-nest: no
Extra: optional, coat hook, attendant step

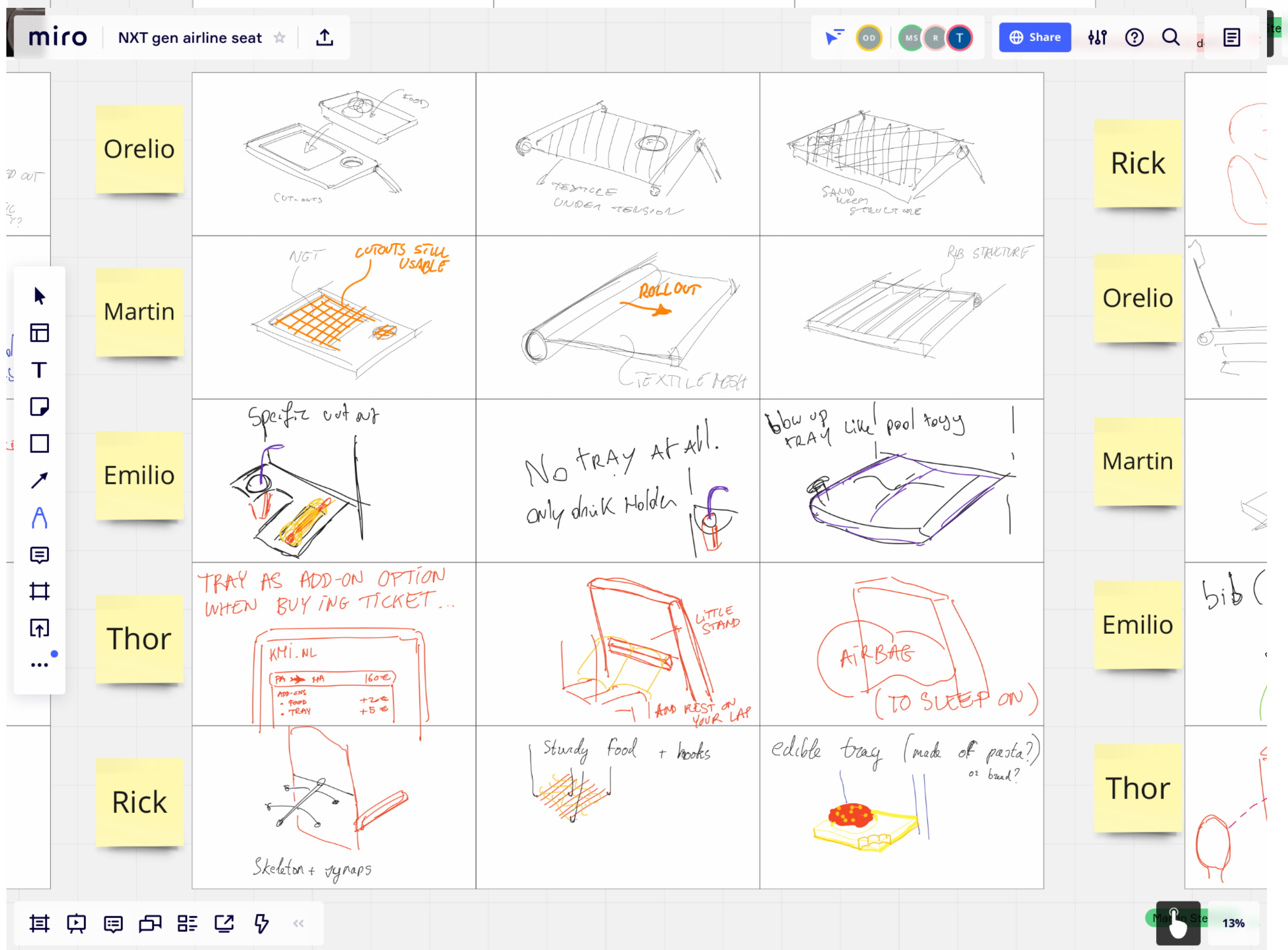

STRETCH
NO STRETCH
THERMOFORMED SHELL 1 PIECE

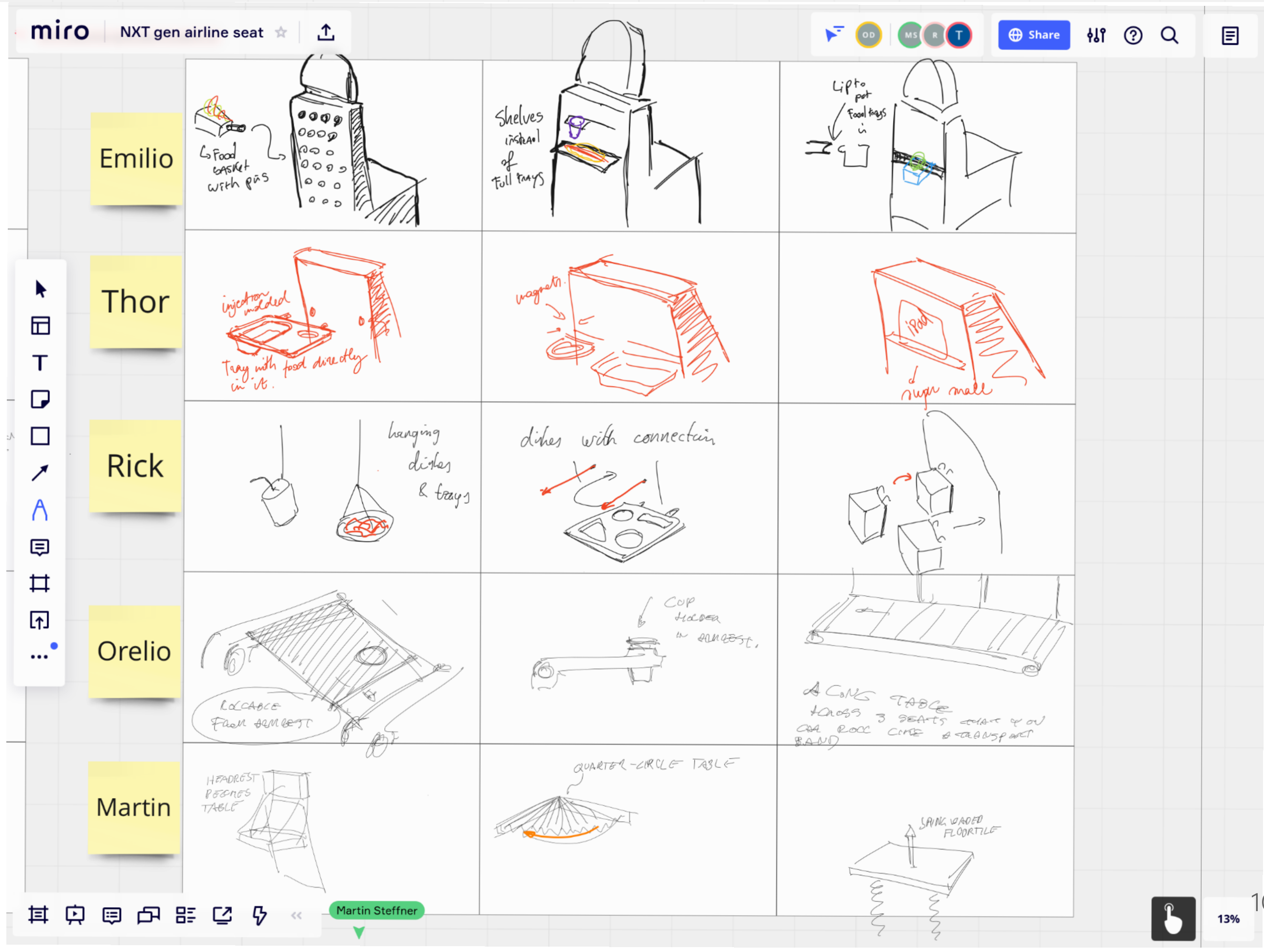

CATENARY
MECHANICAL COMFORT SUPPORT
BRAKE CABLE
HYDRAULIC

3-5-6 brainstorm









Project brief

DESIGN FOR our future

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSCE&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name

initials

student number

street & no.

zipcode & city

country

phone

email

amme (only select the options that apply to you):

: IPD / Dfl / SPD

:

: - - (give date of approval)

: Honours Programme Master

: Medisign

Tech. in Sustainable Design

Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair

** mentor

2nd mentor

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

comments (optional)

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: APPROVED / NOT APPROVED

Procedure: APPROVED / NOT APPROVED

comments

Initials & Name OSD De Jonghe 4794 Student number 4435761

Title of Project Next generation economy airline seat

Next generation economy airline seat — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 2 4 0 2 2-0 2 1 — 1 4 0 7 2-0 2 1 end date

INTRODUCTION**

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

For the last few years, the aviation industry has increasingly been confronted with its impact on the environment concerning their emissions of greenhouse gases.

Flightshame became a popular discussion topic in the media, and it is predicted that more travellers will become aware of the negative impact their flying behaviour has on the environment. (McKinsey, 2020)

Right now, the global aviation sector accounts for 2 per cent of the global carbon footprint and 12 per cent of all transportation sources (atag.org, 2020), in comparison to the 74 per cent for road transportation this may seem like a small number, yet aviation is one of the fastest-growing sources of greenhouse gases. The acceleration in globalization and an inability to innovate as fast as other industries are forcing the aviation sector to make changes.

According to IATA and the United Nations World Tourism Organization (UNWTO), airlines could focus on three areas to address climate change: aircraft efficiency, operations efficiency and alternative fuels.

This project focuses on aircraft efficiency by developing an ultralight aircraft seat for the economy segment during short-haul flights. Weight and fuel-saving are closely related, saving significant cost and carbon emissions. By developing a new ultra-lightweight seat concept I hope to create a design that can benefit the planet, airline companies and its passengers.

space available for images / figures on next page

introduction (continued): space for images

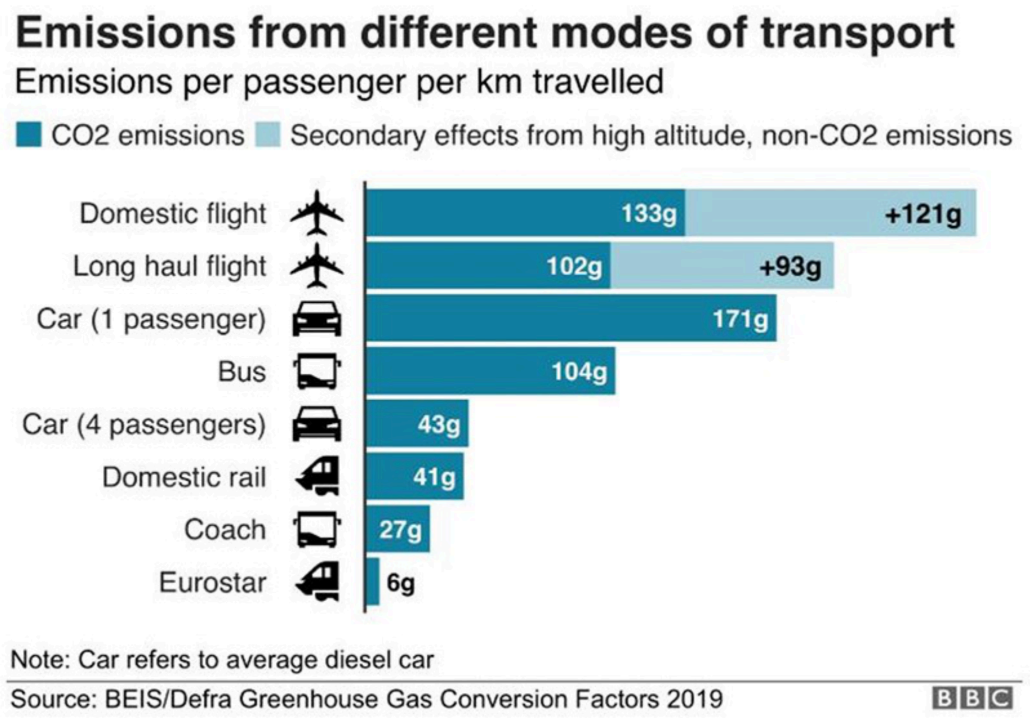


image / figure 1: Emissions from different modes of transport (BEIS-Defta greenhouse gas conversions, 2019).

TO PLACE YOUR IMAGE IN THIS AREA:
- SAVE THIS DOCUMENT TO YOUR COMPUTER AND OPEN IT IN ADOBE READER
- CLICK AREA TO PLACE IMAGE / FIGURE

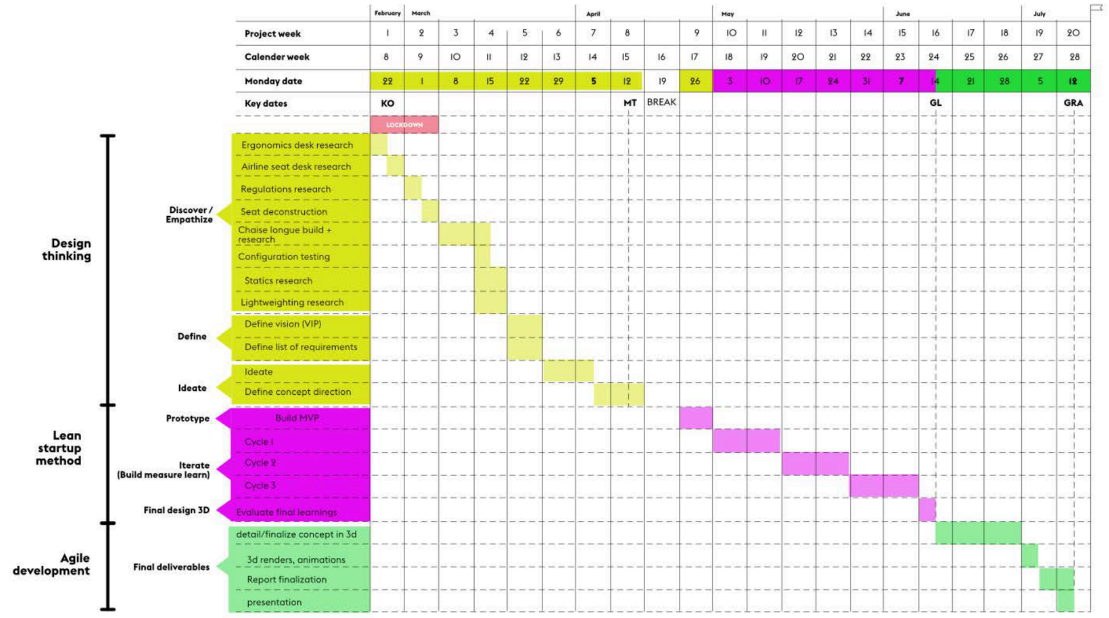
PLEASE NOTE:
- IMAGE WILL SCALE TO FIT AUTOMATICALLY
- NATIVE IMAGE RATIO IS 16:10
- IF YOU EXPERIENCE PROBLEMS IN UPLOADING, COVERT IMAGE TO PDF AND TRY AGAIN

image / figure 2:

PLANNING AND APPROACH*

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 2 4- 2 - 2021 | 1 4 7 - 2021 end date



For this project, I will combine the methods of design thinking, lean startup and agile thinking.

Design thinking will be used in the first phase to explore the topic, empathize with the users, define a clear vision, ideate to come up with solutions and conclude with a clear concept direction.

The lean startup method will be applied to start validating and improving on the concept, by building physical prototypes and iterating on it through 3 repeated cycles of measure, learn and build.

In the final phase, Agile thinking will be used to work towards the final deliverables. Using clearly defined design sprints to work towards the end results which include: The defined 3d model, the presentation material and the finalization of the report.

(In week 8 of the project, after the midterm, there will be a one-week break.)

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

The reason why I chose this project is that I hope the outcome can provide me with a potential springboard to a future career in a mobility design studio focused on developing interiors for trains, planes and buses. Besides, I see an opportunity to explore new advanced design tools and discover how to implement them in my process. Furthermore, this will be a challenging project where I will have to use and eventually be able to demonstrate a large part of my knowledge and skills that I gained in the five years of my design education at TU-Delft.

There are two specific design tools (software) that I want to explore during this project. These two tools are related to computational design, namely Grasshopper and Ntopology. I believe that these tools can provide new opportunities and solutions within complex design spaces. In particular, in areas such as lightweighting and ergonomics.

I am also looking forward to the physical development of the design since a seat is a product that can only be validated and experienced by sitting on it, a hands-on approach by building prototypes and repeatedly evaluating them, will be important.

For me, an aeroplane seat covers my passion to develop a challenging product where aesthetics technology and people intersect. Therefore I am eager to start and see where the design process takes me.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

FEA analysis 1

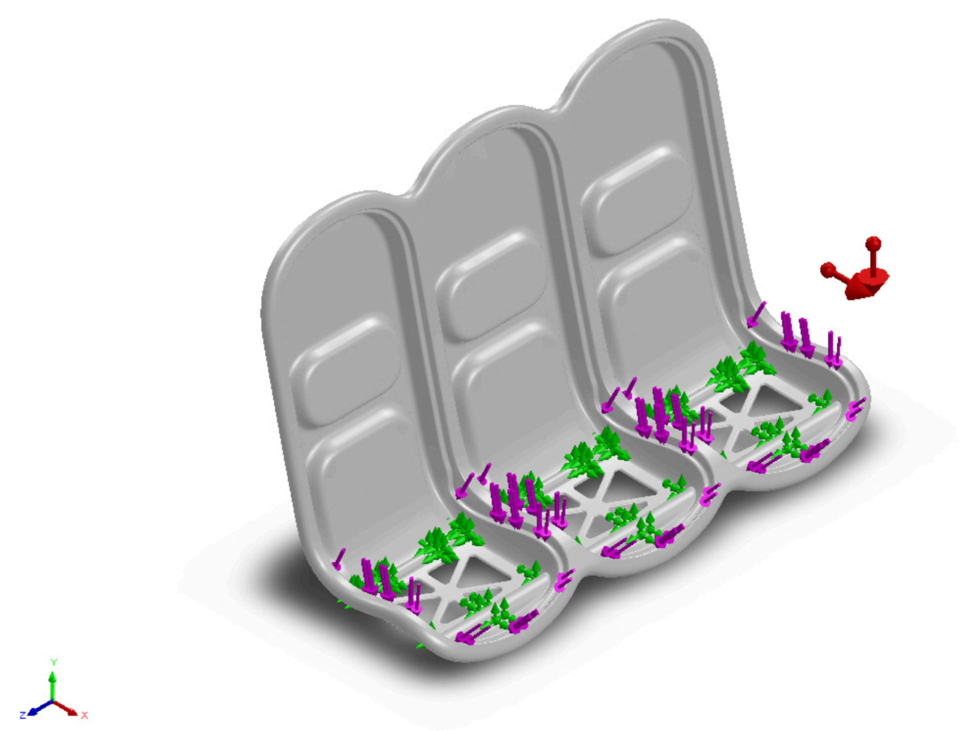
Simulation of frameshell

Date: Thursday, 8 July 2021
Designer: Solidworks
Study name: Static 1
Analysis type: Static

Table of Contents

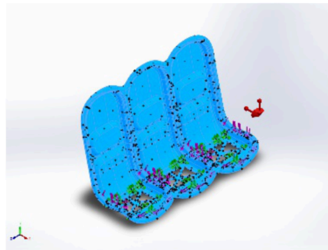
Description

No Data



Model name: frameshell
Current Configuration: Default

Composite Bodies

Document Name and Reference	Properties
Shell-1 	Total number of Plies: 16 Symmetric: Yes

Ply	Thickness(mm)	Angle(deg)	Area(m^2)	Volume (m^3)	Density(kg/m^3)	Mass(kg)	Weight (N)
1	0,17	0	2,72123	0,00046261	1.500	0,693914	6,80036
2	0,17	90	2,72123	0,00046261	1.500	0,693914	6,80036
3	0,17	45	2,72123	0,00046261	1.500	0,693914	6,80036
4	0,17	-45	2,72123	0,00046261	1.500	0,693914	6,80036
5	0,17	45	2,72123	0,00046261	1.500	0,693914	6,80036
6	0,17	-45	2,72123	0,00046261	1.500	0,693914	6,80036
7	0,17	0	2,72123	0,00046261	1.500	0,693914	6,80036
8	0,17	90	2,72123	0,00046261	1.500	0,693914	6,80036

9	0,17	90	2,72123	0,00046 261	1.500	0,693 914	6,8003 6
10	0,17	0	2,72123	0,00046 261	1.500	0,693 914	6,8003 6
11	0,17	-45	2,72123	0,00046 261	1.500	0,693 914	6,8003 6
12	0,17	45	2,72123	0,00046 261	1.500	0,693 914	6,8003 6
13	0,17	-45	2,72123	0,00046 261	1.500	0,693 914	6,8003 6
14	0,17	45	2,72123	0,00046 261	1.500	0,693 914	6,8003 6
15	0,17	90	2,72123	0,00046 261	1.500	0,693 914	6,8003 6
16	0,17	0	2,72123	0,00046 261	1.500	0,693 914	6,8003 6

Document Name: F:\A_PROJECTS\MASTER\A_GRADUATION\analysis\frameshell.SLDPRT
Date Modified: Jul 8 15:38:12 2021

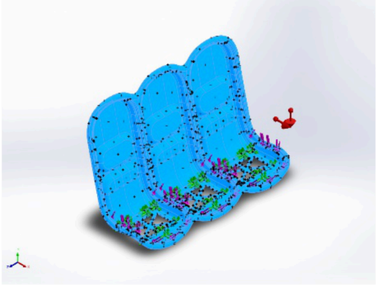
Study Properties

Study name	Static 1
Analysis type	Static
Mesh type	Shell Mesh Using Surfaces
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (F:\A_PROJECTS\MASTER\A_GRADUATION\analysis)

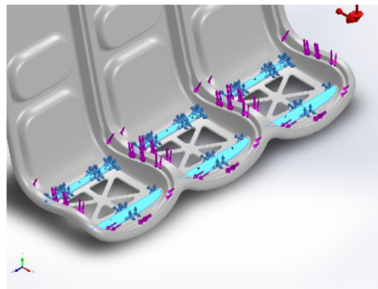
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

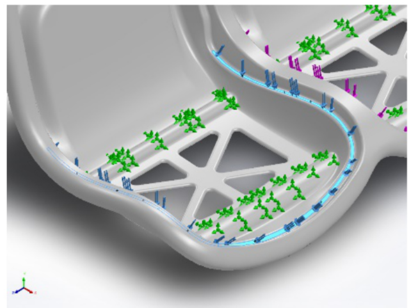
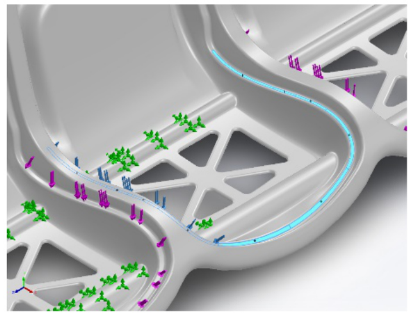
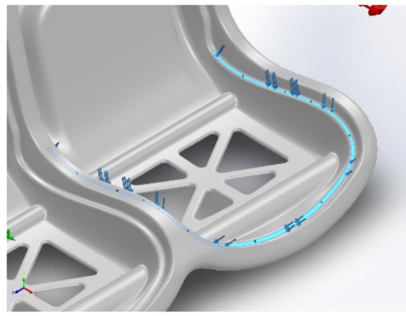
Model Reference	Properties	Components
	Name: Maezio Model type: Linear Elastic Isotropic Default failure criterion: Unknown Yield strength: 2,7e+08 N/m^2 Tensile strength: 3e+07 N/m^2 Elastic modulus: 1,08e+11 N/m^2 Poisson's ratio: 0,394 Mass density: 1.500 kg/m^3 Shear modulus: 2,9e+09 N/m^2	SurfaceBody 1(Body-Move/Copy1)(frameshell)
Curve Data:N/A		

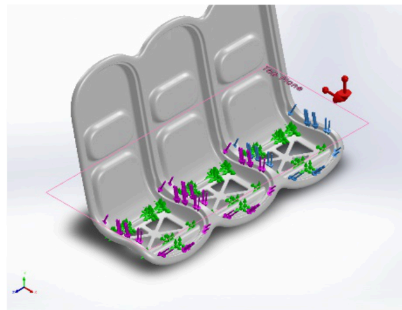
Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		**Entities:** 27 face(s) **Type:** Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-302,682	2.682,72	17,7599	2.699,79
Reaction Moment(N.m)	0,319014	0,0148531	24,4977	24,4997

Load name	Load Image	Load Details
Force-1		**Entities:** 10 face(s) **Type:** Apply normal force **Value:** 770 N
Force-2		**Entities:** 10 face(s) **Type:** Apply normal force **Value:** 770 N
Force-3		**Entities:** 10 face(s) **Type:** Apply normal force **Value:** 770 N

Gravity-1		**Reference:** Top Plane **Values:** 88,29 0 -58,86 **Units:** m/s^2

Connector Definitions

No Data

Contact Information

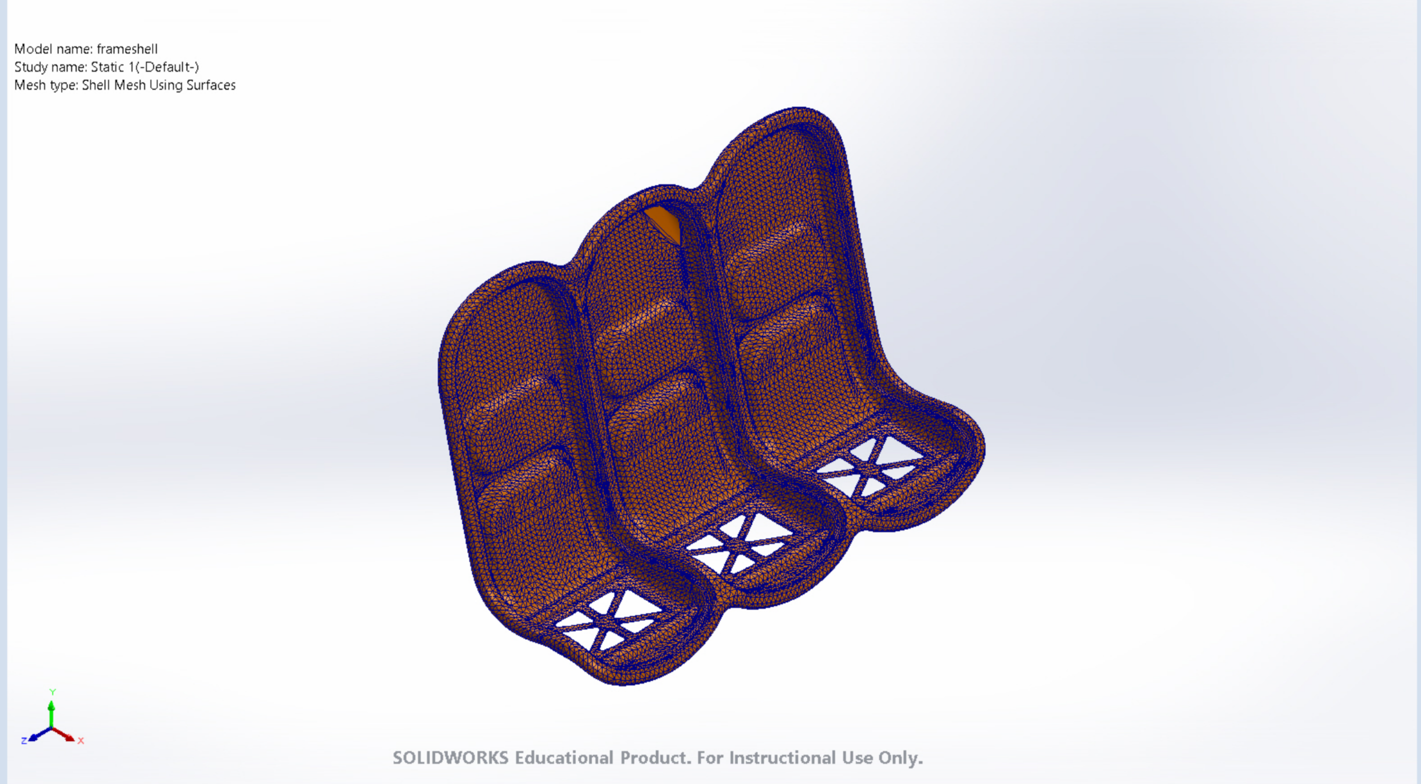
No Data

Mesh information

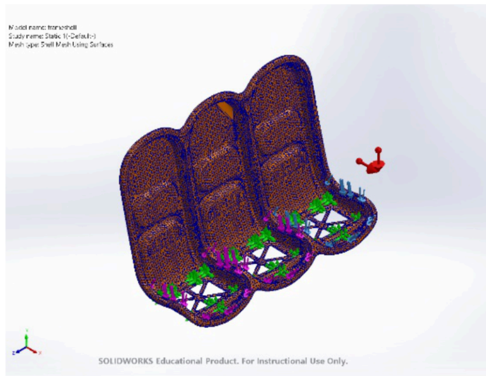
Mesh type	Shell Mesh Using Surfaces
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian check for shell	Off
Element Size	65,9963 mm
Tolerance	2,47444 mm
Mesh Quality	High

Mesh information - Details

Total Nodes	59309
Total Elements	29229
Time to complete mesh(hh;mm;ss):	00:00:30
Computer name:	



Mesh Control Information:

Mesh Control Name	Mesh Control Image	Mesh Control Details
Control-1		**Entities:** 1 component(s) **Units:** mm **Size:** 8,24814 **Ratio:** 8,24814

Sensor Details

No Data

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-302,682	2.682,72	17,7599	2.699,79

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0,319014	0,0148531	24,4977	24,4997

Free body forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0,00429437	-0,0282059	1,26287e-05	0,028531

Free body moments

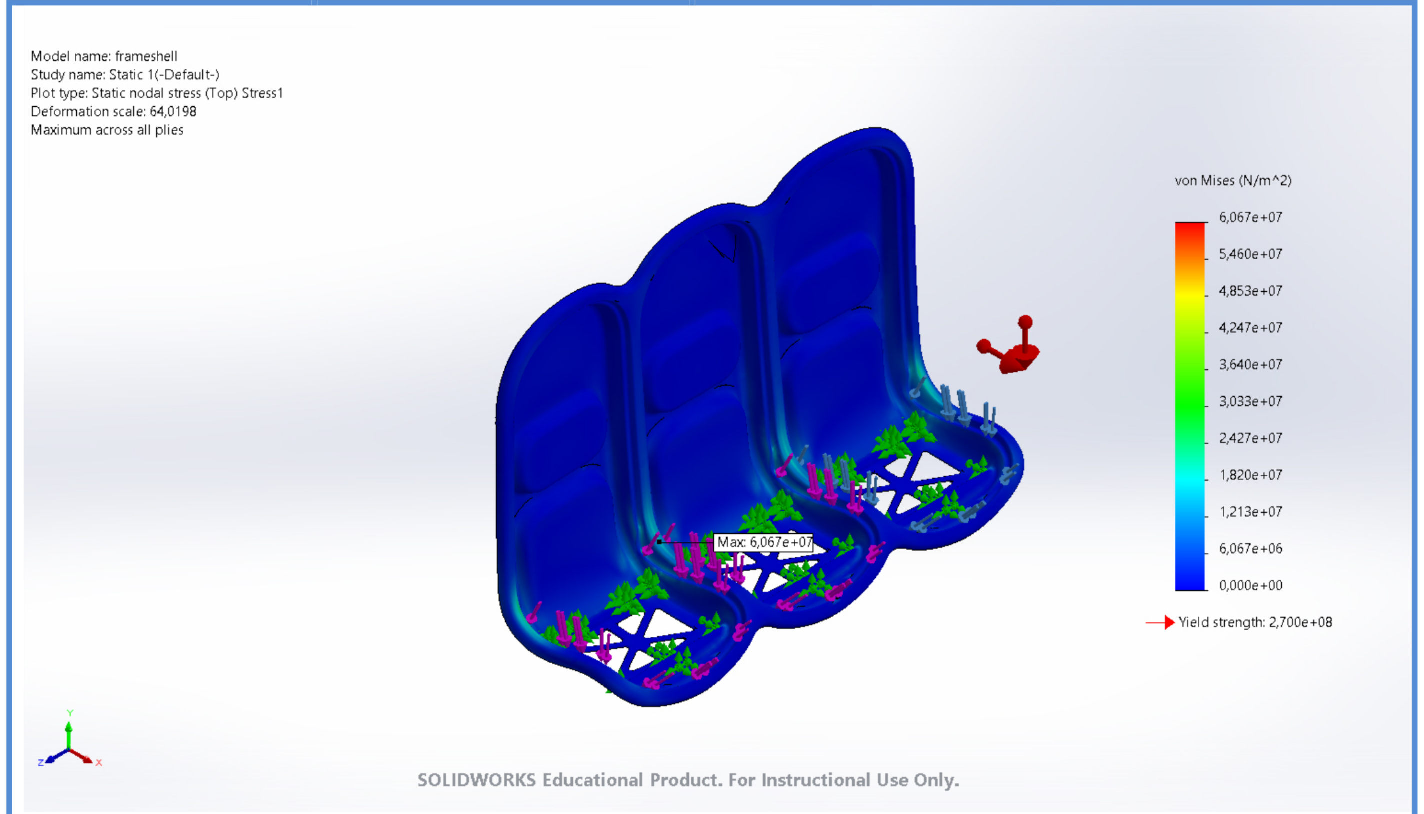
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0,319014	0,0148532	24,4977	24,4997

Beams

No Data

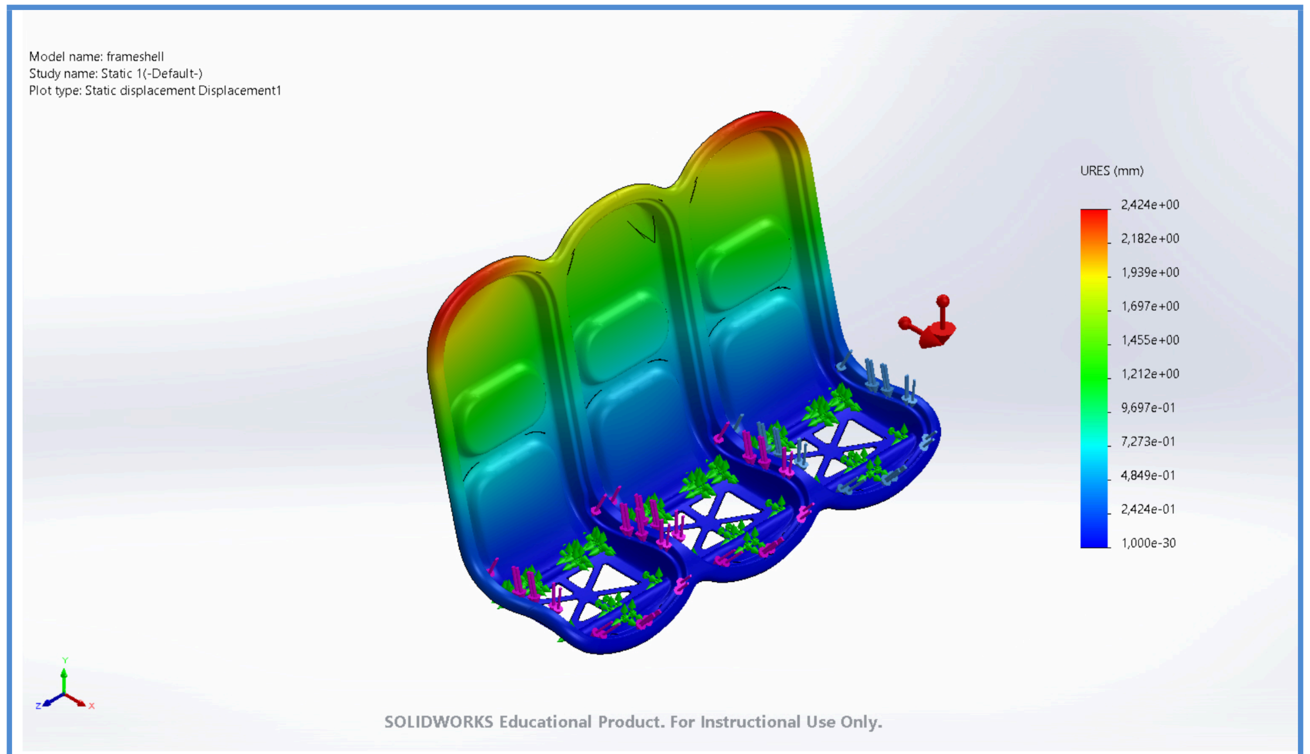
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0,000e+00N/m^2 Node: 8101	6,067e+07N/m^2 Node: 2002



frameshell-Static 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0,000e+00mm Node: 7	2,424e+00mm Node: 54636



frameshell-Static 1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	0,000e+00 Element: 15053	9,554e-04 Element: 18977

FEA analysis 2

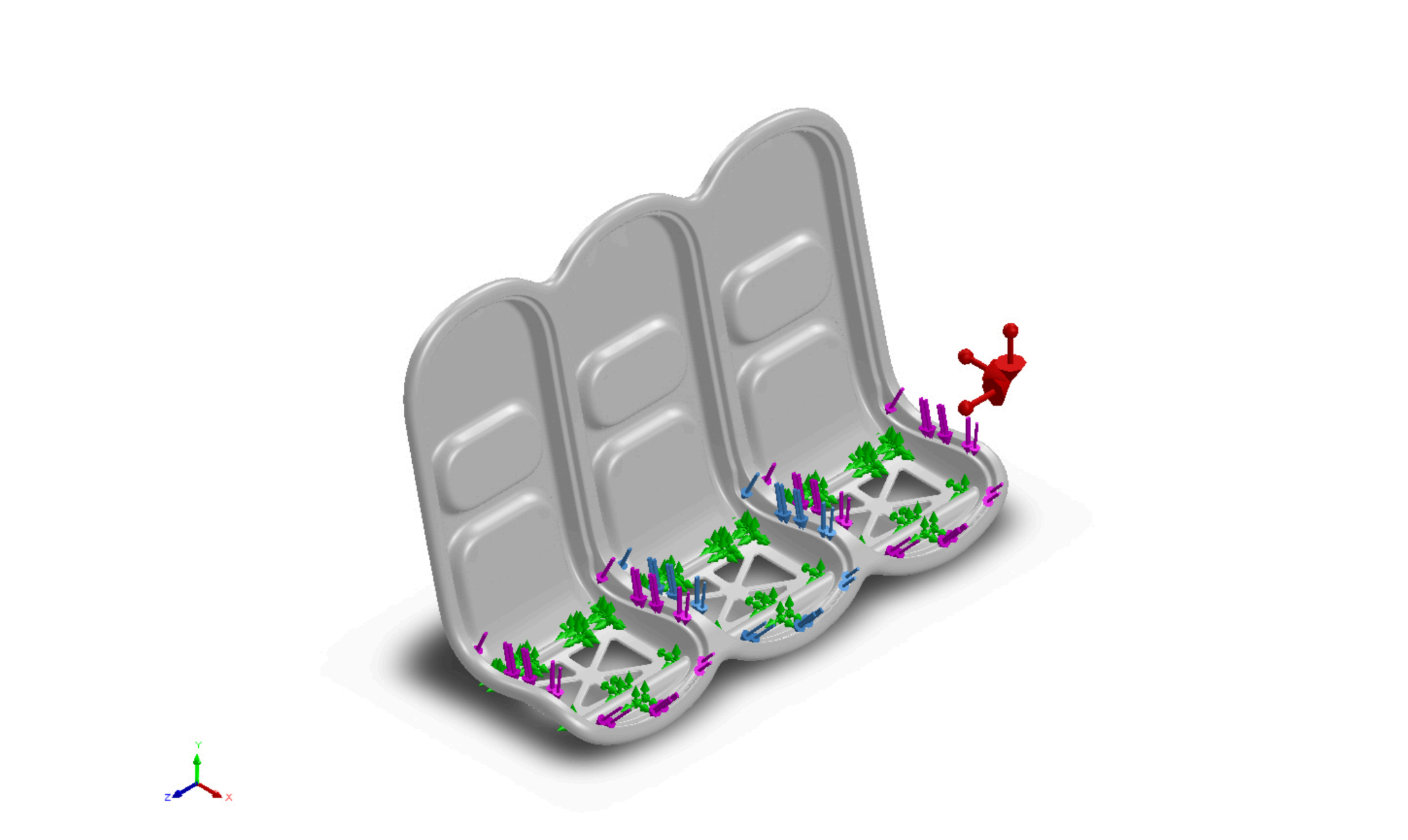
Simulation of frameshell

Date: Thursday, 8 July 2021
Designer: Solidworks
Study name: Static 1
Analysis type: Static

Table of Contents

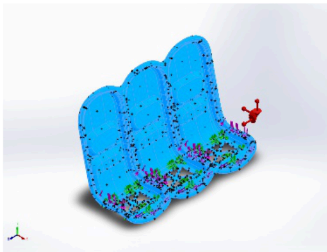
Description

No Data



Model name: frameshell
Current Configuration: Default

Composite Bodies

Document Name and Reference	Properties
Shell-1 	Total number of Plies: 16 Symmetric: Yes

Ply	Thickness(mm)	Angle(deg)	Area(m^2)	Volume (m^3)	Density(kg/m^3)	Mass(kg)	Weight (N)
1	0,17	0	2,72123	0,00046261	1.500	0,693914	6,80036
2	0,17	90	2,72123	0,00046261	1.500	0,693914	6,80036
3	0,17	45	2,72123	0,00046261	1.500	0,693914	6,80036
4	0,17	-45	2,72123	0,00046261	1.500	0,693914	6,80036
5	0,17	45	2,72123	0,00046261	1.500	0,693914	6,80036
6	0,17	-45	2,72123	0,00046261	1.500	0,693914	6,80036
7	0,17	0	2,72123	0,00046261	1.500	0,693914	6,80036
8	0,17	90	2,72123	0,00046261	1.500	0,693914	6,80036
9	0,17	90	2,72123	0,00046261	1.500	0,693914	6,80036
10	0,17	0	2,72123	0,00046261	1.500	0,693914	6,80036

11	0,17	-45	2,72123	0,00046261	1.500	0,693914	6,80036
12	0,17	45	2,72123	0,00046261	1.500	0,693914	6,80036
13	0,17	-45	2,72123	0,00046261	1.500	0,693914	6,80036
14	0,17	45	2,72123	0,00046261	1.500	0,693914	6,80036
15	0,17	90	2,72123	0,00046261	1.500	0,693914	6,80036
16	0,17	0	2,72123	0,00046261	1.500	0,693914	6,80036

Document Name: F:\A_PROJECTS\MASTER\A_GRADUATION\analysis\frameshell.SLDPRT
Date Modified: Jul 8 16:45:48 2021

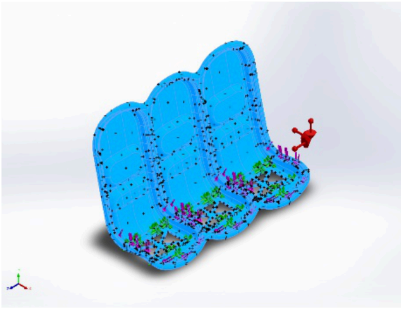
Study Properties

Study name	Static 1
Analysis type	Static
Mesh type	Shell Mesh Using Surfaces
Thermal Effect:	On
Thermal option	Include temperature loads
Zero strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
Inplane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off
Result folder	SOLIDWORKS document (F:\A_PROJECTS\MASTER\A_GRADUATION\analysis)

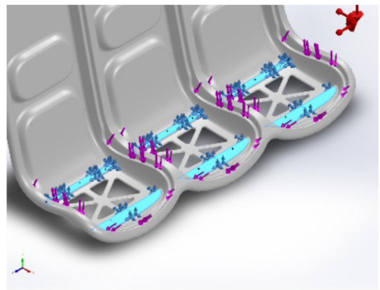
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

Material Properties

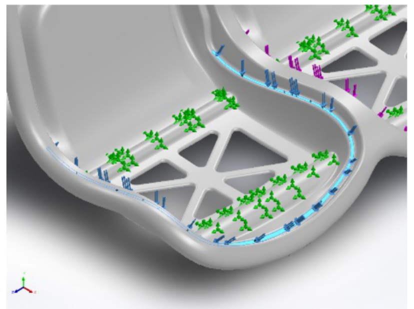
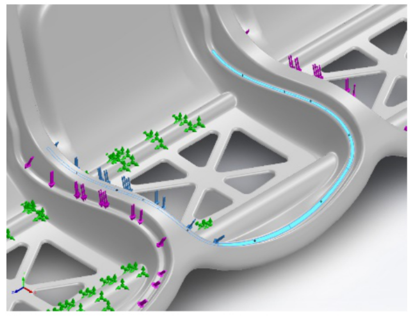
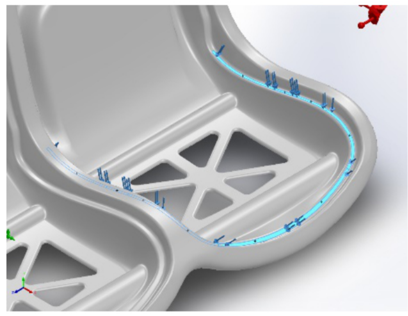
Model Reference	Properties	Components
	**Name:** Maezio **Model type:** Linear Elastic Isotropic **Default failure criterion:** Unknown **Yield strength:** 2,7e+08 N/m^2 **Tensile strength:** 3e+07 N/m^2 **Elastic modulus:** 1,08e+11 N/m^2 **Poisson's ratio:** 0,394 **Mass density:** 1.500 kg/m^3 **Shear modulus:** 2,9e+09 N/m^2	SurfaceBody 1(Body-Move/Copy1)(frameshell)
Curve Data:N/A		

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 27 face(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-302,682	2.139,34	452,453	2.207,51
Reaction Moment(N.m)	0,549751	0,0453299	32,6661	32,6707

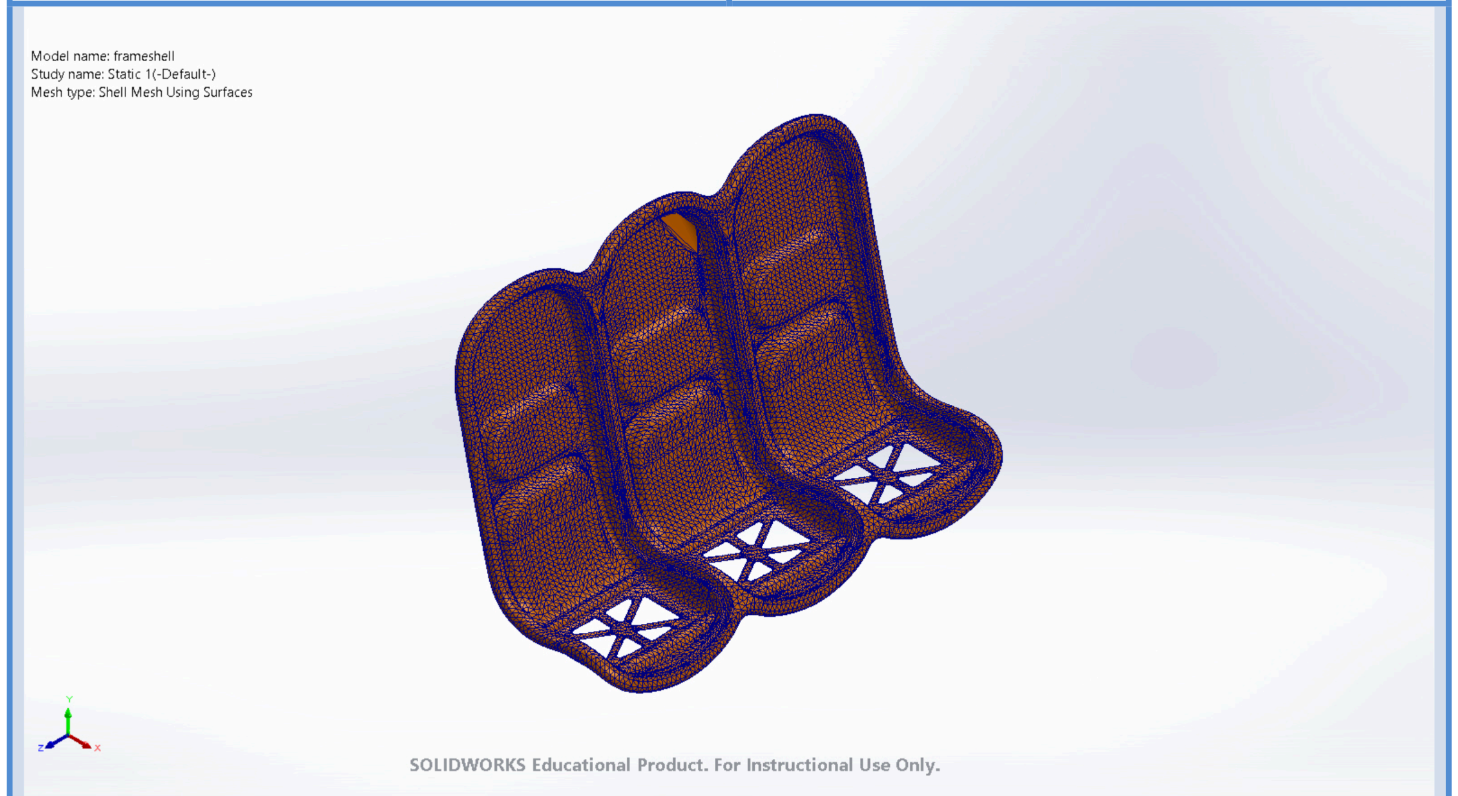
Load name	Load Image	Load Details
Force-1		Entities: 10 face(s) Type: Apply normal force Value: 770 N
Force-2		Entities: 10 face(s) Type: Apply normal force Value: 770 N
Force-3		Entities: 10 face(s) Type: Apply normal force Value: 770 N

Mesh information

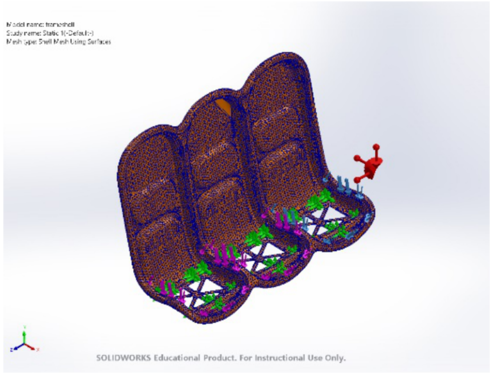
Mesh type	Shell Mesh Using Surfaces
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian check for shell	Off
Element Size	65,9963 mm
Tolerance	2,47444 mm
Mesh Quality	High

Mesh information - Details

Total Nodes	59309
Total Elements	29229
Time to complete mesh(hh;mm;ss):	00:00:30
Computer name:	



Mesh Control Information:

Mesh Control Name	Mesh Control Image	Mesh Control Details
Control-1		Entities: 1 component(s) Units: mm Size: 8,24814 Ratio: 8,24814

Sensor Details

No Data

Resultant Forces

Reaction forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-302,682	2.139,34	452,453	2.207,51

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0,549751	0,0453299	32,6661	32,6707

Free body forces

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	0,00123332	0,0532797	0,00134918	0,053311

Free body moments

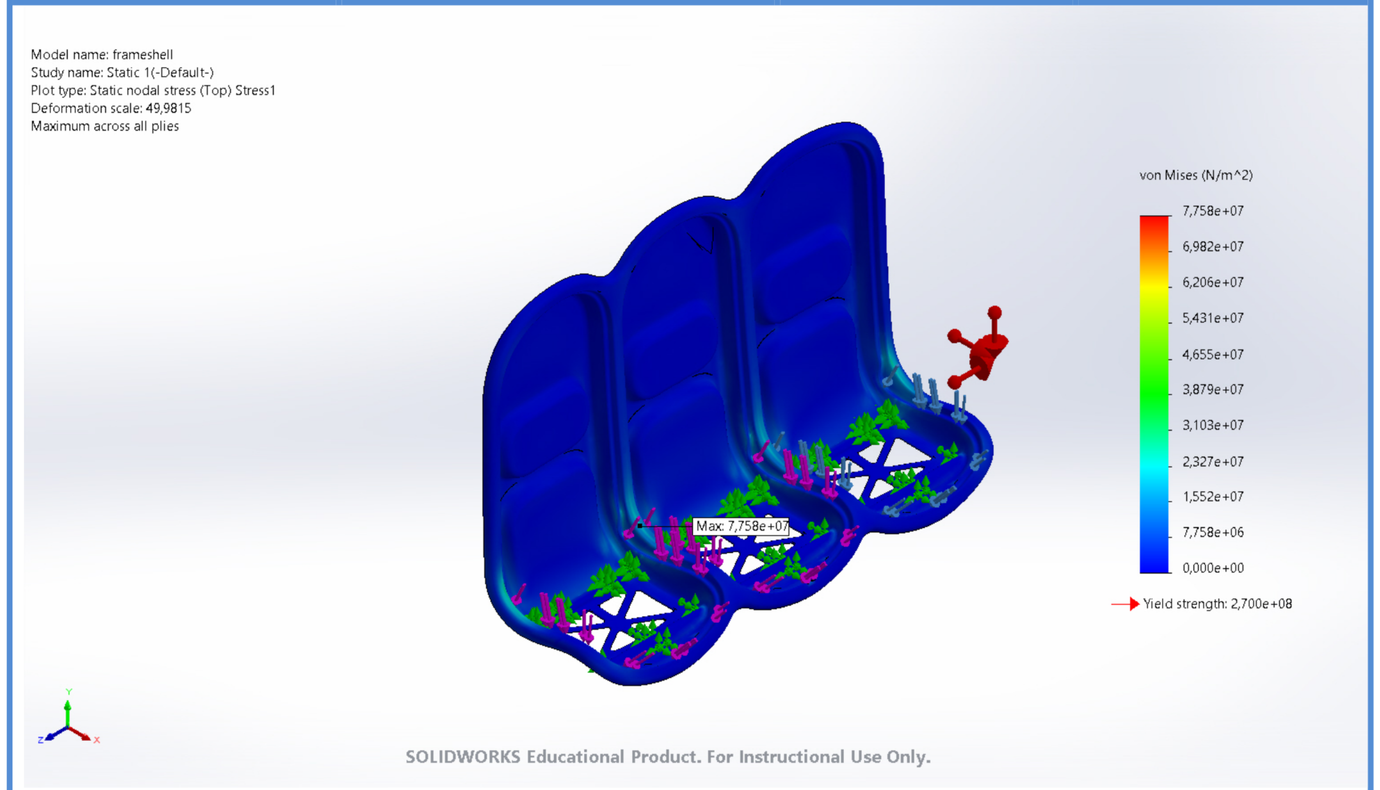
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0,549751	0,04533	32,6661	32,6707

Beams

No Data

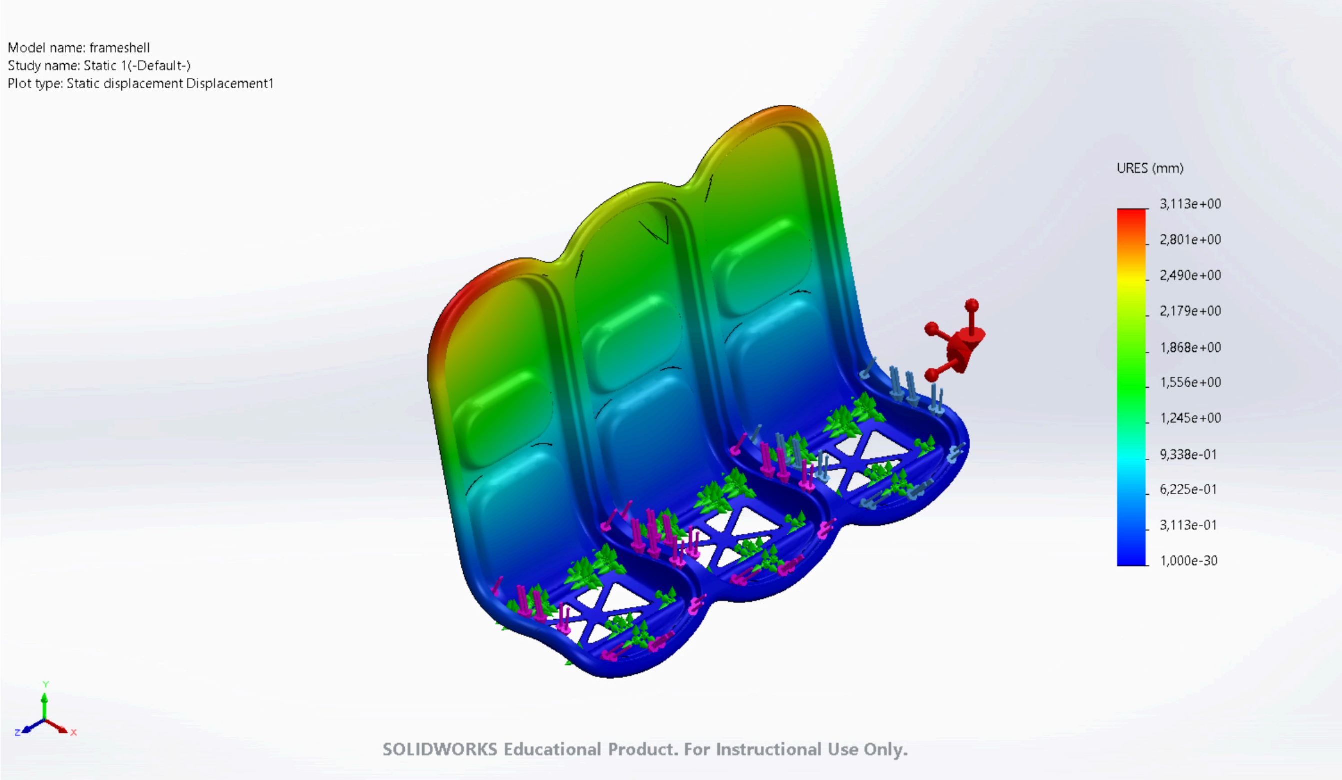
Study Results

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0,000e+00N/m^2 Node: 8101	7,758e+07N/m^2 Node: 2002



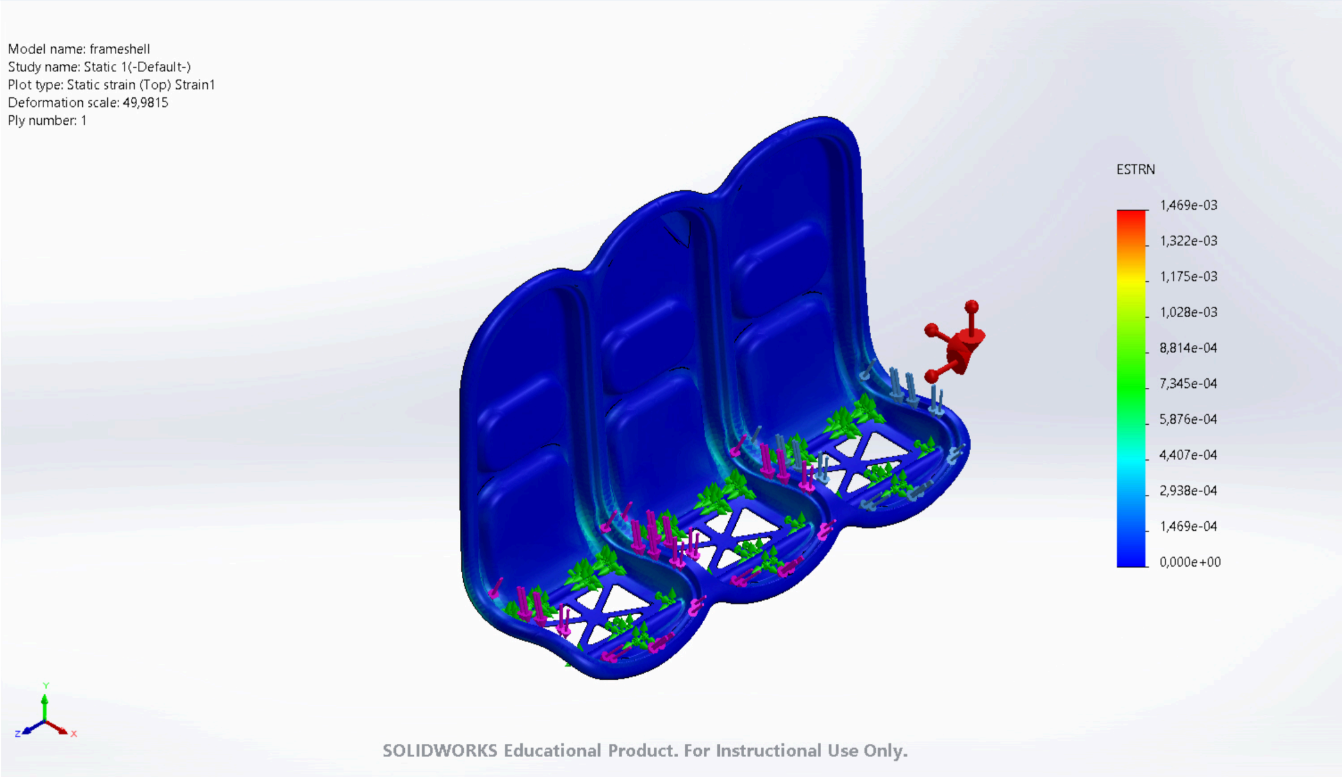
frameshell-Static 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0,000e+00mm Node: 7	3,113e+00mm Node: 3441



frameshell-Static 1-Displacement-Displacement1

Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	0,000e+00 Element: 15053	1,469e-03 Element: 27078



frameshell-Static 1-Strain-Strain1