Feasibility Study & Embodiment Design of a More Efficient Frying Pan for Commercial Kitchens

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NEOSTOVE
ACCELERATING SUSTAINABLE COOKING

TUDelft

Summary

This design report discusses the embodiment design of a more efficient frying pan for gas powered stoves in commercial kitchens, to see if a potential market entry is feasible, viable and desirable. Conventional pans have a thermal efficiency of roughly 25%. This means that only 25% of the heat coming from the combusted gas is used for cooking. The rest - 75% - is not being absorbed by the pan and is wasted as heat to the kitchen environment.

In the beginning of 2022, a start-up called 'NeoStove' developed a proof-of-concept for a more efficient pan. It has proven that it is possible to double the thermal efficiency from 25% to 50%, at the cost of a higher product complexity. This increased complexity poses challenges in the domain of manufacturing, such as thin-walled fin structures to enlarge the effective surface area, as seen in heat sink configurations. A production process called high pressure die casting (HPDC) is used to achieve the required complexity and detailing that enable such a thermal efficient pan. The material used is an aluminium alloy, which is exceptionally suitable for the HPDC process. This process in combination with the alloy offers a set of benefits over a steel counterpart. First, aluminium is a metal with a high thermal conductivity that allows for excellent propagation of heat through the pan resulting in a better heat distribution. Secondly, it is lightweight so it reduces physical strain on joints and ligaments of chefs, and results in a faster heat-up and cool-down time (Newton's Law of Cooling). Thirdly, aluminium is relatively affordable and castable, which helps limiting production costs and putting a competitive product in the market.

From a user perspective, it is important to note that both the increased thermal efficiency and the added geometric complexity of the pan result in a slightly altered way of cooking. The design of a pan has remained more or less the same for thousands of years, so it might be difficult for a chef to adapt. The aim of the new design is to not hamper the workflow of the chef, but have it seamlessly integrated with their existing way of working. It is clear that a product manifesting itself in the harsh commercial kitchen environment requires a simple and robust setup, since physical abuse of kitchen equipment occurs on a regular basis. To illustrate, a typical frying pan with a synthetic non-stick coating has an average lifespan of 4 months among the restaurants interviewed in this study (n=27). The top three reasons for failure of a frying pan (end-of-life) are: 1) wearing-off non-stick coating, 2) warped base and 3) broken handle (-attachment). These challenges - amongst others - are tackled in this project with a set of design choices. First of all, the pan is hard anodized which results in an improved surface hardness and scratch resistance. Secondly, the fin geometry is designed in such a way that it improves thermal behaviour and structural integrity of the pan, preventing it from warping during thermal shock events and reduce the chance of damage from impact forces during drops. Lastly, the handle is issued with a three-point rivet attachment to the pan. This is the strongest analysed attachment technique that is seen on pans on the market, and it passes a 10 kg bending test.

The prototypes developed during this project have been pilot tested at 3 different restaurants and did not show any signs of wear during these multi-week trail periods. User inputs from the pilot tests are used to improve and iterate upon the design.

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Glossary & Nomenclature

Abbreviation		Explanation
B2B	Business-to-business	Selling to business
B2C	Business-to-consumer	Selling to consumer
EoL	End-of-Life	State when a product is not operational any longer and needs to be disposed
MSRP	Manufacturer Suggested Retail Price	Sales price for a given product that the manufacturer or product owner suggests
MVP	Minimum viable product	Terminology for a prototype that has the minimum requirements to be used and tested by the target user as an actual product
	Thermal efficiency	Percentage of emitted heat that is being absorbed by the content of the pan
WTP	Willingness to pay	The amount that a potential customer is willing to pay for a product

Introduction

This chapter gives an insight in the project and its origin. The aim is to give the reader a broader understanding of the factors at play throughout the design process.

Background & Context

A Delft-based startup called ‘NeoStove’ is exploiting the possibility to bring a more efficient cooking pan to the market for commercial kitchens. NeoStove has proven that there is a demand for energy efficient pans in this market. A proof-of-concept made by NeoStove showed that significantly more efficient pans are possible. The significance is determined by the fact that the gain in efficiency makes it possible to have an viable return on investment (ROI) on the product. However, before these pans can go to market in a mature form, the following steps need to be taken:

1. Research the feasibility, viability and desirability of such a concept;
2. Mature the design through the embodiment design phase, from proof-of-concept to series-production ready;
3. Detail design and manufacturing.

The first two steps are conducted within this project. The third step is a potential succession of this project. The figure underneath shows the design phase of this project (embodiment design) in relation to the entire product development phase from concept to market.

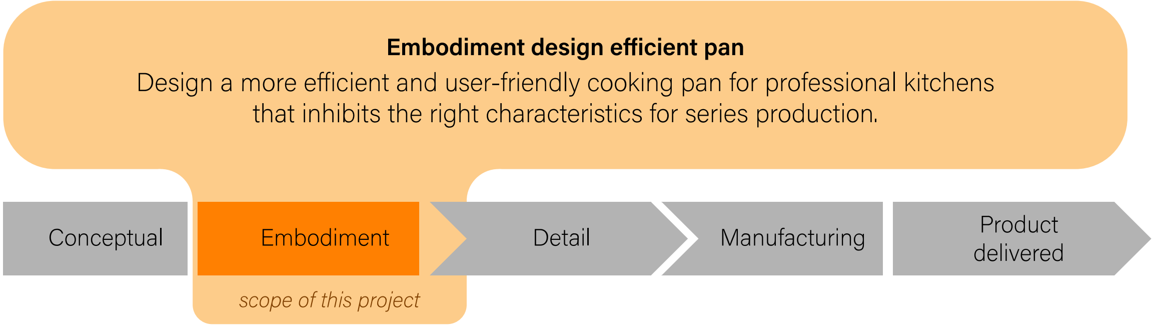


Figure 1 - infographic of the scope of this project in the total product development phase.

Why is there a need for a more efficient frying pan, and why does it not already exist if it is apparently feasible? The answer can be found in recent socioeconomic developments, like the increased focus on sustainability and the sudden rise of energy prices which acts as a catalyst for the invention of energy saving inventions.

The development of the prototype is aimed at commercial kitchens like those in hotels and restaurants. The profit margin of an average restaurant is low, approximately 5% of their revenue according to Roos & Van Dril (2004). Furthermore, the energy intensity of a restaurant or food-related venue is among the highest of the utilitarian buildings (CBS, 2019), so the energy expenses are highly influential for the profit of a restaurant. With the energy prices more than doubling in 2022, many restaurants saw their profit margins disappearing (Entree Magazine, 2022). From that point on, energy costs became a more dominant factor for restaurants to be profitable. Preliminary conducted interviews by NeoStove show that restaurants are actively looking for solutions to reduce their energy costs. According to a study done by RVO, the gas costs for cooking are 67% of the total gas costs of an average restaurant (RvO, 2019), which make cooking costs an expense worthy to reduce.

Problem Definition & Design Challenge

The challenge is to design a more energy efficient (thermodynamics) and user-friendly (product-experience) frying pan for commercial kitchens that inhibits the right characteristics for series-production (manufacturing):

1. **Product Experience**: product-user interaction;
2. **Thermodynamics**: thermal efficiency and behaviour of the pan;
3. **Manufacturing**: how to manufacture, design for manufacturing and assembly

1. Product experience

It is important to get a good understanding of what is being designed exactly and for whom. Kitchen is harsh and dynamic environment. Chefs have their distinct workflow and trades of the craft. The product not only has to support this workflow, it has to seamlessly integrate with the kitchen environment. The requirements from this domain lay the foundation of a frying pan that is desirable, usable and efficient.

2. Thermodynamics

This topic aims to evaluate the thermodynamics behind a frying pan, and determine what properties make a pan efficient, desired and heat resistant. The chapter consists of three fundamental topics. Firstly, the thermal efficiency, of which an increase is already proven by the proof-of-concept. It is important to understand the physics behind this topic, however optimizing the thermal efficiency into its greatest detail is not part of this project. This will be done by a dedicated team of thermal engineers. Input from the thermal team will be used to alter the design. The second topic is the thermal behaviour of the pan, which is closely related to product experience from the user. It covers topics like the ideal heat-up and cooldown rates and desired heat distribution. The third and last topic researches the mechanical durability in thermal environments that the pan will be exposed to. The effect of thermal fatigue, thermal cycles, distortion and thermal shocks on the mechanical properties of the pan will be assessed.

3. Manufacturing

This topic exploits the concept of production related feasibility. It is proven that a more efficient frying pan can be made. However, it is to find out whether it is eligible for series-production, aiming at viable production costs with the given complexity. The first minimum viable product (MVP) of the client is fabricated through an additive manufacturing method, selective laser sintering (SLS), costing 2000 euro to produce. One of the givens in this project is the aimed sales price of the pan is approximately 200 euros. Deducting this value into its cost components, it leaves a mere 50 euros for production costs. Is it possible to produce a pan with added complexity for roughly 50 euros? What production process would suffice? And what would be the effect of economies of scale, how do the production costs evolve from 1,000, to 10,000 and 100,000 units produced? In this context, the topic of manufacturing has paramount importance, especially when striving to build a product with a subsequent production line that offers desired product qualities, production robustness and cost-effectiveness.

Design Challenge

> “Design a more **efficient** and **user friendly** frying pan for commercial kitchens that inhibits the right characteristics for **series production**.”

An elaborate research question can be distilled from the design challenge:

> “Is it advised to enter the market with a more efficient and user friendly frying pan for commercial kitchens that inhibits the right characteristics for series-production, looking at the desirability, feasibility and viability of the proposition?”

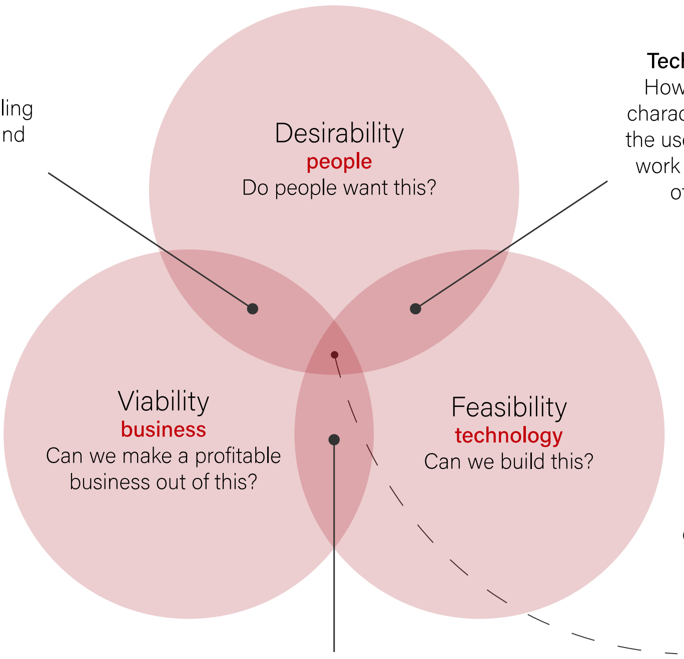
The research question can be split up in several sub questions:

Q	Sub question	Chapter	Domain
1	What should the product characteristics and requirements be such that it aligns with the desires of the target user?	Chapter 1: Product Experience	● Desirability
2	How can the desired thermodynamic characteristics be translated into robust and practical features?	Chapter 2: Thermodynamics	● Desirability ● Feasibility
3	How can the product comply with the established requirements and be mass-manufacturable?	Chapter 3: Manufacturing	● Feasibility
4	How should the manufacturing be setup to ensure a robust and cost-effective process?	3.5. Design for Manufacturing (DfM)	● Feasibility ● Viability
5	Do the production costs compared to willingness to pay offer perspective for a profitable business?	3.6. Production Cost estimation	● Viability
6	How much are users willing to pay for the product and how is this affected?	Chapter 1: Product Experience	● Viability ● Desirability

Product Experience
What should the product characteristics and requirements be such that it aligns with the desires of the target user?

Willingness to Pay
How much are users willing to pay for the product and how is this affected?

Technological embodiment
How can the desired product characteristics be build such that the user understands and likes to work with the evolved principle of a more efficient pan?



Potential for Profitability
Do the production costs compared to willingness to pay offer perspective for a profitable business?

Manufacturability
How can the product comply with the established requirements and be mass-manufacturable?

Target scenario
Desirable
Feasible
Viable

Production Costs
How should the manufacturing be setup to ensure a robust and cost-effective process?

Figure 2 - feasibility, desirability and viability related to this project and the product development.

Methodology

A dedicated design approach is used to research the feasibility, viability and desirability of the proof-of-concept. Embodiment design is combined with lean development (Ries, 2011), consisting of the following setup:

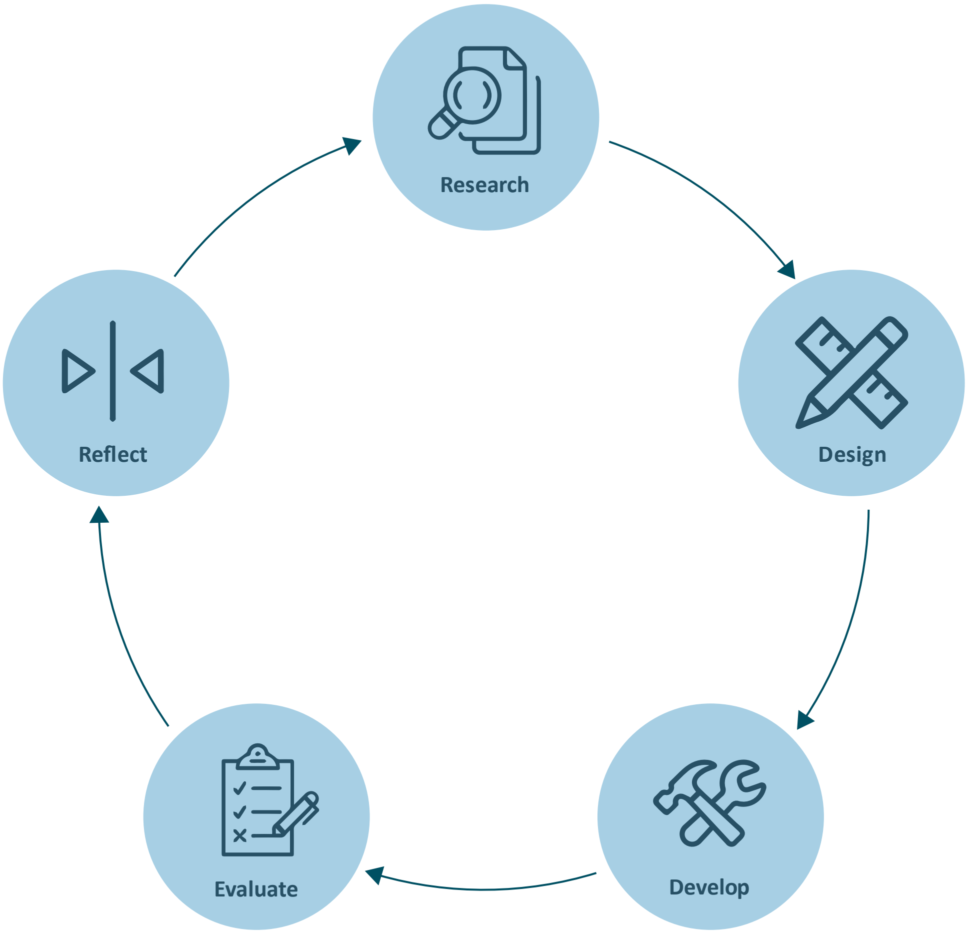


Figure 3 - one design iteration visualized.

Three iterations of the design cycle are executed throughout this project.

1. Research

The research phase consists of literature research, field research (visiting restaurants) and experts interviews (chefs and expert in the topics of metallurgy, manufacturing and thermodynamics).

2. Design

The design phase consists of incorporating the findings of the research phase into a design. This could be a holistic design for an MVP or a design for a sub-component to test a sub-function. Computer aided design (CAD) programs Adobe Illustrator and program Dassault Systemes Solidworks are used to model the designs in 2D and 3D respectively. Computer aided manufacturing (CAM) programs are used to prepare the models for production, such as UltiMaker Cura and CAMWorks.

3. Develop

The prototype phase consists of building prototypes. The aim is to make two MVPs and besides multiple smaller prototypes that will be used to test a sub-function of the pan. Examples of sub-function prototypes are separate handles for ergonomics and bottom geometries to improve airflow, stability and efficiency. Multiple prototyping techniques are used: fused deposit modelling (FDM) using PLA to make preliminary prototypes with UltiMaker S5 and 2+. The V1 is made with selective laser melting/sintering (SLM/SLS) stainless steel 316. Aluminium geometry samples are machined on a 3-axis computer numerical controlled (CNC) vertical milling centre (VMC) and V2 is made on a 5-axis CNC VMC.

4. Evaluate

The test phase consists of thermal tests, usage tests and (multiday) pilot tests with chefs and restaurants. For the thermal tests, the L200 thermocouple is used for exact temperature monitoring and the Voltcraft WB-80 and FLIR one-pro LT are used for thermal imaging.

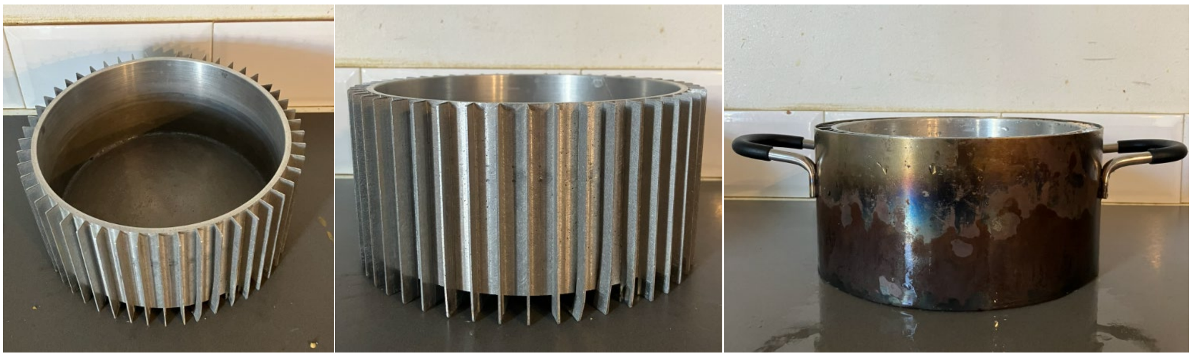
5. Reflect

Reflecting on the gathered information from evaluation phase. Based hereupon, new research is conducted that is incorporated for the design and development of a next prototype.

Prototype Iterations

Prototype 0: proof-of-concept

This prototype is made before the start of the this project and proves that it is possible to double thermal efficiency. It is an aluminium casting alloy, first casted and then machined. However, it is not suitable to cook with, both for safety and usability reasons: an epoxy is used to fill-up the pinhole defects resulting from casting. Furthermore, the product is not coated, lacks pouring sprouts and bottom curves to properly work with any contents.



Prototype 1: MVP 1 / V1 - first pilot tested prototype

Based on the proof-of-concept a usable prototype is developed, called a minimum viable product (MVP). This product is selective laser sintered from stainless steel 316L and is pilot tested at 3 different venues for a total of 3 weeks.

Prototype 2: MVP 2 / V2 - second prototype of the project

The input of prototype 1 is used to develop and build the last prototype of this project: V2. The V2 is machined from 7075 T0 aluminium and hard anodized. It is piloted tested at to 2 different venues for a total of 2 weeks. The input gathered based on the tests of the second prototype are used to iterate and create version 3 (V3, see Figure 3).

Overview of the Final Design

The final design can be split up into two functional components. First, the core, which is the main focus of this project and factually determines its performance. Second, the handle, which is not the main focus but it has to adhere to certain qualifications to enable good control and usage over the pan. Production costs are calculated for production in China and Netherlands at respectively 20 to 50 euro per pan for a 10,000 unit batch size (see 5.7. Production Cost estimation).

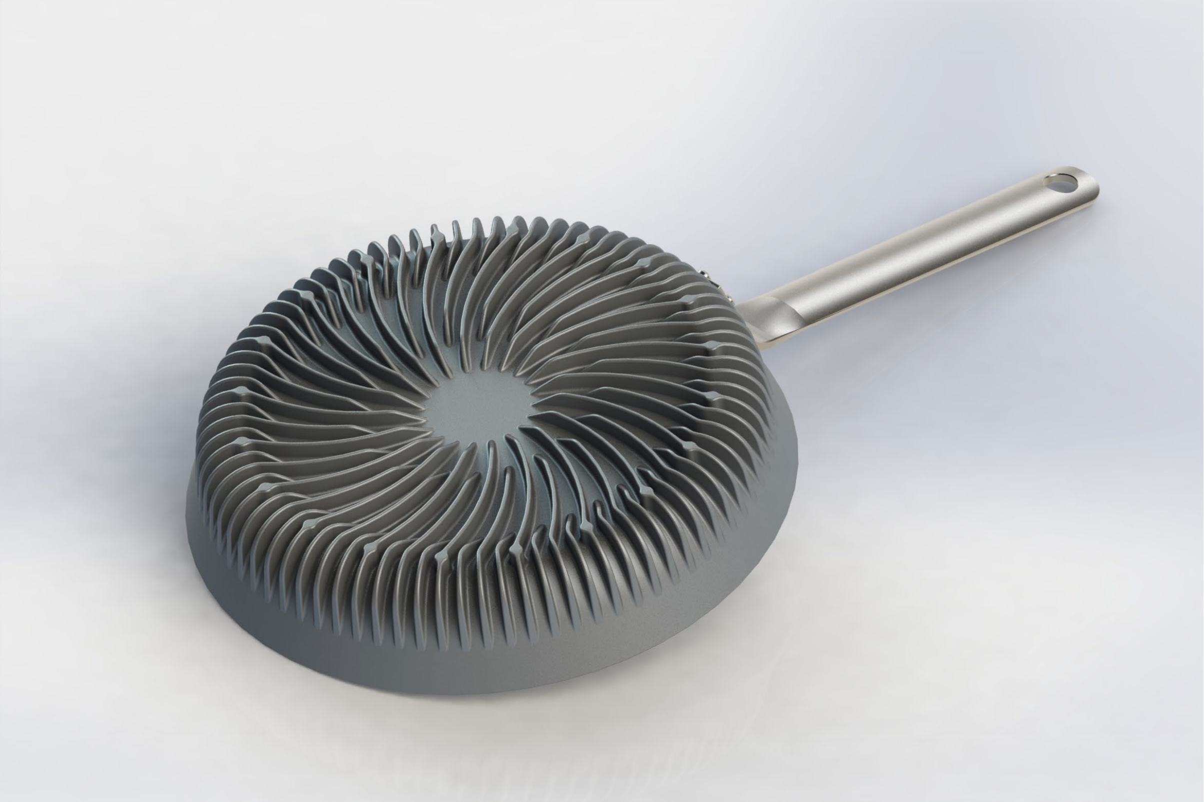


Figure 4 - render of the final model, referred to as version 3 (V3). This is the successor of the built V2.

Figure 5 - side view of the V3.

Manufacturing process: high pressure die casting

A variety of production processes have been evaluated, and the choice is made for HPDC. It is a cost-effective, versatile and accurate process that produces high-quality parts. The downside is that this process can only handle non-ferrous metals and the investment costs are high due to intensive engineering and production costs for the die. However, when the die is finished and works properly, an estimated 200,000 products can be shot before it needs to be replaced.

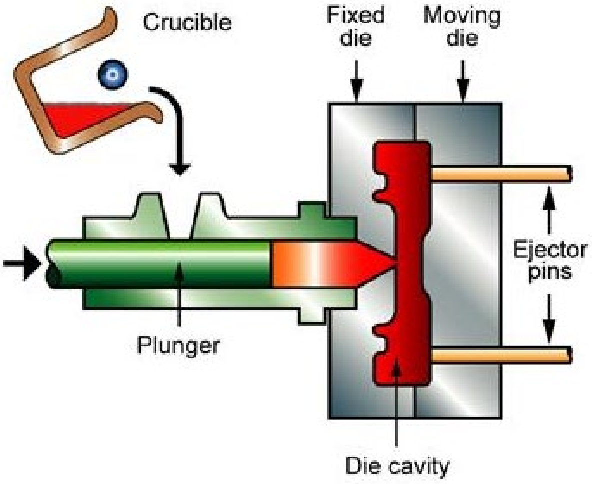


Figure 6 - schematic overview of HPDC machine (Granta, 2022).

Material: 390 casting alloy

In collusion with the decision to HPDC, a suitable non-ferrous metal is selected. The choice is made to use aluminium due to its affordability, suitable mechanical properties and good thermal conductivity. If you look at the market, a great part of the pans that chefs use are made of aluminium, and not without a reason. The downsides of aluminium are that it is not declared food-safe by national health authorities, and has no excellent abrasion, thermal and chemical resistance. This can be tackled by applying a suitable surface treatment. The alloy has to satisfy three main components:

- HPDC castability
- Thermal resistance
- Ability to coat/anodize

It turns out that there is not one alloy that can fully satisfy all of the above components. Therefore, a selection of four high performance alloys is made:

- A360 (Al10SiMg1)
- 390 (Al17Si4Cu)
- A413 (Al12Si)
- 518.0 (Al8Mg)

The exact alloy composition can be chosen in collaboration with the manufacturer and the option to go with a secondary (recycled) alloy. Eventually the 390 casting alloy is preferred for its excellent thermal resistance due to the addition of copper and high silicon content, which also increases fluidity for improved casting properties.

Figure 7 - example casting of the 390 alloy. This alloy is used for engine blocks, valve bodies and piston housings which require a certain level of thermal durability.

Surface treatment: type III hard anodization

Aluminium is not a food-safe material, therefore it requires a coating. According to chefs, when the coating is scratched and the underlying aluminium is exposed, they stop using the pan and throw it away. Although aluminium does not rust, it can still corrode (like galvanic corrosion). Another downside of bare aluminium on the outside is its low hardness and yield, especially at elevated temperatures, making it prone to external damages. These factors affect the lifespan of the pan. The kitchen is a harsh environment where the pan is exposed to rough usage scenarios, like chemical cleaning substances, high temperatures and scratching from brushes and utensils. Therefore, the coating must not only offer non-stick properties, but should also offer resistance to thermal, chemical and mechanical wear. Simply said, the tougher the coating, the longer the theoretical lifespan of the pan.

The pan is anodised all around to enhance tribological properties, like abrasion and corrosion resistance. Furthermore, it prevents galvanic corrosion at the handle interface and it creates the ability for a slightly seasoned natural non-stick layer. More specifically, type III sulphuric acid hard anodizing is used to get a highly durable coating. The aluminium oxide layer is hard, especially compared to the underlying aluminum. The surface hardness is approximately 400-600 MPa (Vickers), compared to 100 MPa for aluminium, 130 MPa for carbon steels and 400 MPa for stainless steels. Its wear-rate is 5 to 10 times lower than PTFE coatings, theoretically increasing the lifespan of the pan. See Chapter 3: Manufacturing, 3.4. Surface treatment for more details on the surface treatment.

Figure 8 - the second prototype (V2) right after anodizing.

Shaping & dimensioning

The shape and exact dimensioning affect the usage and thermal properties of the pan. Mainly, two parts can be distinguished:

- Top side (frying surface), where shape and dimensions determine usability for cooking
- Bottom side with fins responsible for thermal efficiency and thermal behaviour

It is important to mention that the optimization of thermal efficiency is beyond the scope of this project, hence the fin geometry and dimensions are fixed at a certain value. The possibility to later adjust these values is taken into account during the design process. HPDC offers a range of dimensional adjustability from details and wall thicknesses ranging from 1 to 8 mm (GRANTA, 2022). This is basically the domain in which the thermal engineering team of the client can optimize the thermal efficiency of the product. The following general dimensions are selected for the final design:

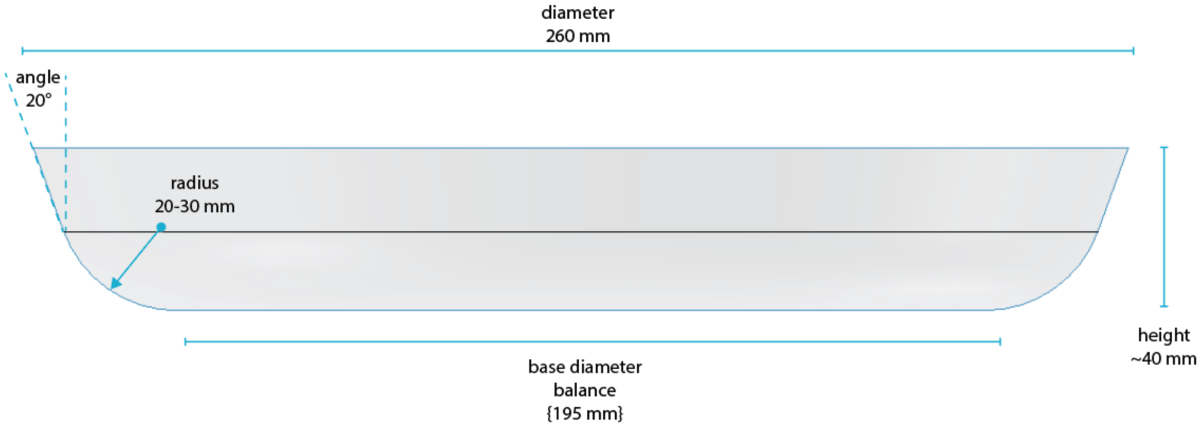


Figure 9 - dimensioning of the frying surface of the pan.

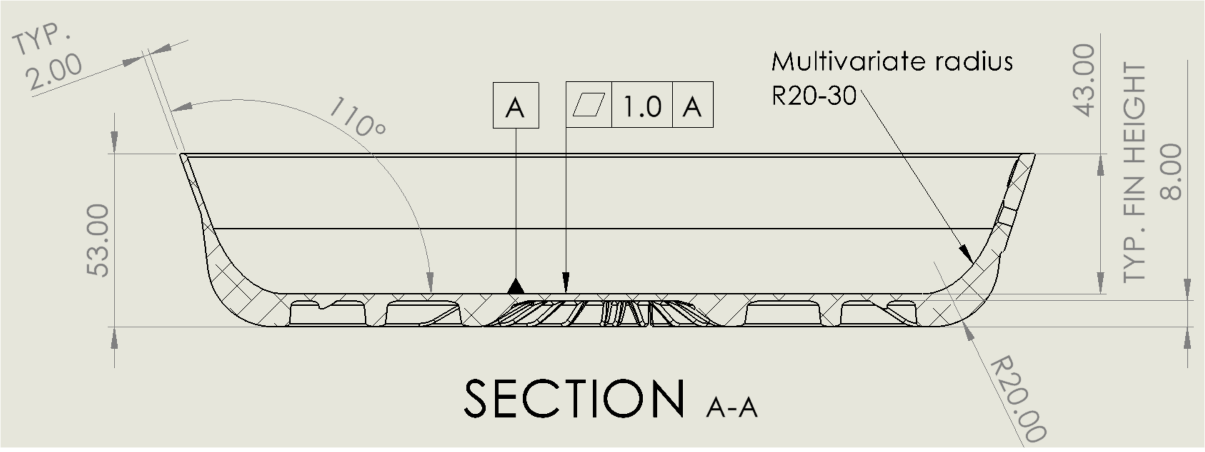


Figure 10 - technical drawing of section of the pan. Frying surface specifications.

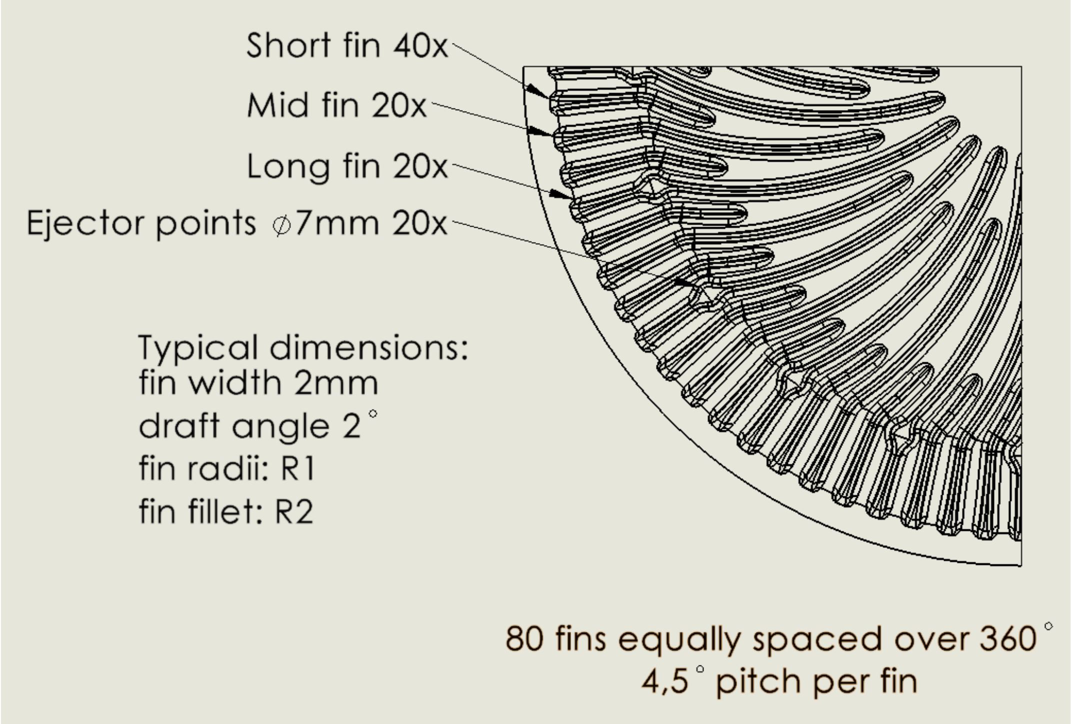


Figure 11 - technical drawing of bottom view quarter. Bottom geometry specifications.

The combination of material, production process and shape make a product that is light, strong and with sufficient amount of detail to suffice the requirements for a highly efficient frying pan. Due to its fin structure, the prototype's wall can be thinner, making it lighter and still enable good heat distribution and prevent warping due to added stiffness. It has the following characteristics compared to a conventional aluminum frying pan (desired improvements in green, pain points in red):

	Prototype V2	**Typical conventional pan**
Size	26 cm	26 cm
Mass	600 gram	800 gram
Thermal efficiency*	35%	18%
Heat capacity	540 kJ	720 kJ
Heat-up time from r.t. to 200 C*	135 seconds	220 seconds
Cool-down time to 150 C	65 seconds	120 seconds

**on a calibrated 2 kW stove*

Handle

A good handle will not determine the success of the pan. However, a poor handle can jeopardize the success of a good pan. Since plenty of good handles already exist on the market, a mimicking strategy is used to get the properties for the right handle. For this project, product development of the handle is out of scope. An ergonomic optimization project can definitely be a future option for the client.

Handle material: stainless steel 304

Not only the core of the pan will be exposed to the harsh kitchen environment, also the handle will be. Therefore the handle should be of corrosion and thermally resistant material. The material used for the handle is austenitic 304 stainless steel, with its known corrosion resistance due to the addition of chromium. Compared to other stainless steels, it has respectable availability and processability. Furthermore, it has a thermal conductivity of 15 W/m.k, among the lowest of the available metals, to retard heat propagation into the handle and help it keep cooler. The advantage of using stainless steel is that it does not require a coating, which saves post-processing and costs.

Handle production: blanking and bending

The handle is a simple metal strip before processing. To get it into shape, two blanking and two bending operations are required. The first blank is to create the eyelet and the second blanks are to create the holes for the three-point rivet connection. The first bend is to set the ergonomic curvature over the length of the handle, and the second to bend the 55-degree angle that aligns with the side of the pan.

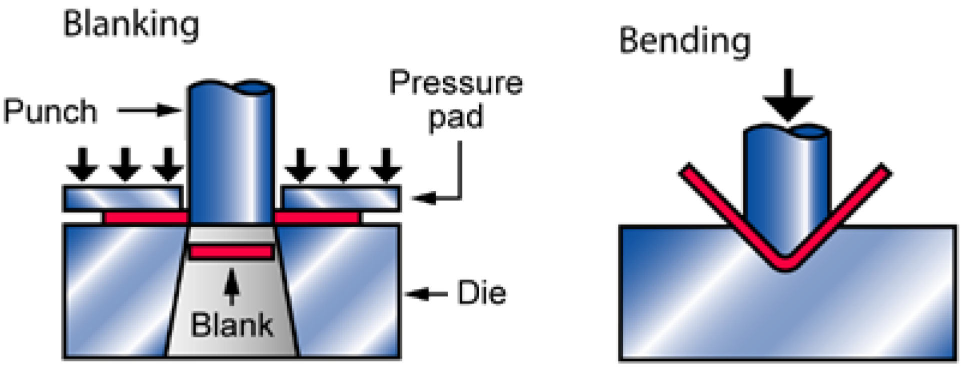


Figure 12 - schematic representation of the blanking and bending process.

Figure 13 - metal strip after blanking operation.

Figure 14 - metal strip after bending operation.

The handle can be post-processed by deburring and/or sandblasting to remove any burrs and sharp edges.

Attachment to pan: 3-point rivet

The final assembly step is to rivet the handle to the pan. This is done on three points to ensure a robust and statically determined attachment. The 5 mm solid stainless steel mushroom head rivet is used (DIN 662), as can be seen in Figure 13.

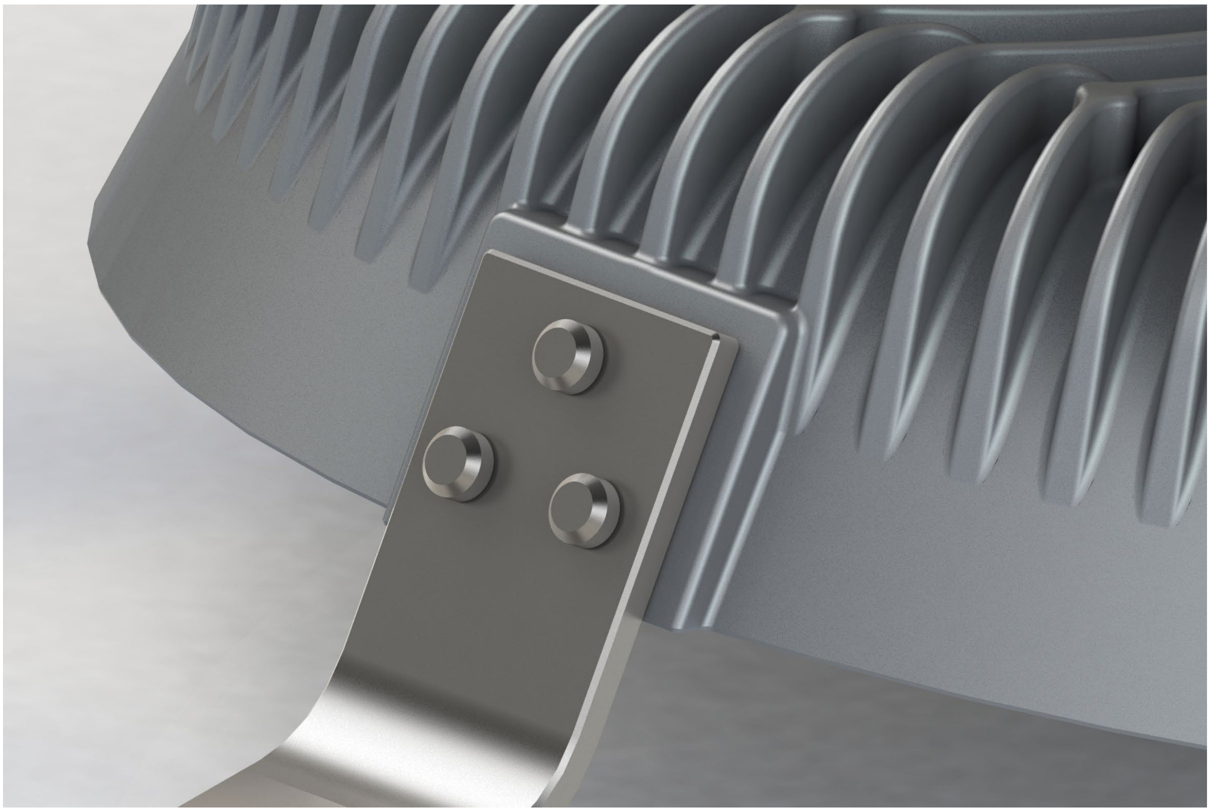
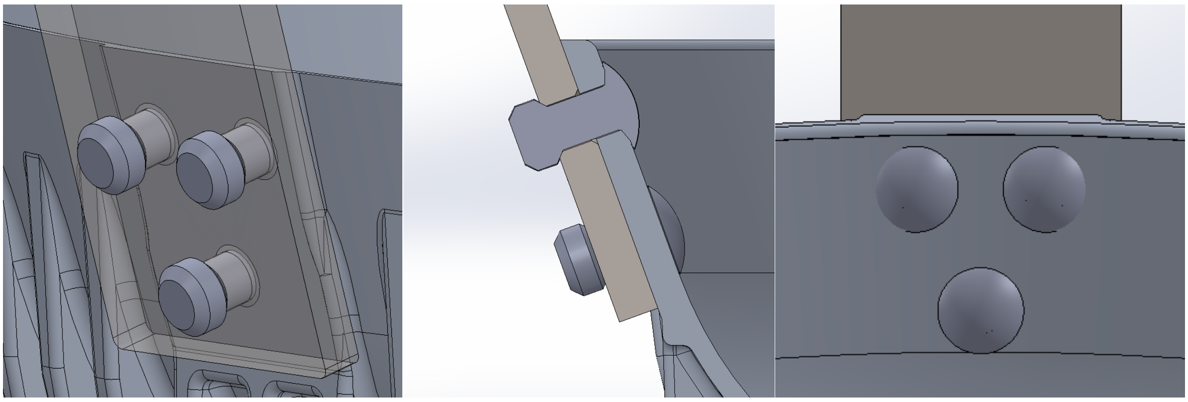


Figure 15 - close-up of the handle attachment.



Shaping & dimensioning

The main topics relevant for the design of the handle are ergonomics and compatibility in the kitchen environment.

Ergonomics must ensure a good grip and control over the pan. Furthermore the handle should not become too hot, hence the choice for a low conductive steel.

Figure 16 - Hand holding the handle.

Compatibility is to ensure that the pan and its handle seamlessly integrate in the kitchen. The handle is designed in such a way that it does not clash with other pans on the stove and that it can be stored conveniently: an eyelet for hanging and an elevated handle for stacking.

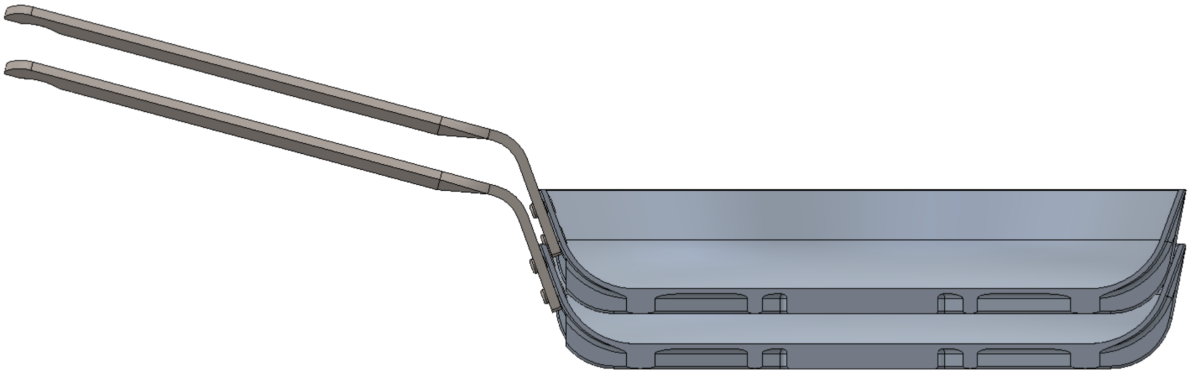


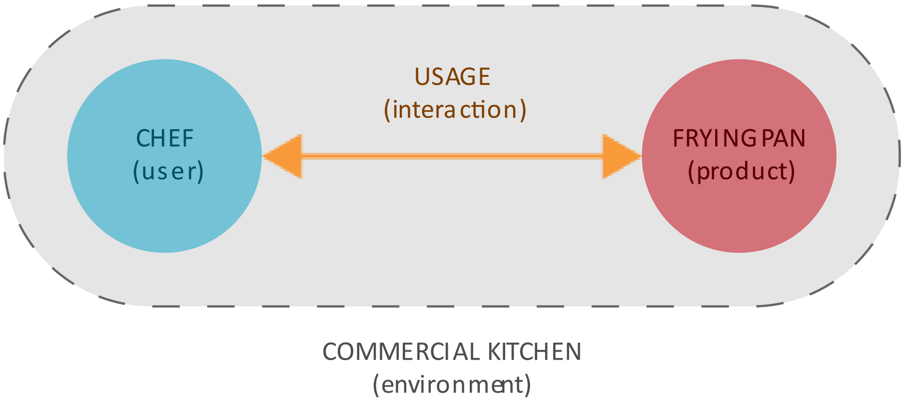
Figure 17 - section view of two prototypes stacked.

Figure 18 - prototype 2 hanging in the kitchen during a pilot test.

Chapter 1: Product Experience

This chapter aims to give an insight in the product-user interaction and supports the design decisions made in the user-experience realm. The main drivers in this realm which influence the design are the target user, scenario and environment. The goal of this phase is to establish a list of requirements relevant to the product-user interaction that helps shaping the final design. The following questions are relevant (5WH):

1. **Who** is going to use the product?
2. **What** is the product?
3. **Where** is the product going to be used?
4. **When** is the product used?
5. **Why** do people use the product?
6. **How** is the product used?



The presented information in this chapter is supported and derived from 39 interviews with people working in the gastronomy branch directly or indirectly related to a cooking activities with a frying pan. Over 12 different restaurants have been visited. The extensive list can be found in Appendix C. List of interviewees.

1.1. User

As described in the introduction, the product is targeted at commercial kitchens, like those of restaurants and other food-producing venues. The target user will be the chef working in the kitchen. The famous French chef August Escoffier (1846-1935) invented the kitchen hierarchy named the ‘kitchen brigade’. It dictates the typical hierarchy of kitchen personnel in a commercial kitchen, which is still common practise in restaurants today.

	Role	
1	Executive Chef	The top chef in the kitchen who oversees all culinary operations, creates menus, and manages the kitchen staff.
2	Sous Chef	The second-in-command who assists the Executive Chef in managing the kitchen staff, supervises the preparation and cooking of food, and may also be responsible for ordering supplies and maintaining kitchen equipment.
3	Chef de Cuisine	Also known as the Head Chef, who oversees the kitchen in the absence of the Executive Chef and manages the preparation and cooking of food

4	Chef de Partie	A chef who is responsible for a specific area or station in the kitchen, such as the sauté station, the grill, or the pastry section.
5	Commis Chef	An apprentice chef who is in training and works under the supervision of the Chef de Partie.
6	Kitchen Porter	A support staff member responsible for cleaning the kitchen and washing dishes.

The kitchen brigade gives a good understanding of the official members of a kitchen, i.e. the kitchen personnel which are the target users of our product. A variety of ranks of the kitchen brigade are interviewed throughout this project - from low to high ranked - to get feedback on the process and the product. Repeated interviews are conducted to track progress regarding the development of the pan. Pilot tests (both supervised and unsupervised, both single moment and multi-day) are performed with prototypes to get feedback from the field under unbiased and real-life scenarios.

Appendix C. List of interviewees and Appendix D. Pilot Tests offer an overview of conducted interviews & pilot tests.

Besides the user, there is also the purchaser of the pan (this can be the same person). They have different requirements for the pan. Both the user and the buyer can decide whether a certain purchase will be made: they are both part of the decision making unit (DMU), so both their requirements are important to understand. From the interviews and research conducted, the drivers that influence the overall desirability of a frying pan can be summarized:

Decision Making Unit	
User	**Purchaser**
Chef, kitchen personnel	*Manager, owner, chef*
Desired product attributes	
Thermal behaviour - a combination of heat stability, volatility & heat distribution.	Durable / longevity - the longer it lasts the lower the depreciation.
Usability - convenient cooking and usage of the pan to be able to do what it is mend for: frying food.	Sustainable - some parties care about sustainability to comply with certain certifications.
Ergonomics - ergonomic handle, good grip, not too heavy.	Cost-effective / affordable - low purchase costs, good return on investment or low operational costs compared to competitor product.
Cleanability - being able to conveniently clean the pan after usage. Both the frying surface as well as the polymerized grease on the bottom.	
Compatibility - compatible with multiple tools in the kitchen, like standard pan size, lids, dishwasher, oven and different types of utensils.	

The purchaser is mainly concerned whether the product yields a financial benefit or not. This benefit can be in the form of improved productivity, lower operational costs or a longer lifespan. In the contrary, the user of the pan mainly cares about user characteristics relevant to the work in the kitchen. The next chapter discusses how these characteristics can be found on available products on the market.

1.2. Product

The final concept will be casted in aluminium and anodized to enhance surface hardness. There are countless other combinations available on the market that offer each their distinct product qualities. The main differences are listed below, not only to get an overview of what the offering is, but also to see how variables like material and production process affect product characteristics and pricing. A frying pan can be systematically decomposed into the following functional variables, which relevance will be independently discussed in this chapter:

- Material
- Main shaping process
- Product architecture
- Surface treatment
- Handle
- Handle attachment

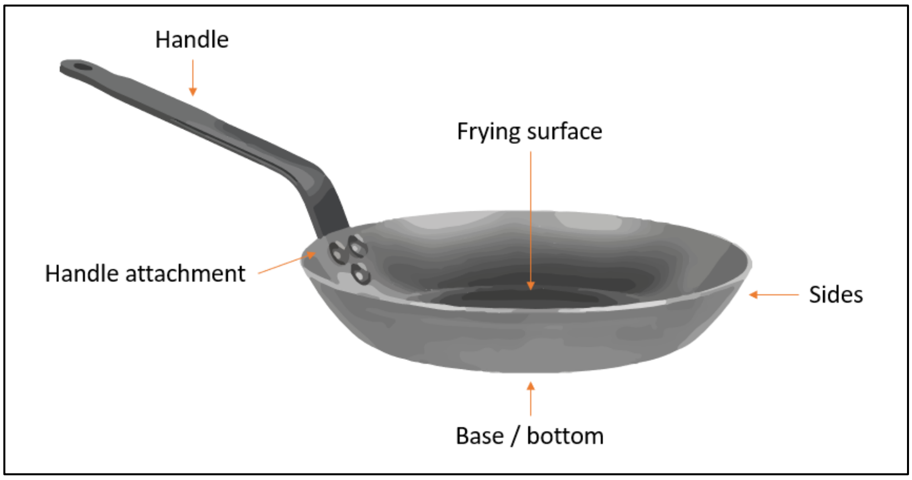


Figure 19 - basic anatomy of a frying pan

Material

The choice for material can be split up into two main categories that are available in the commercial kitchen equipment market: ferrous and non-ferrous metals, both with their distinct advantages and disadvantages. Many chefs indicate that ferrous pans (steel, iron) are favourable due to their durability and preferred thermal behaviour (high heat stability). However, the field research showed that chefs mainly use aluminium pans in the kitchen, because they are light, fast to heat-up/cool-down (high heat volatility) and affordable. Both metals need to be researched to find out how obtrusive their drawbacks are for the development of the pan: is a steel pan really to slow? Is an aluminium pan not heat resistant enough?

Material	+	-
Ferrous *steel, cast iron*	Durable, heat resistant	Not die-castable, heavy, slow
Non-ferrous *aluminium, copper, magnesium, zinc*	High conductivity, lightweight, die-castable	Less durable, less heat resistant, prone to warping, not food safe

Main shaping process

The above materials are commonly shaped via two main shaping processes: casting and sheet forming. Casting gives more form freedom, but also casting defects and potentially a lower material quality, like higher porosity which affects thermal conductivity (Biceroglu et al., 1976a). Sheet forming uses wrought materials that have close to pure characteristics, but the form freedom is limited to what can be cold-formed.

Main shaping process	+	-
Casting *sand-casting, die-casting*	Form freedom	Minimum wall thickness, porosity, energy intensive
Deformation *drawing, blanking, bending, stretching, forging*	High volume, cost-effective	Limited form freedom

Getting the fins onto a pan requires form freedom in the process. Therefore, the casting process is a promising method to research.

Product architecture

Product architecture describes in what fashion the materials are put together. Single-layer refers to a singular material. Multilayer refers to multiple materials either hot-rolled or -stamped together to achieve enhanced multilayer product characteristics. A common example is an outer layer of food-safe stainless steel which is durable and corrosion resistant (Figure 21, blue line), that protects the pure & highly conductive material like copper or aluminium on the inside relevant for enhanced heat distribution (Figure 21, yellow).

Product architecture	+	-
Single layer	Simple	Only 1 material, trade-off in properties
Multilayer *Disc-bottom, all-clad*	Multilayer/ multi-material advantages	Complex to produce, requires accurate production process control. If not done well, might result in thermal insulation interface, instead of the desired conductivity

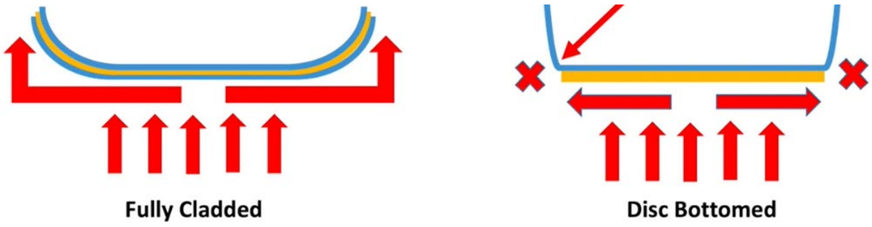


Figure 20 - schematic examples of different multilayer architectures.

If thin-walled (<1mm) stainless steel is used, multilayers are desired, because the steel itself may be very durable, but not conductive. In pans are made from high conductive materials (carbon steels, cast irons, copper or aluminium), no multilayer setup is required anymore.

Surface treatment

The surface treatment of a frying pan can serve three purposes: protection, non-stick properties and food safety. Surface treatment is crucial for not food-safe materials like aluminium, which is also relatively soft, especially when hot. The decrease in mechanical properties at elevated temperatures can lead to damage, like warping of the frying surface. In the case of an aluminium pan with a certain coating, if the protection layer wears off, aluminium can leach into the food so it is important for this layer to be durable. For delicate dishes, like fish, good non-stick properties are desired by the chef. Metal surfaces give the worst non-stick, ceramic coatings give fair non-stick and polymers (PTFE) give excellent non-stick. The table below lists the most used surface treatments:

Surface treatment	+	-
Ceramics	Durable	Wears-off
Enamel	Durable	Brittle
PTFE	Excellent non-stick	Wears-off fast
Seasoning	Natural, re-seasonable	Requires good care
Anodizing *(only aluminium)*	Durable, integrated, good heat transfer	Wears-off

An anodized and ceramic coating seem to have equal properties. However, the anodized coating is an aluminium oxide - which is conductive and improves heat transfer - whereas an ceramic coating is often a silica-polymer blend, which has very bad conductivity. Furthermore, an aluminium oxide layer is grown into the pan via anodizing, creating an integrated layer. However, this process is more expensive, but worth researching further.

Handle

A good handle does three things: makes the pan feel light (even when full), gives good control over the pan during usage and does not get too hot. Furthermore, it should be robust and heat-resistant since it is exposed to mechanical and thermal loads.

Handle	+	-
Steel	Heat resistant, oven safe, durable	Gets hot, high conductivity
Polymer	Stays cold, low conductivity	Prone to thermal deformation
Wood	Stays cold, natural touch & good grip	Prone to burning, absorbs water, can rot

Since chefs are continuously picking up hot things in the oven, they tend to walk around with an (oven) towel to prevent their hands from burning. Furthermore, most chef indicates that it is unpreventable to have a handle that remains cold and that a slightly hot handle is part of the trade. Durability and compatibility with the oven and the cleaning station weigh higher than a cold handle, therefore, the steel handle is desired over the other options. Attention has to be paid to selecting the right steel alloy with (ideally a low conductive alloy), getting the right shape, preventing sharp edges (deburring) and designing for effective attachment.

Handle attachment

One of the main failure points of a frying pan is a defective handle attachment. This can be solved by creating a highly robust handle attachment. From all the pans observed, a single or double point connection score unsatisfactory on longevity, because it results in possible movement through the orthogonal undefined plane. This can be solved by simply adding a third connection point, that statically determine the attachment. The follow attachments are studied:

Handle attachment	+	-
Screw	Simple, cost-effective	Weak, can unscrew, requires thread
Rivet	Robust, cost-effective, common	Requires holes, good tolerances are key
Bolted connection	Robust	Can unscrew, requires bolt, nut and washers
Weld	Robust	Conducts heat, energy intensive
Integrated *Casted, forged or bend together with pan*	Highly robust	Higher production costs, less modularity/design freedom, highly conductive

The most robust pans on the market are equipped with a three-point rivet connection. These seem to last the longest and are desired by chefs interviewed. The only challenge is to design a good interface connection, prevent galvanic corrosion at the interface, keep tolerances in mind and pick the right rivets.

Existing Pan Comparison

The tables underneath list the offering of frying pans from a renowned branch in the pan manufacturing industry. The pans of this brand (DeBuyer) are highly valued by chefs because they are qualitative, simple & robust. However, each of them has its own advantages and drawbacks which are outlined below.

All medium sized, 24cm diameter		
MSRP	€30	€120
Material	Aluminium	Aluminium
Process	Sheet forming	Casting
Architecture	Single layer	Single layer
Surface treatment	PTFE	Ceramic
Handle	Steel	Stainless steel
Attachment	3-point rivet	2-point rivet
Thickness	4 mm	6-9 mm
Weight	900 g	1.300 g
Advantages	Lightweight, affordable, good non-stick for how long it lasts	Thick bottom resistant to warping, good heat distribution
Drawbacks	Relative thin aluminium bottom is prone to warping, low abrasion resistance of PTFE	High total heat capacity results in slow cooldown rate

All medium sized, 24cm diameter		
MSRP	€40	€50

Material	Carbon Steel	
Process	Sheet forming	
Architecture	Single layer	
Surface treatment	None Seasonable	Pre bee-waxed Seasonable
Handle	Steel	
Attachment	3-point rivet	
Thickness	3mm	
Weight	1.400g	
Advantages	Robust, solid handle attachment, heat resistant, good heat stability	
Drawbacks	Bigger sizes are heavy, low heat volatility, seasoning offers no superb non-stick	

All medium sized, 24cm diameter		
MSRP	€45	€120
Material	Stainless Steel	Stainless Steel
Process	Sheet forming Hot-press	Sheet forming Hot-rolled
Architecture	Multilayer Disc-bottom	Multi-layer All-clad
Surface treatment	None	None
Handle	Stainless steel	Stainless steel
Attachment	Spot weld	3-point rivet
Thickness	6mm bottom	2.8mm
Weight	1.350g	1.200g
Advantages	Food safe, durable, corrosion resistance (SS304)	Food safe, durable, robust handle attachment, superb corrosion resistance (SS316)
Drawbacks	Food might scorch at the edges because the is no multilayer there (Figure 21), no non-stick	Expensive to produce, bonding several layers together requires accurate process control, no non-stick

To conclude, a major difference in usage characteristics can be seen between steel and aluminium pans. Aluminium pans require additional surface treatment, are more affordable but less durable. Steel pans do not require additional surface treatment, are robust and heavier so also less volatile in heating-up and cooling down. Pilot tests and interviews indicate that sufficient heat volatility is very important to enable high productivity in the kitchen, therefore aluminium is preferred over steel. However, the drawbacks must be taken into account and solutions are required for food safety and durability, such as a durable surface treatment.

Competitor Product: TurboPot

One competitor of NeoStove is 'TurboPot', a company which brought a more efficient set of pans on the market in the USA. Their product is - according to their website - twice as efficient as a conventional pan. This product has been tested during an experimental setup to verify this, and it has an efficiency gain of 1.5x (and not twice) according to experiments performed (Appendix E. Thermal Experiments).

TurboPot makes use of straight fins that are impact bonded onto the pan (Figure 23). This method seems to be cost-effective since TurboPot offers their pans online for $58 per unit. However, this method does not allow much design freedom or for fins to be continuing on the side of the pan. Thermodynamical tests show that side fins increase the thermal efficiency by 20% for the experiment performed on a 2 kW stove (5%-point, from 24 to 29% in the experiment). This is a significant increase. Furthermore, the fin setup does not allow for an optimal heat distribution. Therefore, this study aims to find a way of manufacturing a pan with radial side fins on an industrial scale, and leave room for further thermal optimization.

Figure 21 - TurboPot skillets as shown on their website (TurboPot, 2023).

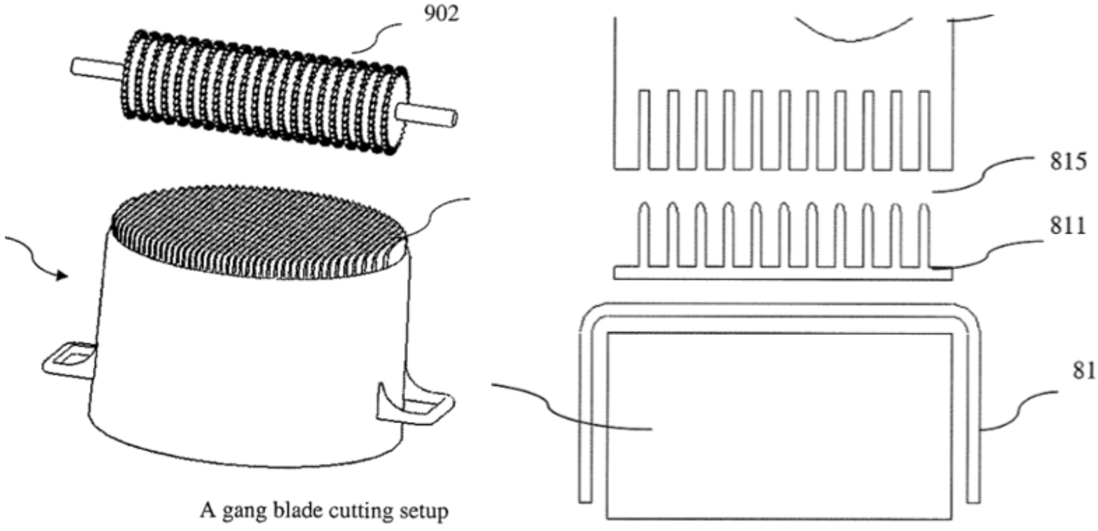


Figure 22 - documentation of the TurboPot US patent 'methods of making energy efficient cookware' (Huang, 2009)
Left: gang blade cutting setup for creating the straight fins. Right: visualization of impact-bonding the fins onto the pan.

1.3. Operational Environment

The commercial kitchen environment is vastly different from domestic kitchens. Processes occur on a significant higher intensity, with more power, more often and for prolonged periods of time. The dishwasher runs at 95 °C and the stove burners have a 5-10 kW power rating, compared to a respective 65-80 °C and 1-5 kW for domestic applications. This is one of the reasons - to illustrate - that for example PTFE-coated frying pans last merely 3 to 6 months. Especially during peak hours, there is no time to adhere to the operational manual of delicate items. Naturally, all delicate items have been out phased in the commercial kitchen in an evolutionary fashion. What remains, are tough and durable products that can keep up with the heat in the kitchen, often made from durable materials which offer thermal, cryogenic, mechanical and chemical resistance.

This tough environment creates a list of requirements that the product need to adhere to if it is willing to survive the natural selection process. Furthermore, it is important to note that both intended and unintended conditions need to be taken into account.

Intended conditions	**Unintended conditions**
Continuous temperatures up to 260 °C	Continuous temperatures above 260 °C
Wear-off frying surface through frying, utensils and rinsing	Wear-off frying surface due to metal utensils and harsh chemicals, e.g. from the dishwasher
Mechanical load on handle (10 kg)	Mechanical load on handle above 10 kg
Exposure to sodium and natrium compounds	Impact forces due to dropping
	Strong chemical compounds present in cleaning substances (natrium hydroxides, natrium sulphate, decyl octyl glycosides and glucopyranose)

Longevity of the product is difficult to predict due to majority of variances among user environments. Chefs have been interviewed that wear-out a frying pan within weeks, but other chefs take good care of their pan and manage to use it for over a year. In that regard, both intended and unintended conditions have to be designed for as much as reasonably possible.

1.4. Usability: cooking & secondary use cases

Usability is quite a broad concept that encompasses the full usage of a frying pan. To simplify things, the usage can be split up in two categories: its primary usage (cooking) and secondary usage, such as storage, cleanability, compatibility with other kitchen equipment, etc.

The following table illustrates a typical process of preparing a meal with a frying pan, of which both primary and secondary usage processes can be distilled:

Occurrence	Order comes in	Chef puts pan on fire	Pan is hot, start frying	Frying done	Dish served	Use pan again / Store away
Action		Pan heating up, in the mean-time, prepare cold side of the dish	Frying + continue preparing dish	Make plate	Wait for pan to cool down	Wash pan
Time		2'	5'	1'	3'	1'
						Σ = 12'

The process of preparing a meal takes 12 minutes in the above example, which is a gross average of observations. The main bottleneck is the heat-up time of the pan. In some restaurants, pans are pre-heated if possible to reduce the heat-up time. However, this requires an extra step which only works if there are enough pans available and there is plenty of space to do so. As field research found out, many restaurants are located in city centres where space is scarce and kitchens are small. Furthermore, during rush hour the pre-heating of pans is the first step in the process that will be cancelled out, both due to a lack of pans that are used-up as well as no time to do so. Therefore, it is beneficial to enable a fast heat-up time of the pan.

The following table illustrates the same process with prototype 2 (V2). Gains compared to a conventional frying pan are marked in green.

Occurrence	Order comes in	Chef puts pan on fire	Pan is hot, start frying	Frying done	Dish served	Use pan again / Store away
Action		Pan heating up, in the mean-time, prepare cold side of the dish	Frying + continue preparing dish	Make plate	*Wait for pan to cool down*	Wash pan
Time		1'	5'	1'	2'	1'
		Pan is hot within a minute	*Some dishes might be done slightly faster*		*Faster temperature response, quicker cool down*	Σ = 9'

The main gain is within the heat-up time of a pan, especially compared to steel pans, the first prototype (V1) warms-up very fast according to the chefs. The main findings are:

- Heat-up time can be easily boosted with thin walls, but will come at the expense of heat stability, heat distribution and resistance to warping/general robustness;
- There is hardly a time gain on the frying time of dish; chefs indicated that this is impossible, but pilot tests showed that a hotter pan can get some dishes done slightly faster;
- A too fast and hot pan is not desired, because it requires constant attention and increases the risk of burning food;
- Cooldown time is also important for two reasons: accurate temperature control to prevent burning of food after the fire is turned off, and the pan needs to cool-off slightly before it can be washed and stored away.

Primary usage: cooking

Apart from simply heating up food, a certain browning of the food is desired, called frying, hence the word ‘frying pan’. This browning is created through the Maillard effect occurring at temperatures between 145 and 165 °C degrees, resulting in an enhanced taste. The terms frying, braising and searing simply refer to the process of creating the Maillard effect to enable desired food characteristics. The following table lists typical pan temperatures for different modes of cooking.

Cooking mode	**Heat**	**Temperature**	**Heat transfer**	
Fry	High	> 150 °C	Wet	Convective
Sear	High	> 150 °C	Dry	Conductive
Braise	High & low	> 150 °C, then simmer < 100 °C	Dry & wet	Convective & conductive
Sauté	Medium	> 100 °C	Wet	Convective
Simmer	Low	< 100 °C	Wet	Convective
Maillard reaction		*140 – 165 °C*		

Besides heating up food and creating the Maillard Effect, one important aspect is the circumvolution of the food to ensure all-around and even frying. This circumvolution in a frying pan is done via two main fashions: stirring and wokking.

Figure 23 - different modes of moving food around.

For stirring, the following attributes are important to optimize to enhance product experience:

- Weight & stability, to prevent the pan from moving or tipping over during stirring;
- Durability of frying surface (surface treatment/coating), to prevent wearing. The pan should have the hardest and wear resistant surface viable, because it drastically increases the lifespan;
- Side height and curvature, to prevent the food from falling out

For wokking, the following attributes are important to optimize to enhance product experience:

- Pan handling ergonomics, because the pan needs to be lifted and moved around, also when fully loaded;
- Side height and curvature, to have the food tossing over instead of falling out

Good shape and dimensioning of the sides are important for an intuitive and desired wokking workability and to prevent food falling out of the pan. Further details on the topic of ergonomics are discussed in chapter 1.5. Ergonomics.

Action	Influential	Variables
Stirring	Side height and curvature	Side height
		Side radius
	Stability on stove	Weight
		Fin/bottom geometry
	Durability of frying surface	Hardness of surface
		Wear-rate of surface
Wokking	Side height and curvature	Side height
		Side radius
	Handle ergonomics	Handle position
		Handle shape
		Handle dimensions
		Handle material and temperature
		Weight and weight distribution

The above topics are crucial to ensure a proper working of the pan during cooking. Figure 25 gives a schematic overview of some dimensional variables that influence usability of the pan.

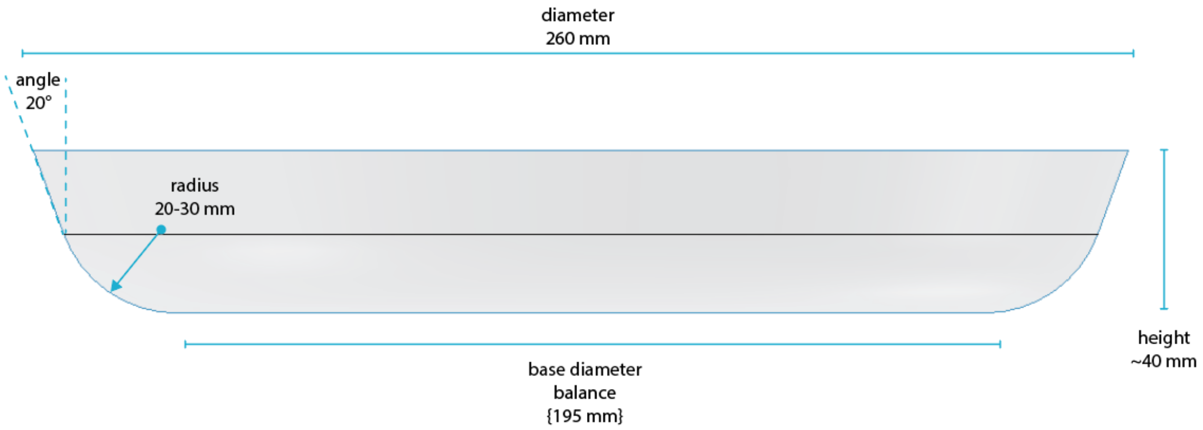


Figure 24 - schematic overview of parameters that influence usability of the pan

The shape and dimensioning of the side is crucial to enable wokking and tossing, whilst preventing the food from falling out of the pan. Multiple pans are analysed and discussed with chefs. Based on their input, a set of PLA 3D prints is made to verify the shapes through a iterative rapid prototyping manner. The shape of the pan is determined by the dimensions of the sides, combined with the size of the pan, also referred to as (outside) diameter:

1. Size of the pan (diameter = 260mm)
2. Side angle
3. Side radius
4. Side height

See Figure 25. These 3 parameters determine the base diameter, also called 'effective frying area'.

The (1) size of the pan is fixed, in this case at size medium (260mm) which is a universal and highly common size in the kitchen. If the (2) side angle is too large (horizontal), the food will slip out during wokking. If the side angle is too steep (vertical), it is not possible to toss food around: it will just bounce against the side wall. The ideal angle is found to be 20 degrees, enabling smooth tossing and retracting of the food. The (3) side radius should enable smooth transition between base and side wall. If the radius is too small, the food also bounces against the side wall. If the radius is too big, the transition from base to side is smooth, but the effective frying surface will decrease drastically in size, reducing the amount of food a chef can fry in the pan. The ideal radius for a size Ø260mm pan is found to be 30 mm. The ideal (4) side height of the sides are approximated at 40 mm. This creates enough space to wok the food around without the risk of it falling out of the pan. Higher sides increase the content of the pan, however this will result in a smaller base diameter, reducing the effective frying surface.

Secondary usage

As described in the previous chapter, pans are operated in a highly dynamic environment with wide variety of users and tools. The pan needs to seamlessly integrated in the existing workflow of the kitchen. Product attributes like cooperability, versatility and compatibility within the kitchen environment are crucial.

Storage

Pans need to be stored conveniently without damaging other product or itself. Storing mainly occurs in two manners: stacking and hanging. Therefore, the following design features are taken into account:

- Eyelet for hanging
- Smooth corners and curvatures, no sharp edges to prevent damage to adjacent equipment and users. Especially with the new fin configuration this is a new point of attention.
- Scratch-proof hard-anodized surface;
- Size compatibility so that the pans can be grouped by universal size and can be stacked into each other

Standing on stove

When the pan is standing on the stovetop, two points are important: first of all, the pan (especially its handle) should not clash with neighbouring pans. Secondly, a stable and smooth interface should be established between the bottom of the pan and the grates of the stove. This is compromised due to the introduction of the fin structure, compared to a conventional pan.

The handle requires a minimum starting height of 50 mm to prevent clashes with neighbouring pans and enable optimal use of space on the stove (Figure 24). Among all the frying pans analysed, 50 mm is the maximum typical height.

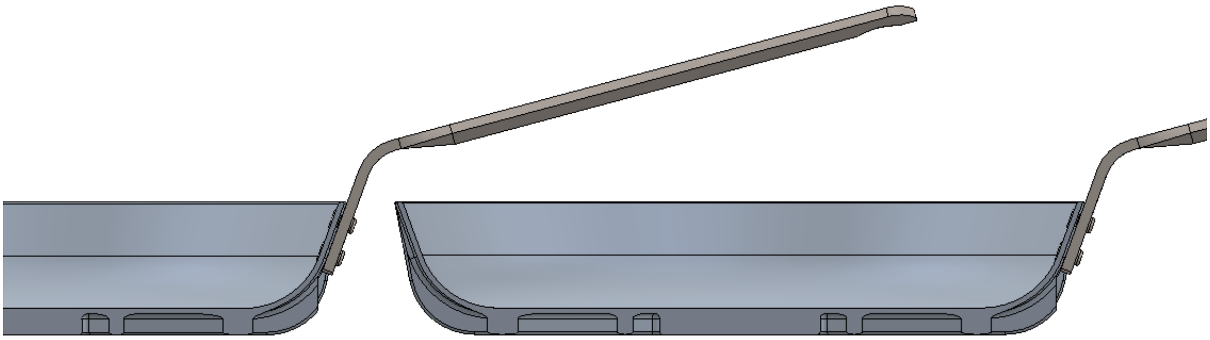


Figure 25 - image of two pan close to each other with overlapping handles.

Figure 26 - Prototype 2 (V2) on commercial kitchen stove in one of the pilot restaurants.

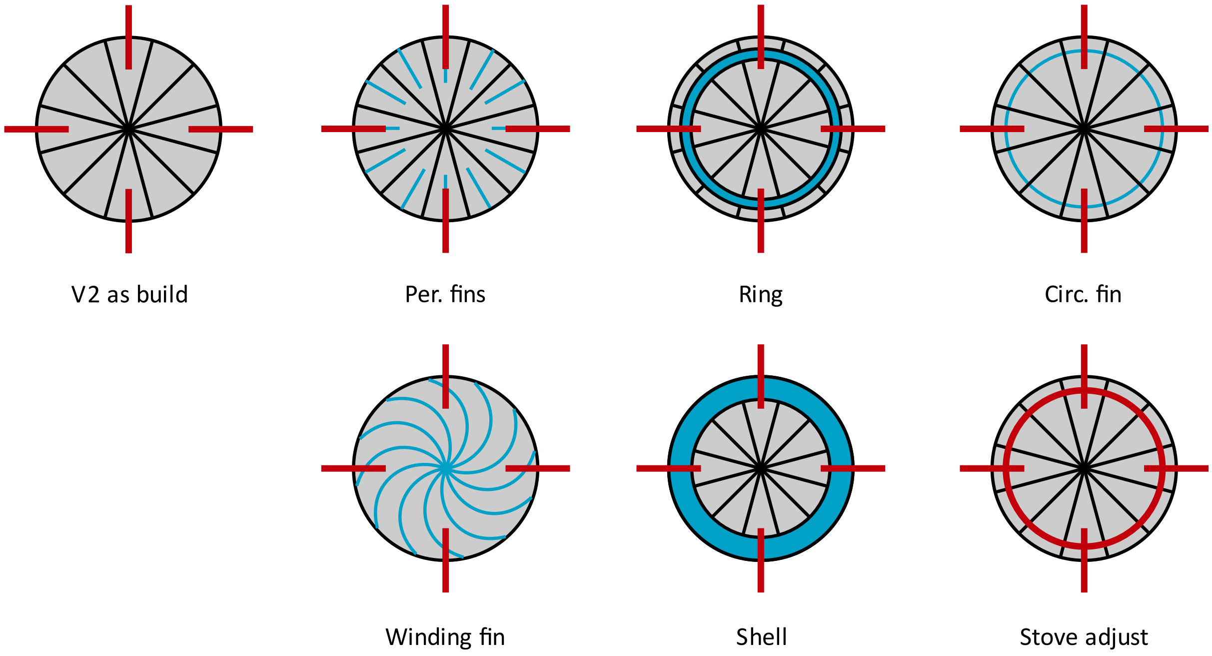
Chefs like to move their pans around on the stove, without taking the effort to lift them. Pilot testing showed that this 'sliding' phenomenon is compromised due to the introduction of fins especially with the second prototype, V2 (Figure 24). A selection of solutions is proposed:

A. Circular ring
B. Circular fins
C. Peripheral fins
D. Winding fins
E. Shell (V1 has a shell)
F. Stove adjustment

These six concepts are scored on the following five parameters:

Parameter		Requirement
Stability		Should not tip over or wobble on a 4 grate stove top.
Slideability		Should be able to slide around and rotate without any hick-ups, like a normal pan.
Production complexity and costs		Should have no separate components, non-retracting or non-reachable features. Ideally single step main shape production.
Thermal performance and behaviour		Should cater for the most optimal airflow, efficiency and characteristic length. Should be relatively low in weight as well.
Robustness		No thin, sharp, separable or protruding features. Integrated features are preferred over separately assembled features.
Cleanability		See next chapter. No small cavities and channels. Every part should be directly reachable for optimal cleaning.

The solutions are visualized in Figure 25. The adjustments that aim to solve the stability are coloured in blue. The stove grates are coloured in red, and are typically 5-10 mm thick. The images are not to scale, and only the base is visualized from a bottom view (not the sides).


V2 as build

Per. fins

Ring

Circ. fin

Winding fin

Shell

Stove adjust

Figure 27 - concepts to improve stove top stability. Stove grates in red. Proposed adjustment in blue.

All options except two (peripheral and winding fins) are certain to enable slideability and stability on the stove. To tackle the uncertainty of the remaining two, their bottom geometries are 3D printed to assess their slideability and stability in practise (Figure 26).

Figure 28 - left: peripheral fins, right: winding fins.

With both options, the stability increases to a desired level compared to a regular setup as made in V2. However, the slideability of the peripheral fin setup is still not superb, having some irregularity and friction when sliding around. The winding fin arrangement performs remarkably well: it is easily rotated and slid around, given that the stove grates are level and have no protruding features.

Now the practical uncertainties are tackled, the solutions can be rated on the relevant parameters. The first 4 parameters have a weight factor of 2, and cleanability has a weight factor of 1. Two points are assigned if it completely satisfies the requirement, 1 point if it positively satisfies the requirements, -1 point if it dissatisfies the requirement and -2 points if it crucially dissatisfies the requirement.

	Peripheral fins				**Circular ring**				**Circular fin**				**Winding fins**				**Shell**				**Stove adjustment**			
	-2	-1	+1	+2	-2	-2	+1	+2	+2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Stability		🟧						🟩			🟩				🟩					🟩				🟩
Slideability		🟧						🟩			🟩			🟧						🟩			🟩	
Complexity				🟩		🟧						🟩			🟩			🟧				🟧		
Thermal				🟩				🟩	🟧							🟩			🟩					🟩
Robustness				🟩		▨	▨					🟩				🟩		🟧					🟩	
Cleanability				🟩	🟧							🟩			🟩			🟧					🟩	
Weighted	10				8				10				11				5				11			

The two best rated solutions (peripheral fins and winding fins) score the worst on the to be improved parameters: stability and slideability. The third best option, circular fin, drastically compromises thermal efficiency. Another good option would be a stove adjustment, but any adjustments are undesired according to the client since the pan should be universally and directly deployable. The circular ring, as seen on some Chinese counterparts (Figure 27), offers ideal stability and slideability, but it requires - like the shell - an additional part that needs to be well assembled, increasing part complexity and risk for failure. For the same reasons, a shell scores low, because it adds weight, costs and complexity. Although the rating of the solutions are in close proximity, the highest rated ‘winding fins’ solution will be developed further.

Figure 29 - fin configuration of Chinese product with circular ring.

Cleanability
A major problem with especially frying pans is that they get dirty quickly, due to the burning of food onto the pan, called polymerization. Therefore being able to clean the pan with all the measures possible is desired. However, with the introduction of fins and airducts, cleaning the irregular surface becomes a lot harder compared to conventional pans. The general rules are:

- By having a more abrasive resistant surface, more thorough cleaning measures can be used, like sponges and brushes, without wearing-out the surface;
- By having a smooth surface, the dirt spots can be reached easily;
- Having a non-iron surface leads to less covalent chemical bonds to be formed between the food and the pan, resulting in less sticking of especially protein rich foods.

Do’s and don’ts for improved cleanability:

	Do	**Do not**
Surfaces	Flat	Rough
Transitions	Even	Uneven
Angles	Smooth radii	Sharp corners
Cavities	Accessible, shallow and wide	Inaccessible, deep and narrow
Cleaning - chemical resistance	Chemical proof	Chemical deterioration
Cleaning - mechanical resistance	Abrasion resistant surface	Soft surface

Harsh cleaning chemicals make use of potent chemicals to remove highly polymerized dirt. They contain natrium hydroxides, natrium sulphate, decyl octyl glycosides and glucopyranose (Granta, 2022; HG, 2022). Stainless steels are resistant to these chemicals, but aluminium is not, so it requires a durable and chemical resistant coating.

Other versality and compatibility features
Other compliances that enable kitchen compatibility are:

- Oven-safe, so no wooden or plastic components on the handle with a melting/combustion temperature below 260 degrees Celsius;
- Dish-washer safe, all around corrosion resistance, hot water temperature resistance and resistance to dishwasher chemicals and detergents;
- Use of standardized sizes, so that the pan can not only be stacked, stored and used conveniently, but also for lids to be swapped around universally

1.5. Ergonomics

Chefs use their frying pans several hours per day, so a specific point of attention should be dedicated to interactive ergonomics. A badly designed pan increases strain on the user and can lead to repetitive strain injury (RSI) and musculoskeletal disorders (MSD). Especially ligaments and joints of chefs in the wrist and shoulder are prone to injuries due to constant heavy loads and odd gripping positions (Karelia et al., 2021; Tan et al., 2021). User interviews and pilot tests showed the following complaints about current handles with respect to ergonomics:

- Flat metal handles 'cut' into hand palm;
- Completely round and smooth handle is neither desired, since it requires squeezing to prevent the pan from rotating around the axis of the handle with full loads;
- Handles that are too low and close to fire get hot and might come into clash with other pans, which makes them difficult to grasp;
- Metal handles can get hot. This is not a big problem because chefs always have a towel around, but it is desired to have a handle that remains 'cold' (≤ 50 °C) and is oven-compatible (glass transition temperature > 250 °C)

Good handles possess the following characteristics according to chef interviews:

- Reduce the perceived effort to lift a heavy pan
- Give a good grip and control over the pan, even with full loads
- Do not cut into the hand
- Do not get too hot (<50 °C) under typical frying conditions
- Are oven-compatible
- Are simple and robust

Three sub topics are addressed to ensure ergonomic usage of the pan:

A. Handle position, shape and dimensions
B. Handle material and temperature
C. Weight and weight distribution

A. Handle position, shape and dimensions

The handle of the pan is an important component, because it is the predominant location that the user physically comes into contact with the pan. This study does not aim to analyse and redesign a completely new handle, it rather looks at existing handles to mimic good characteristics and either omit or improve upon bad characteristics.

The first topic is the general positioning of the handle, which is affected by three variables (Figure 25):

- Starting height
- Angle relative to the horizontal
- Grip length

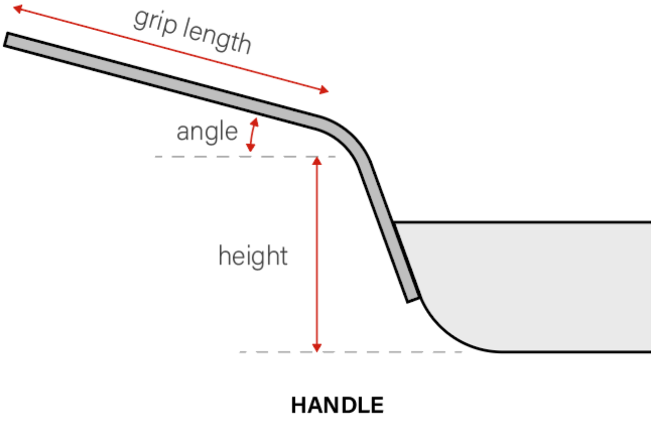


Figure 30 - general positioning variables of the handle.

These three variables strongly determine the gripping position and coherent ergonomics of the user, as can be seen in Figure 26. For ergonomics, the handle should be as low as possible to also allow for smaller people to have an ergonomic gripping position. However, paragraph 1.4 'Secondary usage' dictates that the handle should start at an height of at least 50 mm to prevent clashes with neighbouring pans. The angle of the handles of the highly appreciated DeBuyer pans are 20 degrees. Although being a good handle, this angle is perceived as too much, uncomforting the gripping position. Therefore, it is reduced to 15 degrees, which is seen as an improvement by the chefs. It also prevents smaller chefs to over-contract their forearm through the horizontal, which is perceived as strenuous and is the case with a 20 degree handle. The grip length is approximated at p.95 hand length (±200mm), this is equal to existing handles on the market.

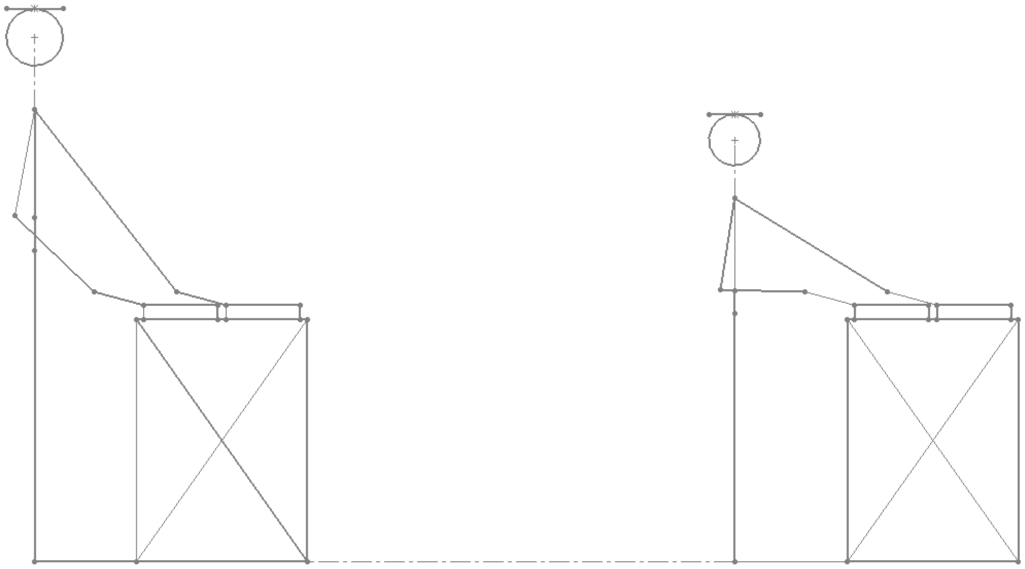


Figure 31 - p.95 and p.05 person grabbing a pan on top of a 0.85m high stovetop given the aforementioned dimensions.

By taking a section of the handle, the dimensioning can be distinguished that largely determines the comfort of the grasp. Looking at the section, the following variables are relevant (Figure 27):

- Width
- Height
- Section radius
- Edge fillet

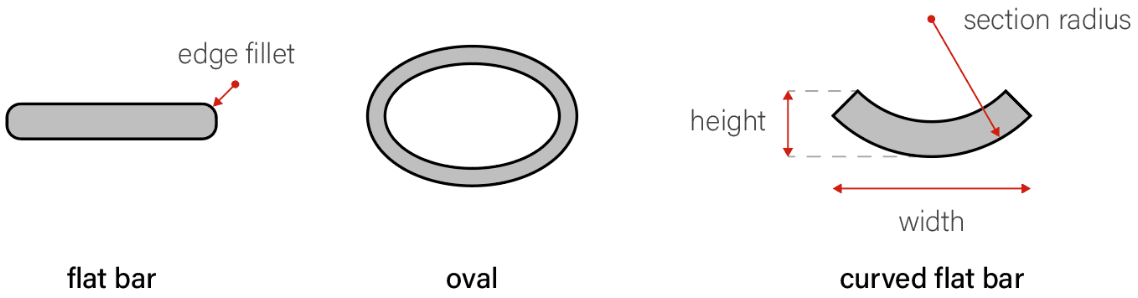


Figure 32 - proposed handle sections.

The most common shapes find their origin in a flat bar or a tube. For polymer handles, it is a solid rather than a tube. The width of the handle should be wide enough to prevent rotation of the pan around its axis. Therefore, a perfectly round section would not suffice. The maximum width is limited by the hand size p.05 from DINED, at approximately 30 mm. Any smaller would require more gripping force to prevent rotation, any larger would pose problems for people with small gripping circumference. The height of the handle section is relevant for creating a smooth grip along with the coherent section radius. Naturally, a larger hight would enable an all-around curvature. This height should be smaller than the width to enable good gripping orientation, i.e. < 2/3 of the width. The section radius should be R20 - 40 mm. Lastly, if a flat bar / rectangular profile is chosen, the edges should have a fillet of R≥2 mm to prevent 'cutting' in the hand.

	Variable	**Requirement**
General	Handle starting height	≥ 50 mm
	Handle angle	± 15 deg
	Grip length	± 200 mm
Section	Width	± 30 mm
	Height	balance
	Edge fillet	R ≥ 2 mm Smooth edge
	Section radius	R 20 - 40 mm

The following DINED dimensions are used.

	2004		2016	
values in mm	**Dutch adults (20-30) mixed**		**Dutch students (17-27) mixed**	
	p.05	*p.95*	*p.05*	*p.95*
elbow height, standing	962	1206		
shoulder height	1275	1585		
arm length	630	810		
elbow-grip length	297	385		
hand grip circumference	108	150		
length pointing finger			64	80

B. Weight & distribution

The weight of the pan affects a lot of properties. From an ergonomic perspective, the pan should comply with occupational health and safety requirements, in the Netherlands this is the ARBO-legislation. A fixed weight limit does not exist, but the recommended weight limit (RWL) is determined by internationally acknowledged formula from the National Institute for Occupational Health and Safety (NIOSH):

*RWL = load weight * horizontal movement * vertical movement * rotation angle * frequency * duration*

The variables in this formula are multiplied by a specific weight factor, so it cannot be simply replicated. However, the formula gives a good indication of variables that matter. The exact formula and multiply factors can be found in Appendix M. *NIOSH recommended weight lifting* formula. The outcome of this method is the following recommended weight limit:

RWL = 6.25 kg (depending on specific use case and variables).

Besides the ARBO-legislation, there is also the NEN-norm. The NEN-norm for pans describe that a second handle is required for pans over 5 kg when filled up with water to their given limit (*NEN-EN 12983-1 General Requirements*, n.d.). Since a second handle is perceived as highly inconvenient by chefs, the requirement is to have the full-loaded weight of the pan not to exceed 5 kg. The content of a 26 cm pan is roughly 2 litre, resulting in a maximum pan weight of 3 kg. This is a lot, and undesirably heavy. Chefs were asked what they feel is a good weight for pans they work with in their kitchen. Based on this, the upper weight limit is 1,6 kg. Ideally, lighter is better.

The centre of mass should be colinear in line with the handle, preventing the pan from out of balance rotations. A slightly heavier handle is preferred, moving the centre of mass closer to the handle.

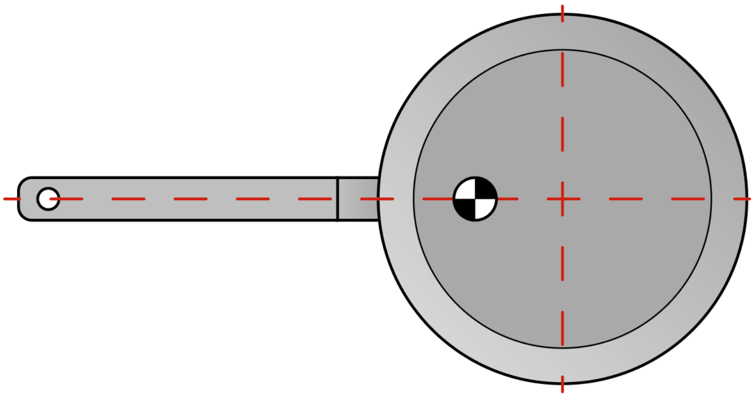


Figure 33 - centre of mass approximation.

C. Material and temperature

The handle should not get too hot. In contrast with the pan itself, the handle should be made from low conductive materials and isolated from the hot air as much as possible. Therefore, it is suggested to make it from stainless steel: one of the lowest conductors of all metals (15 W/m.k) and excellent thermal durability, corrosion resistance and strength.

1.6. Thermal behaviour

When chefs talk about their favourite pan, one of the main topics that they want to explain is the thermal behaviour of a pan. It might be difficult for them to translate this into objective physics, but its importance may not be neglected. In the contrary, the thermal behaviour of a pan is what makes it beloved or hated among chefs. This chapter aims to give an insight in the desired thermal characteristics of a pan from a user perspective. The table underneath lists two ends of a spectrum: thin-walled lightweight pans versus thick-walled heavyweight pans. It illustrates the characteristics that the pans at either side of the spectrum possess. The desired characteristics are marked in green. The goal is to develop a pan that possesses all of the desired attributes listed underneath, which may be difficult due to their opposing nature.

			
Weight	*Light*	*Medium*	*Heavy*
Wall thickness	*Thin*		*Thick*
Heat volatility *heat-up & cool-down time*	*Fast*		*Slow*
Heat stability *total heat capacity*	*Low*		*High*
Heat distribution *hot spots*	*Poor*		*Good*

Heat volatility: heat-up and cooldown rate

Ideally, the pan should heat up and cooldown fast for enhanced control over the pan, so that chefs safe time waiting for the pan to be at the desired temperature. However, a high volatility inherently results in lower heat stability, which can compromise predictability and might result in burning food.

Heat stability: heat capacity

When the chef is cooking and puts food in the pan, a cold mass enters the hot pan. According to the 0^{th} law of thermodynamics the temperature will cancel out and reach an equilibrium. The heavier a pan, the more heat energy is stored and the temperature will be more stable. If a pan is light, it can only hold a small amount of heat, resulting in the temperature to drop more fiercely. This phenomena is called 'heat stability'. To enable a consistent Maillard effect on the food, the temperature may never drop below 150 °C after food is added to the pan, otherwise it will cook the food instead of frying it, compromising food quality. Therefore, chefs like a pan with sufficient heat capacity. However, a too high heat capacity (i.e. a ‘too stable’ pan), can lead to slow heat-up and cooldown times.

Heat distribution

The pan should be heated uniformly to prevent hotspots and cold spots. Thin-walled pans have poor heat distribution because there is less material for the heat to propagate and spread through, leading to localized burn spots, whilst other parts are not hot enough to create the Maillard effect.

Chapter 2: Thermodynamics

Within the development of a conventional frying pan, the topic of thermodynamics seems largely underexposed. The introduction of thermodynamics is what makes this project innovative and potentially evolutionary: a new solution to an existing way of cooking. This chapter aims to decompose the thermodynamics from A to Z of a frying pan and looks at what effect certain design decisions have on the frying pan: both in a behavioural and mechanical manner.

2.1. Thermal efficiency

Thermal efficiency of a frying pan is the amount of heat (energy) absorbed by the content of the pan, divided by the amount of heat (energy) used in the total system, i.e. what is combusted by the gas stove. The following formula described thermal efficiency:

$$\eta = \frac{|W|}{|Q_{in}|}$$

$$\eta = efficiency$$

$$Q_{in} = energy\ added\ to\ the\ system\ (combusted\ gas)$$

$$W = work\ done\ (heatup\ of\ content)$$

Thermal efficiency is in the end the main performance indicator that the client aims to improve. Experiments conducted (Appendix E. Thermal Experiments & Outcomes), online sources and research (Karunanithy & Shafer, 2016) show, that conventional pans have a thermal efficiency ranging from 10% to 30%, depending on type of pan, material, size, burner setup and specifications. This is low, especially given the fact that pans are existing for thousands of years and largely remained the same without a significant change in efficiency.

One way to determine the thermal efficiency of a pan is to do a boiling test. It takes approximately 315 kJ to boil 1 liter of water from room temperature (20 °C) to 95 °C (95 °C is taken instead of 100 °C due to the phase change of the system and losses in latent heat). To calculate the work that needs to be done, the following formula can be used:

$$W = m.C.dT$$

$$m = mass\ of\ content$$

$$C = specific\ heat\ capacity\ of\ content$$

$$dT = temperature\ difference\ between\ start\ and\ end\ state$$

$$W = 1\ [kg] \cdot 4200\ \left[\frac{J}{kg.K}\right] \cdot 75\ [K]$$

$$W = 315\ [kJ]$$

To determine the amount of energy that is put into the system Q_{in}, it is required to know how much gas is combusted up until the moment the water reaches 95 °C. This can be done in a variety of ways:

1. Determine the power of the burner used, ensure consist pressure
2. Weigh the amount of gas that is combusted
3. Add a pressure gauge and flow meter to the system

To give an example, for an average pan, it takes 5 minutes to boil 1 liter of water on a 5 kW gas stove on full power.

$$Q_{in} = 5\ [kW] \cdot 5\ [min] \cdot 60\ [sec]$$

$$Q_{in} = 1500\ kJ$$

This gives the following net thermal efficiency:

$$\eta = \frac{|315\ [kJ]|}{|1500\ [kJ]|}$$

$$\eta = 21\%$$

However, with the same pan and the same amount of water, it is also possible to reach a higher efficiency due to different environmental influences. The efficiency is depended on a variety of parameters, which not only involve parameters of the pan itself. There are two main strategies to improve the efficiency:

- Product optimization, by adapting the material and shape of the pan
- External optimization, by adapting the stove and the pan's direct surroundings

In this project, the scope is to optimize the product, not the external factors. Preliminary conducted research found out that external factors are largely fixed and restaurant owners are not willing to change their stove setup frequently, since it requires a larger intervention than swapping around pans.

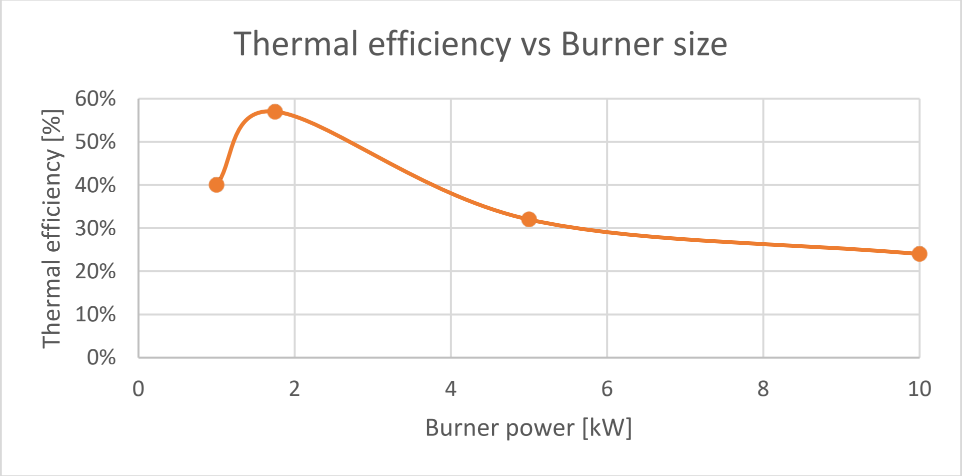


Figure 34 - thermal efficiency versus burner rating with the same pan.

When comparing the thermal efficiency of two pans among each other, it is required to have them tested at the exact same test setup to ensure a fair comparison such that external influences are kept to a minimum.

The main idea of improving the thermal efficiency of throughout this project is to enhance the characteristic length of the pan. The characteristic length is the ratio between volume of a body and its effective surface area. The characteristic length is denoted as:

$$Lc = \frac{V_{body}}{A_{surface}}$$

Aiming to have this value as low as possible results in a faster and more effective heat transfer. Lowering volume means less mass to heat up, thus less energy wasted when heating up the pan resulting in a higher efficiency. A higher surface area means more area to capture heat from the hot air, also resulting in a more efficient pan. Examples from the industry that make use of this principle are heat exchangers and heat sinks. They exchange heat from a hotter to a colder medium through use of optimized surface area.

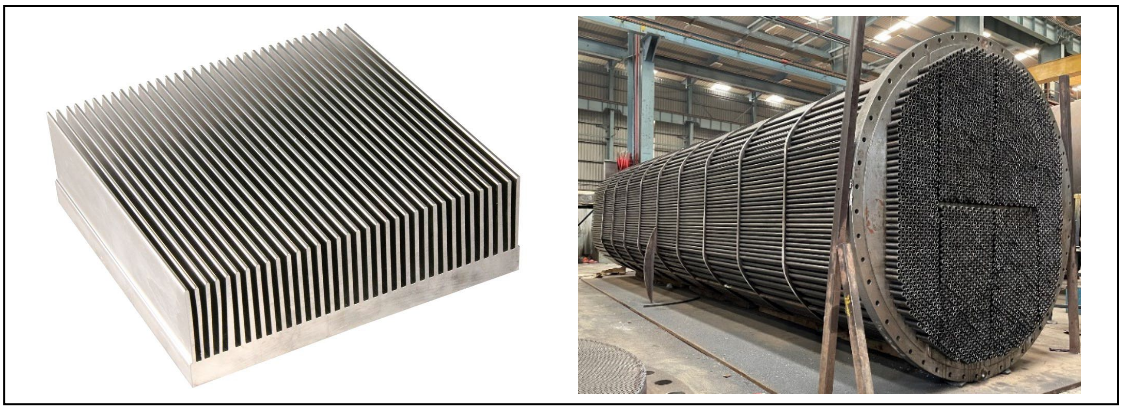


Figure 35 - heat sink (L) and industrial heat exchanger (R).

This same principle can be seen on the first prototypes of the client's pan. These prototypes are significantly more effective than a regular pan (36% versus 17% when boiling 1L of water on 5kW stove) and proofed the concept of a more efficient pan (Appendix E. Thermal Experiments & Outcomes). These designs are used as a starting point for the design of the frying pan.

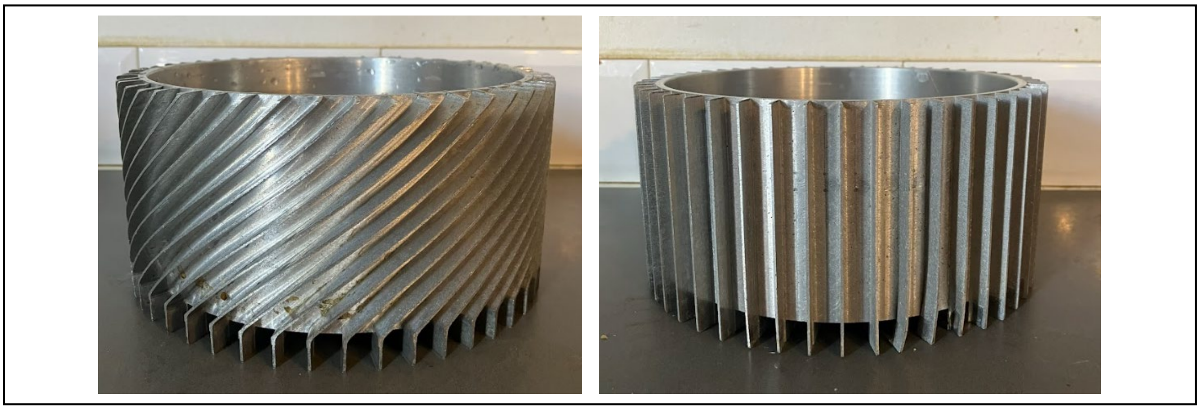


Figure 36 - proof-of-concept prototypes (V0).

However, improving thermal efficiency of a frying pan is not as simple as changing the characteristic length as much as possible. Other factors are at play and solving them can be split up in two domains:

1. Advanced thermodynamics, such as convective thermodynamics, modelling and simulating to incrementally improve the thermal efficiency. This is a topic that this project will not cover. The scope of this project is to see if the concept of a more efficient frying pan is desirable for the target user, feasible for series-production and viable for the client;
2. Thermodynamics for product experience, which is among the scope of this project. Having a super-fast and efficient pan is not always desirable. It might result in an uncontrollable pan that burns the food rather than frying it. The considerations when designing a thermodynamically improved pan will be covered in the following chapter.

2.2. Thermal performance and behaviour

This is a topic where objective mathematics meet subjective user-perception. This paragraph aims to translate the sometimes subjective and irrational desires of a chef into the underlying mathematics.

As described in the previous chapter, a chef wants to have a fast heat-up time (but not too fast), a heavy pan (but not too heavy), and a fast cool-down time (but not too fast). This all relates to the cooking behaviour of a pan. If you ask a chef about his opinion on a cast iron pan (which is heavy), there is a solid chance that he will say that it is the best pan that exists, because it cooks so ‘nice’. If you look around in the kitchen of the chef, there is not a single cast iron pan to be seen. Why this discrepancy?

Heat volatility: heat-up & cool-down time

Chefs want to have a quick heat-up time of their pan so they can start cooking and save time. After cooking, it is desirable to have a pan that does not stay hot for long, so the pan does not burn food after it is taken of the fire. Both of these parameters are concerned with a rate of temperature change of the pan: the faster the temperature changes, the better the thermal performance of the pan. These are basically the ‘horse powers’ of the pan: temperature change rate (TCR) in Kelvin per second.

$$\dot{T}\ [K/s]$$

Estimating the exact heat-up and cooldown time of a yet to be build prototype can be quite an complex task, since there are three modes of heat transfer that need to be combined: radiation, convection & conduction. For this study, the *exact* heat-up time is not a prerequisite; merely an estimation model is required that can assess the relative impact of a design decision: for example, what is the influence of changing the wall thickness from 2 to 3 mm. Since gas stoves are a predominantly a convective heat source, the main mode of heat transfer is through convection. According to performed research, radiative heat transfer is rather small during the combustion of fuels and may be neglected (Edwards & Balakrishnan, 1973; Macmillan & Beck, 1989). Since a pan is not a solid but a thin-walled product, it is assumed that there is a uniform temperature distribution throughout the product and no temperature gradient. Hence, the conductive heat transfer part is neglected.

An analytical convective heat transfer model is used to estimate the heat-up and cooldown rates of different configurations:

$$T(t) = T_{env} + (T_0 - T_{env})\, e^{-\frac{hAt}{\rho V C_p}}$$

$$T_{env} = environmental\ temperature$$

$$T_0 = initial\ temperature\ at\ t = 0$$

$$h = convective\ heat\ transfer\ coefficient$$

$$A = effective\ surface\ area$$

$$t = time\ in\ seconds$$

$$\rho = density\ of\ material$$

$$V = volume\ of\ body$$

$$C_p = specific\ heat\ capacity\ of\ material$$

The facets of this formula describe the pans' performance and efficiency. All the temperature variables (T) in the function are situational depended and not design dependent, which makes them irrelevant for design. In the contrary, the variables in the exponential function $e^{-\frac{hAt}{\rho V C_p}}$ are variables that can be adjusted through design:

- An increase in the variables hAt in the numerator increase $\dot{T}$ (TCR).
- An increase in the variables $\rho V C_p$ in the denominator reduce $\dot{T}$ (TCR).

Numerator

- Convective heat transfer coefficient is a value between the 2.5 - 20 W/m2.K (for free air). The variance is high, almost a factor ten. An inaccurate estimation of this coefficient leads to a factor ten offset in the exponential function. Therefore, it is from utmost importance to verify this number to get to a useful result. This can be done by e.g. curve fitting with an experimental setup, which is done in the next paragraph.
- Area, is the effective surface area that either dissipates (cooldown) or captures (heat-up) heat. This is the key value to be optimized in order to create a more efficient pan.
- t is the moment in time at which the resulting temperature $T(t)$ is calculated. The higher value t, the more T_0 and T_{env} have approached each other (thermal equilibrium, 0th law of thermodynamics).

Denominator

The product of the denominator is the total heat capacity (C), and consists of density, volume and specific heat capacity. Needless to say, if one of the values in this product is increases, the TCR reduces, making the pan slower to react.

$$C = \rho V C_p$$

This formula within the within the bigger picture of the convective heat transfer model adjudges the following: a prototype made of a material with a relatively low density, low volume and low specific heat capacity results in a high TCR and vice versa. The plot below shows a selection of materials with their density and specific heat capacity.

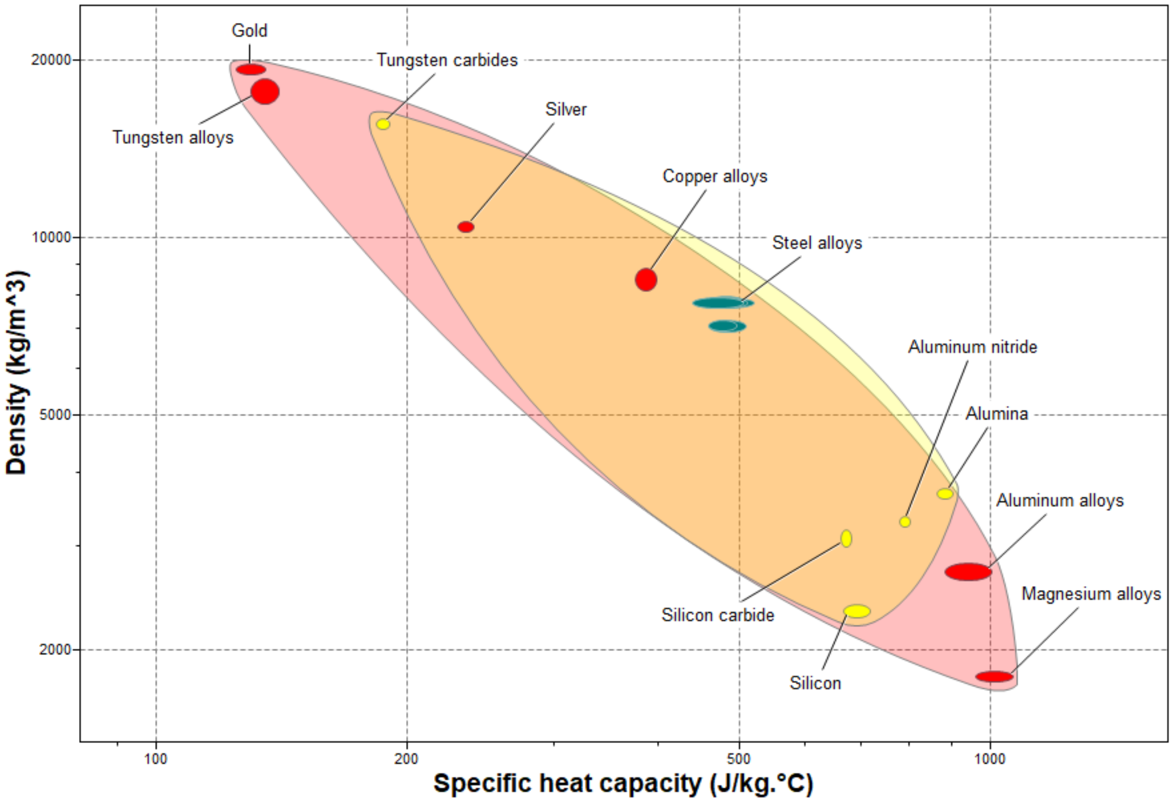


Figure 37 - density over specific heat capacity. Filter: good conductor; max. service temperature ≥ 150 °C (Granta, 2023).

Alloys containing aluminium, magnesium and/or silicon are preferred, because they are lightweight and can store a sufficient amount of heat desired for cooking.

Modelling

Plotting the convective heat transfer formula gives a rough estimation of the temperature change for a certain model over time. To make sure that the model gives an reliable estimation, it is curve fitted using the data of an experimental test using a physical model (a real pan). Via curve fitting, the convective heat transfer coefficient is approximated (Figure 34).

Different manufacturing methods have limitations such as limitation in the product wall thickness and usable materials. This paragraph aims to assess the influence of parameters like wall thickness and type material on the TCR. The above explained heat transfer model is used to assess the impact of such design changes. The main questions to be answered:

- How do different wall thicknesses affect heat-up and cooldown time (TCR)?
- What is the influence of material on TCR?

The value for the relevant wall thickness is chosen by looking at typical manufacturing wall thickness limits. For rougher methods like sand casting, the minimum limit is 3 mm wall thickness. For finer methods like high pressure die casting, investment casting and machining the typical advised limit is 2 mm.

The material determines the weight, which is the influential for the TCR. For this case, the most common product materials and their densities are compared: steel (7,800 kg/m3) and aluminium (2,700 kg/m3). Steel is roughly three times as heavy, which can significantly influence the TCR.

First, a steel concept is modelled with 2 and 3 mm uniform wall thickness. The model is curve fitted to a conventional counterpart: DeBuyer steel 4 mm thick frying pan (dotted line).

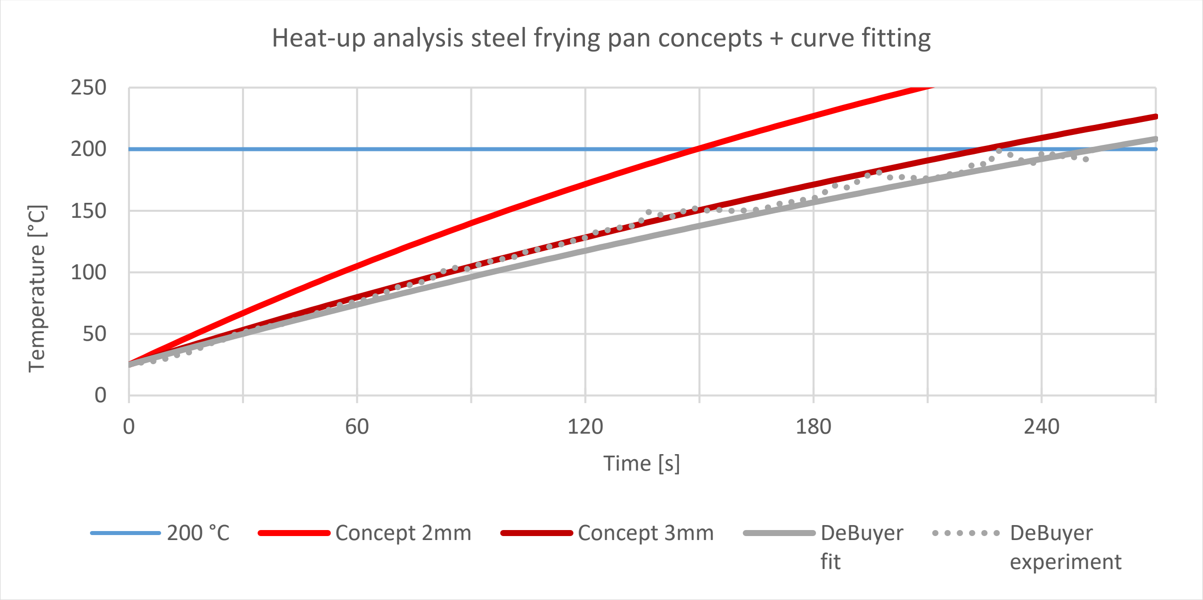


Figure 38 - Heat-up time of a steel frying pan concept with 2 and 3mm uniform wall thickness, curve fitted to a comparable steel DeBuyer pan.

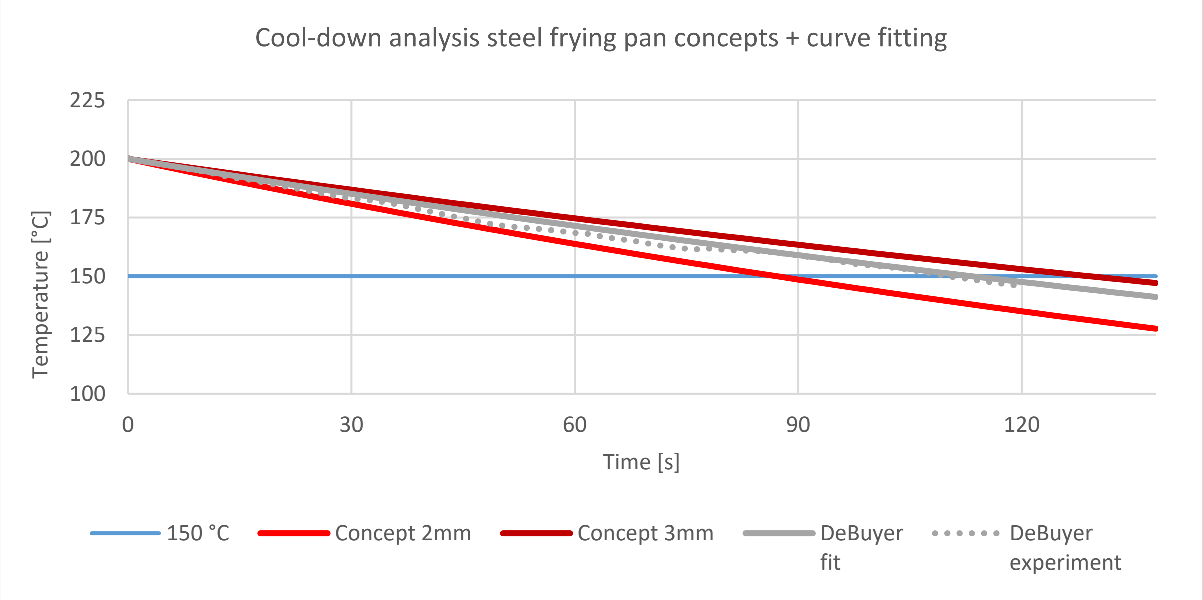


Figure 39 - Cool-down time of a steel frying pan concept with 2 and 3mm uniform wall thickness, curve fitted to a comparable steel DeBuyer pan.

The steel concept with 3 mm uniform wall thickness would not pass the requirements regarding the heat-up and cool-down time (too low TCR). The 2 mm concept does pass these requirements:

Steel concept with 2 and 3 mm wall thickness comparison			
	2 mm	**3 mm**	**Requirement**
Heat-up time *25 --> 200 °C*	150 s	225 s	< 200 s
Cool-down time *200 --> 150 °C*	90 s	130 s	< 120 s

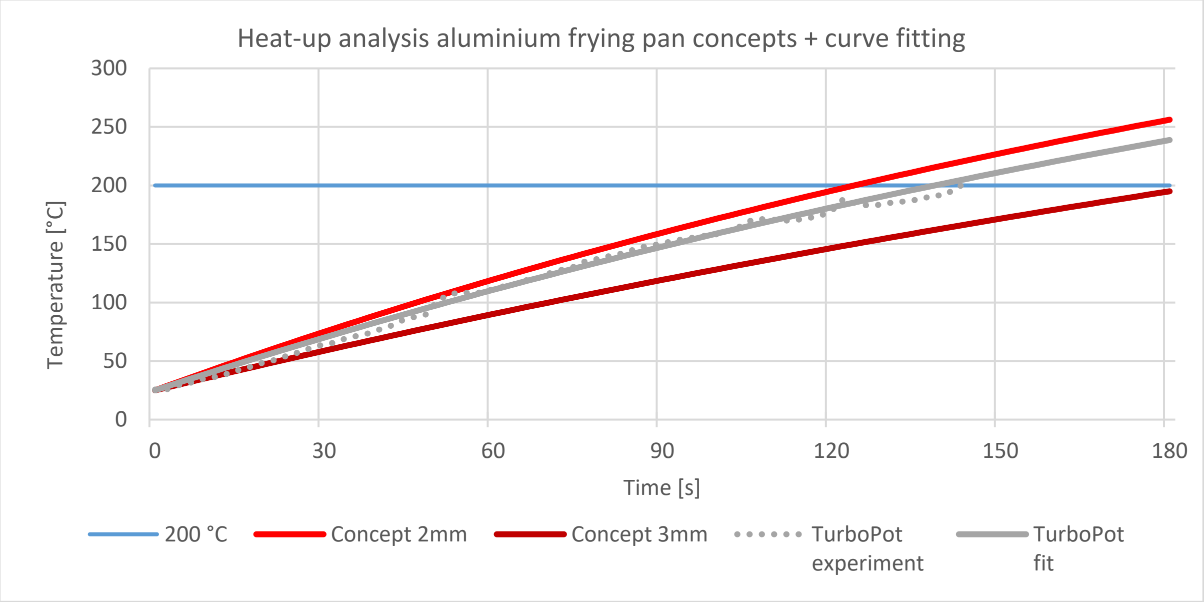


Figure 40 - Heat-up time of a aluminium frying pan concept with 2 and 3mm uniform wall thickness, curve fitted to a comparable aluminium TurboPot pan.

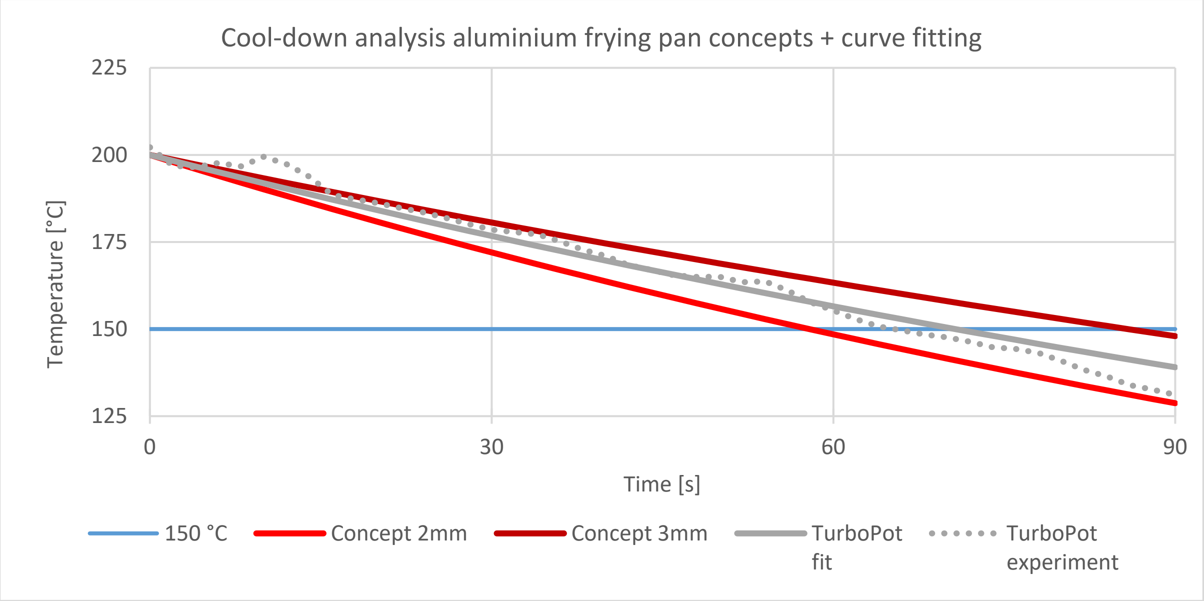


Figure 41 - Cool-down time of a aluminium frying pan concept with 2 and 3mm uniform wall thickness, curve fitted to a comparable aluminium TurboPot pan.

Comparing the outcomes result in a pass for both the 2 and 3mm uniform wall thickness:

Aluminium concept with 2 and 3 mm wall thickness comparison			
	2 mm	**3 mm**	**Requirement**
Heat-up time *25 --> 200 °C*	125 s	175 s	< 200 s
Cool-down time *200 --> 150 °C*	60 s	85 s	< 120 s

The TurboPot frying pan performs quite well both on thermal efficiency but also in heat-up and cool-down time. Since both diameter, weight and ideology is the same, this pan is curve fitted to a 3D model of exact the same pan to get accurate result on the prediction of the concepts before prototyping starts. Albeit TurboPot seems to be performing equal to the modelled prototype, it must be taken into account that both the prototypes (V1 and V2) are unoptimized yet by the thermal team. The general lay-out is fixed, but incremental chances can be made to optimize the thermal efficiency.

In conclusion, a pan made from steel requires a thinner wall to enable a sufficient TCR, otherwise it does not abide by the requirements of the chef. Meanwhile, aluminium pans tend to suffice these requirements and have more freedom for wall thickness, mainly because they are lighter in weight. However, merely looking at the speed of the pan also has its setbacks. This will be discussed in the following paragraphs.

Additional details, exact data and measurements can be found in Appendix E. Thermal Experiments.

Heat distribution: thermal conductivity

Most gas burners have a weak spot: the centre area above the burner is the coolest due to the radially outward exertion of combusted gas (Figure 38). One of the main ‘tasks’ of a frying pan is to propagate the absorbed heat to the coolest part of the pan (centre) to foster an even heat distribution.

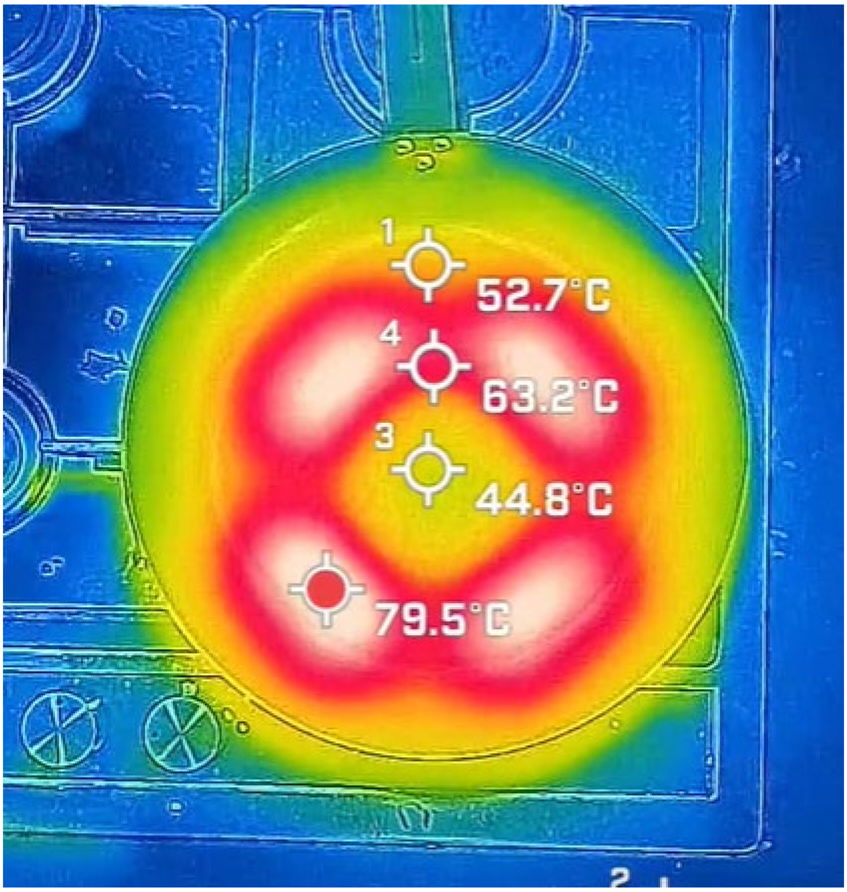


Figure 42 - IR thermal imaging of frying pan with a cold center (red/white = hot, blue = cold).

When heat propagates through a material, it occurs via thermal conduction. This can be represented one dimensionally via the following formula:

$$Q = kA\,\frac{(T1 - T2)}{d}$$

$$k = thermal\ conductivity$$

$$A = cross\ sectional\ area$$

$$Tx = temperature\ at\ location$$

$$d = distance\ between\ locations\ T1\ and\ T2$$

The parameters that can be influenced for design are the thermal conductivity (k) and cross sectional area (A). Temperature (T) and distance (d) are situational dependent. Playing around with the cross-sectional area creates a paradox: a higher cross-sectional area (A) results in higher conductivity, but it will inherently increase the wall thickness of the pan. This will result in more volume, thus a slower TCR, as calculated in the previous paragraph. This can be tackled by increasing the surface area compared to the volume to optimize the characteristic length (Lc).

The following list gives an overview of materials and their thermal conductivity for reference:

Material Group	**Thermal conductivity (W/m.K)**
Diamond	2200
Silver	420
Gold	320
Copper alloys	300
Aluminium alloys	150
Magnesium alloys	100
Tungsten alloys	100
Carbon steels	50
Technical ceramics (carbides, nitrides, etc.)	20 - 200
Stainless steels	15
Non-technical ceramics (stones & glass)	1 - 5

A selection of materials is plotted looking at the maximum service temperature (≥ 150 °C) and the thermal conductivity. The material groups that pass the selection are a variety of technical ceramics, ferrous and non-ferrous alloys. Noticeable is the prevalence of the aluminium atom among the technical ceramics that enable an acceptable thermal conductivity (Figure 42).

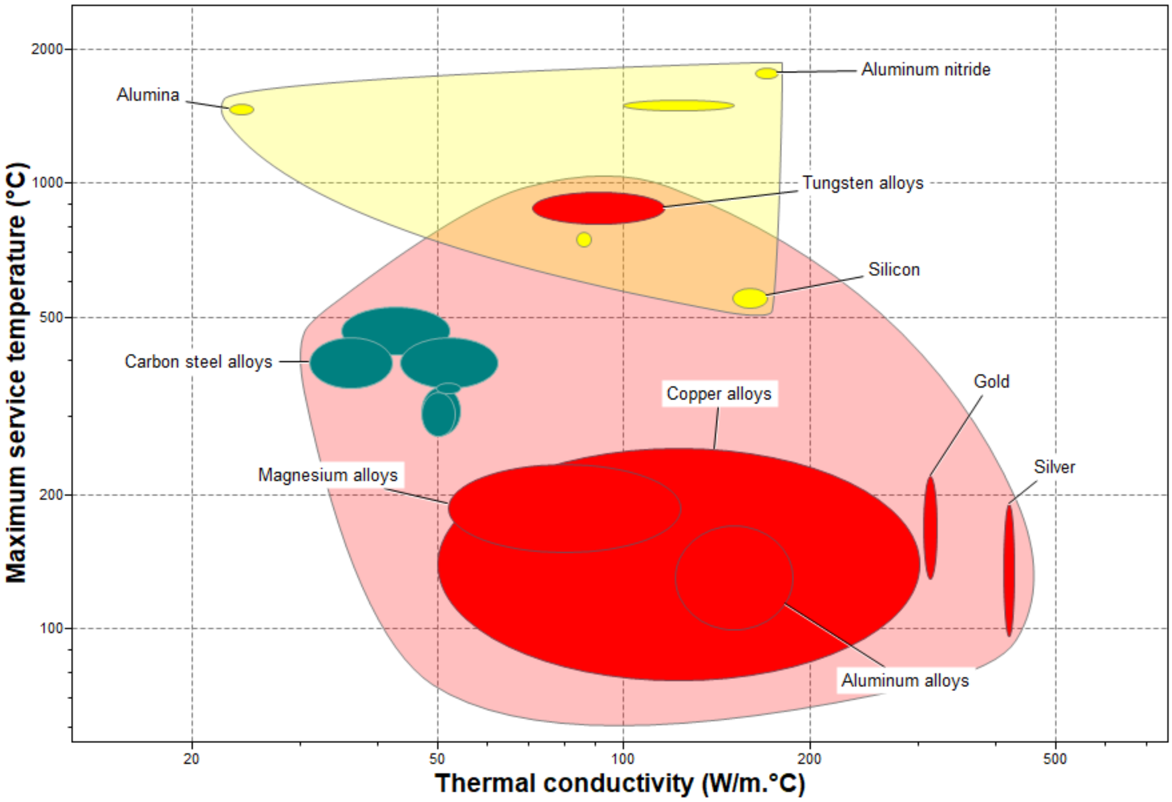


Figure 43 - max. service temp. versus thermal conductivity. Filter: : good conductor; max. service temperature ≥ 150 °C (Granta, 2023).

Although some materials have a significantly higher thermal conductivity than the other, looking at the above plot, all of the materials are conductive enough to service the purpose of a more efficient frying pan. This is because the distance that heat has to transfer through the material of the pan is relatively small: the pan mainly consists of thin walls. Once the pan is heated up, the material does not have to facilitate high conductivity rates anymore. However, a high thermal conductivity does foster heat distribution and a faster heat-up and cool-down time. Looking at the V1 prototype made from stainless steel (low conductivity, k = 15 W/m.K), it is regardless very efficient due to its enormous effective surface ($A=0.16m^2$; conventional pan $A=0.07m^2$) but the TCR was highly unsatisfactory. This is the reason that stainless steel is deemed not conductive enough as a core materials and is therefore excluded.

Heat stability: total heat capacity

Chefs like a thermally stable pan that does not drop in temperature when (cold) food is thrown into the pan. To ensure heat stability, the pan must be able to store a certain amount of energy, which is calculated via the following formula:

$$Q = mC_p dT$$

$$m = mass\ of\ pan =\ \rho V\ [density\ of\ material \cdot volume]$$

$$C_p = specific\ heat\ capacity\ of\ material$$

$$dT\ = temperature\ difference$$

After an amount of cold food is thrown in the hot pan, a thermal equilibrium will emerge after some time. The zeroth law of thermodynamics states that the energy within a system always moves towards an equilibrium:

$$Q_{loss} = Q_{gain}$$

To illustrate the effect of throwing food in a pan, the following example is used:

1 kg of beef (T0=20 C, Cp = 3000 J/kg.K) is thrown into a pan. The pan has a starting temperature of 200 degrees and the fire is turned off.

$$C_{beef} = mC_p = 1\ [kg] \cdot 3000 \left[\frac{J}{kg} \cdot K\right] = 3000\ [\frac{J}{K}]$$

$$C_{pan} = mC_p = 1\ [kg] \cdot 900 \left[\frac{J}{kg} \cdot K\right] = 900\ [\frac{J}{K}]$$

There should emerge an equilibrium between both entities:

$$Q_{beef} = Q_{pan}$$

$$C_{beef} \cdot dT = C_{pan} \cdot dT$$

$$3000\ [\frac{J}{K}] \cdot (T_{eq} - 10\ [°\mathrm{C}]) = 900\ [\frac{J}{K}] \cdot (200\ [°\mathrm{C}] - T_{eq})$$

$$T_{eq} = 54\ [°\mathrm{C}]$$

Now, if the pan becomes twice as heavy (m=2kg), C_{pan} will double and the outcome will be:

$$T_{eq} = 81\ [°\mathrm{C}]$$

Of course, this equilibrium will take several minutes to establish. However, normally the fire is on and heat will be added so a temperature drop like this will not occur in practise. Nevertheless, this example gives an indication of how the total heat capacity of the pan affects heat stability. Not only the weight is important but also the specific heat capacity:

Substance	**Specific heat capacity (Cp) in [J/kg.K]**
Copper	385
Steel	500
Aluminium	900
Stone	1000
Beef (=60% water)	3000
Water	4200

To give a more realistic and practical guide, multiple pans are studied and rated from unsatisfactory to excellent heat capacity. Some practical examples, all size 26 cm:

				
Material	Cast Iron	Aluminium	Steel	Steel
Mass	2,400 g	800 g	1000 g	320 g
Cp	500 J/kg.K	900 J/kg.K	500 J/kg.K	500 J/kg.K
C	1200 J/K	720 J/K	500 J/K	160 J/K
Perceived thermal stability	Excellent	Very good	Satisfactory	Unsatisfactory

Multiple pans in the field are compared and discussed with pans. The result is that the frying pan should have a minimum heat capacity of 500 J/K to prevent a ‘cold blast’. See Figure 33 for an overview of the specific heat capacity and density of a selection of materials. Looking solely at the total heat capacity, a high density combined with a high specific heat capacity is desired. Obviously, this makes the pan heavier, so in that regard a material with simply a high specific heat capacity per kilo is desired, making the pan both lightweight and thermally stable.

2.3 Thermal shock, distortion and fatigue

This chapter analyses the effect of high temperatures on the pan. Where the previous chapter described the user perception on thermodynamic behaviour of the pan, this chapter discusses the influence of thermodynamics on the mechanical integrity of the material.

Burned gas reaches temperatures of over 1200 °C. Test runs validated this, and the temperature underneath the pan is generally around 900 °C, rapidly decreasing when moving away from the heart of the flame (Figure 43). The pan itself seems to not get hotter than 250 - 300 °C. At this point, it reaches a thermal equilibrium: the amount of heat lost to the environment is equal to the heat absorbed. Even the fins of the prototypes do not seem to get hotter than 300 °C. However, this is difficult to measure with high accuracy due to the low response of the thermocouple and the hot environment where the fins are exposed to the flame. Even in extreme scenarios, actual fin temperatures exceeding 300 °C have not been measured, possible due to the ability of the pan to quickly transfer and dissipate heat when extremely hot. The typical operating temperature of the pan is around 200 °C, which is the benchmark temperature for the thermodynamic study.

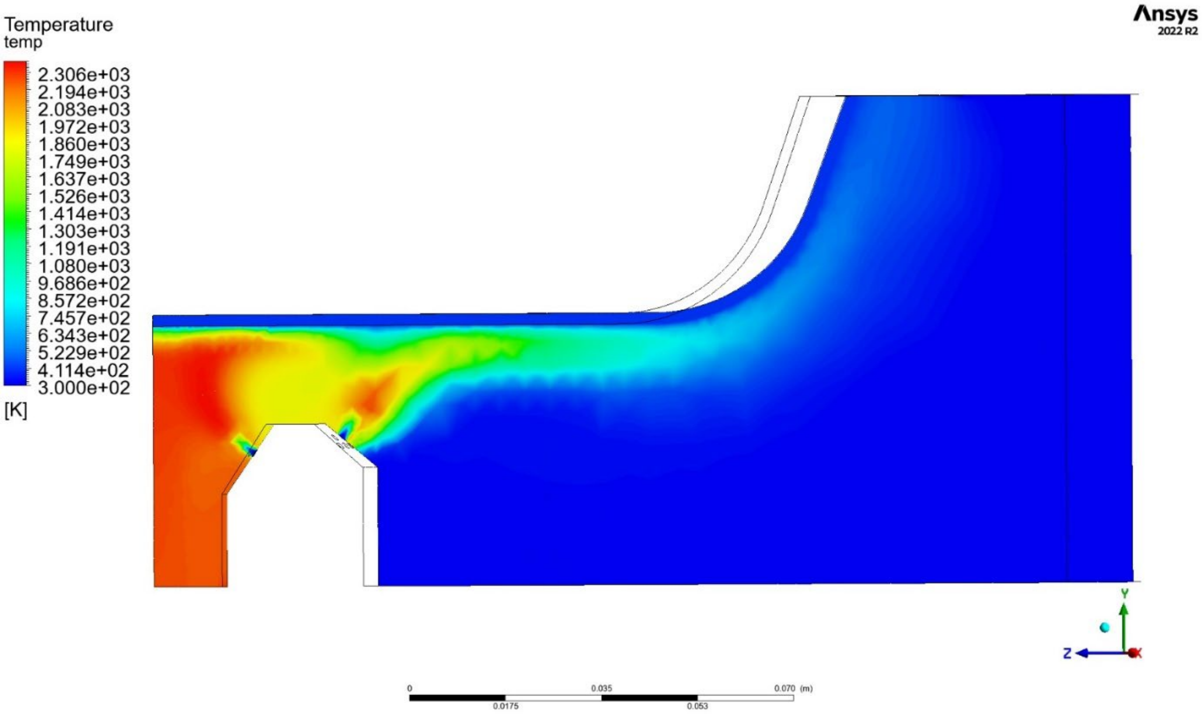


Figure 44 - temperature gradient around a pan, modelled in Ansys.

Thermal mechanics

When a substance is heated, its mechanical properties change, often in a negative way. This is also the case with aluminium. The elevated temperatures are studied to assess the effect on the pan. The underneath graph shows the change in yield strength with temperature for a typical die-cast alloy. Instead of the 390 alloy, the similar A360 alloy is plotted due to the data available.

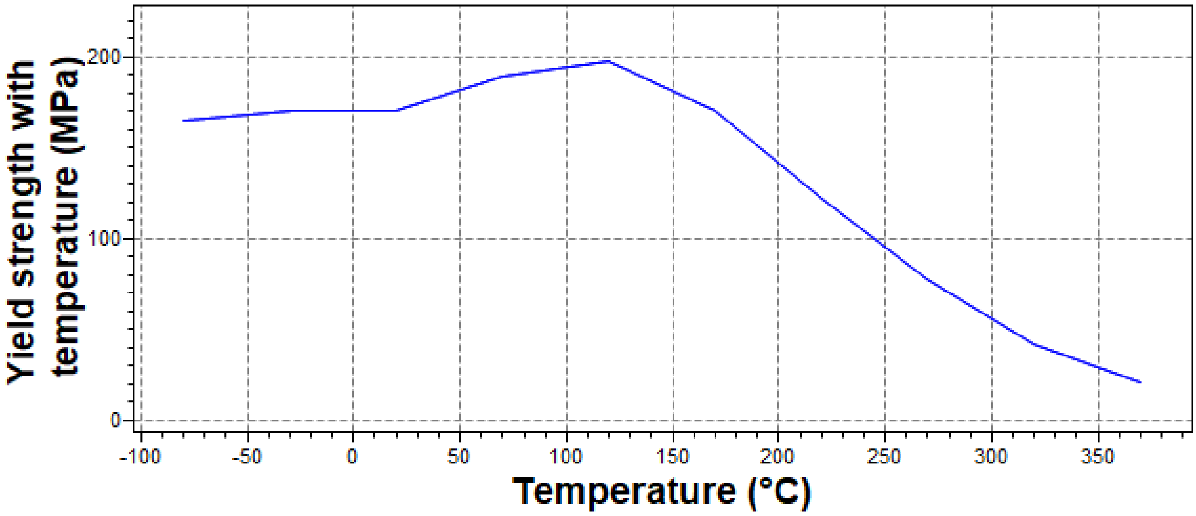


Figure 45 - yield strength of A360 with temperature

At temperatures above 180°C, the yield strength is below 80% of the claimed value for room temperature. Therefore, the maximum service temperature is set at approximately 180°C for this alloy for structural components. It is not advised to use aluminium as a structural component in continuous elevated temperatures above 180°C. Albeit the pan should maintain a certain structural integrity to prevent warping, the pan is not necessarily a structural component, so exceeding this temperature is won't be catastrophic. Nevertheless, the effect of elevated temperatures on the mechanical properties and its resistance to warping should be assessed, since it is one of the main end-of-life reasons for a frying pan. Warping can be tackled with two main design interventions: choosing the right material and optimizing the geometry.

Optimizing geometry

Warping occurs due to a large temperature difference in the material, which expands and contracts under sudden temperature changes. If cold water is thrown into a hot pan, a large temperature difference emerges between the cooled frying surface and the hot bottom of the pan. This creates a difference in thermal expansion, resulting in internal stresses and possibly a warped surface. Large, thin and flat surfaces are most prone to warping due to their low resistance to bending, which is exactly how conventional pans are made. Therefore, most pans have a thick and reinforced bottom to prevent warping. The downside is that this makes the pan less efficient and slow to warm-up and cool-down. Instead of making the bottom thicker, one could also increase the resistance to bending of the system through smart design. This resistance to bending can be described with the *area moment of inertia*, which is expressed in [mm^4].

As field research found out, aluminium pans in the kitchen start to be prone to warping when the wall thickness drops below 4 mm. The new fin structure can allow a lower wall thickness due to the added area moment of inertia, as can be seen in Figure 45. Comparing these simplified sections, the gain in resistance to bending over the vertical axis is approximately 53 to 297 mm^4, almost a factor 6.

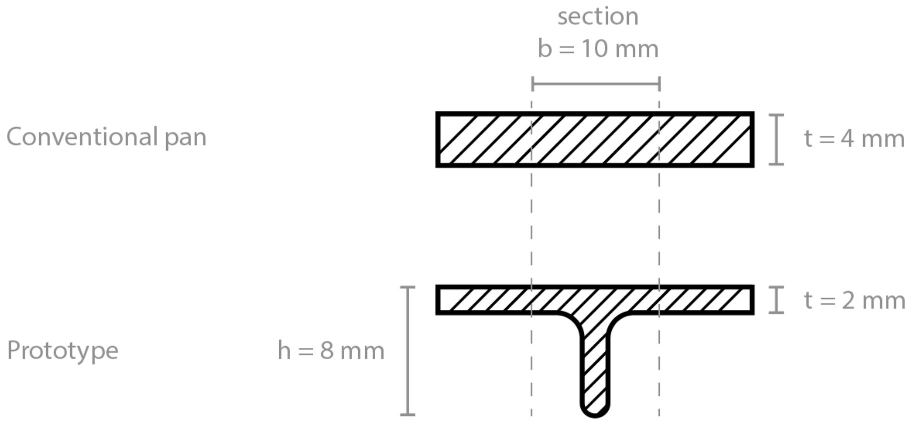


Figure 46 - simplified section of 4 mm conventional pan versus the proposed concept.

The area moment of inertia for the full pan base is compared for 5 different models (size 26 cm) in CAD software Autodesk Solidworks version 2023. The first three models are conventional frying pans with a uniform wall thickness of respectively 2, 3 and 4 mm. The latter models are the proposed design of this project (V3), and the TurboPot competitor product. The V3 is 24% stronger per weight than the 4 mm conventional frying pan, and 15% stronger per weight than the TurboPot. Both prototype 1 and 2 did not show any effects of warping after extensive (pilot) testing and dry heating tests to 260 °C and cooling back with tap water (see Appendix E. Thermal Experiments & Outcomes). Concludingly, it is highly unlikely that the proposed design will warp.

Further details can be found in Appendix Q. Area moment of inertia compared.

Choosing material

The plot underneath shows the effect of heat on the yield strength of a selection of alloys. Steels are barely affected at elevated temperatures, however, aluminium is. Therefore, selecting the right aluminium alloy is crucial for the given application.

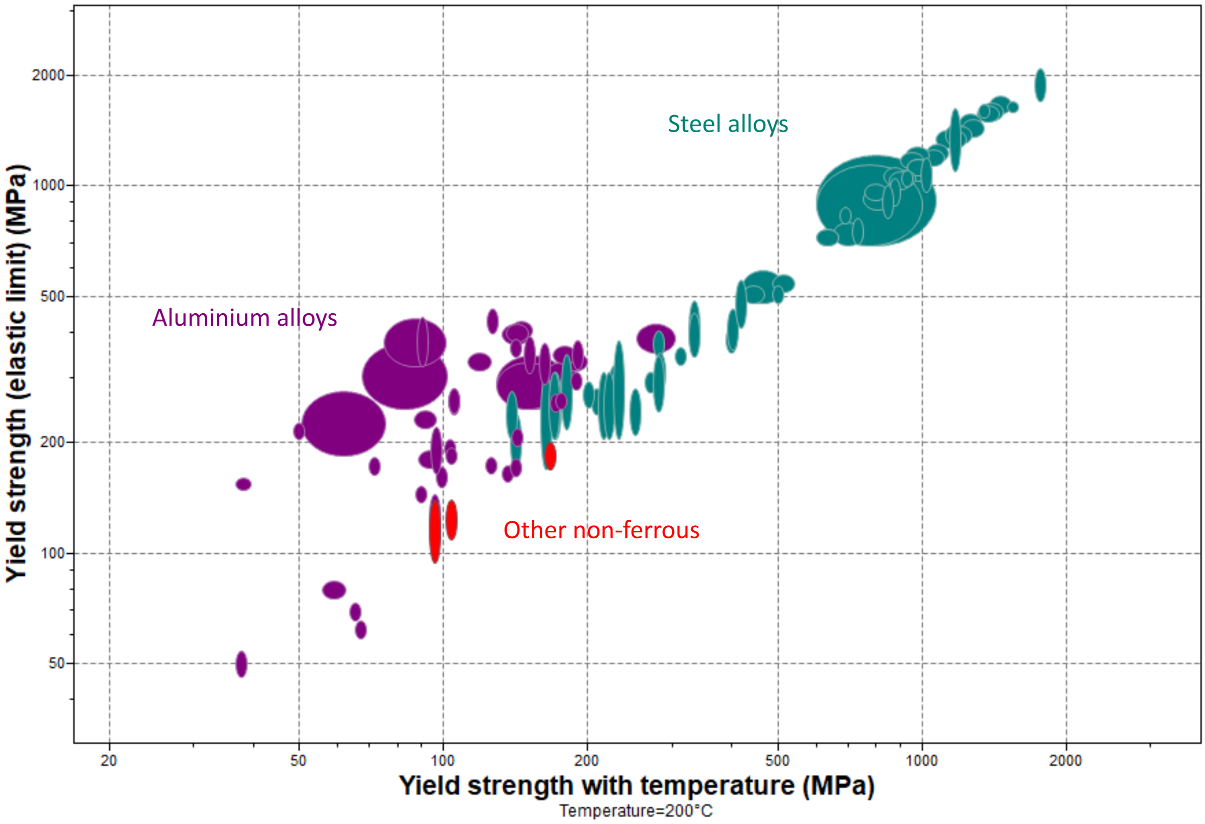


Figure 47 - Yield at 200 °C versus Yield at r.t. (Granta, 2023).

Thermal Shock Resistance (TSR)

Thermal shock resistance is a measure to determine a material's ability to resist shocks caused by a sudden change in surface temperature. The surface of a frying pan is typically at 150 degrees when the frying is done and the tap water is at room temperature. The typical temperature shock is estimated to be 130°C, with extreme outliers to 180°C (20°C to 200°C).

The magnitude of the permissible temperature change to avoid thermal shock is:

TSR = (yield strength × thermal conductivity) / (young's modulus × thermal expansion coefficient)

Typical values for the thermal shock resistances of some materials are shown below:

Material	Thermal Shock Resistance [°C]
Titanium alloys	900
Low alloy steel	300
Aluminium alloy	100 - 300
Stainless steels	150

The range for aluminium is relatively large, because aluminium itself is rather soft, but its alloying elements can make it very strong:

- Adding zinc to the alloy drastically increases the strength and therefore the thermal shock resistance (Granta, 2023);
- Magnesium, copper and manganese can be added to enable heat treatability of the alloy, which also increases strength and thermal shock resistance (GRANTA, 2023).

It is important to choose an alloy that has a TRS of at least 130 °C, since this will reduce the chance for material defects over time. On the long-term, the effect on thermal shocks has to be investigated to assess if a TSR of 130 is indeed high enough to prevent product failure due to thermal shocks. Figure 42 shows the thermal shock resistance of a selection of materials: more pure aluminium alloys have a low TSR, and alloys with that contain a higher content of alloying elements (like silicon, copper, magnesium, manganese and zinc) have a high TSR. For steel, alloys with increased carbon content have a high TSR, and alloys with chromium and nickel have a low TSR (austenitic stainless steels). This is because of the changing lattice structure during alloying, where carbon creates stronger bonds with iron compared to chromium and nickel seen in stainless steels.

See alloy selection in Chapter 3: Manufacturing.

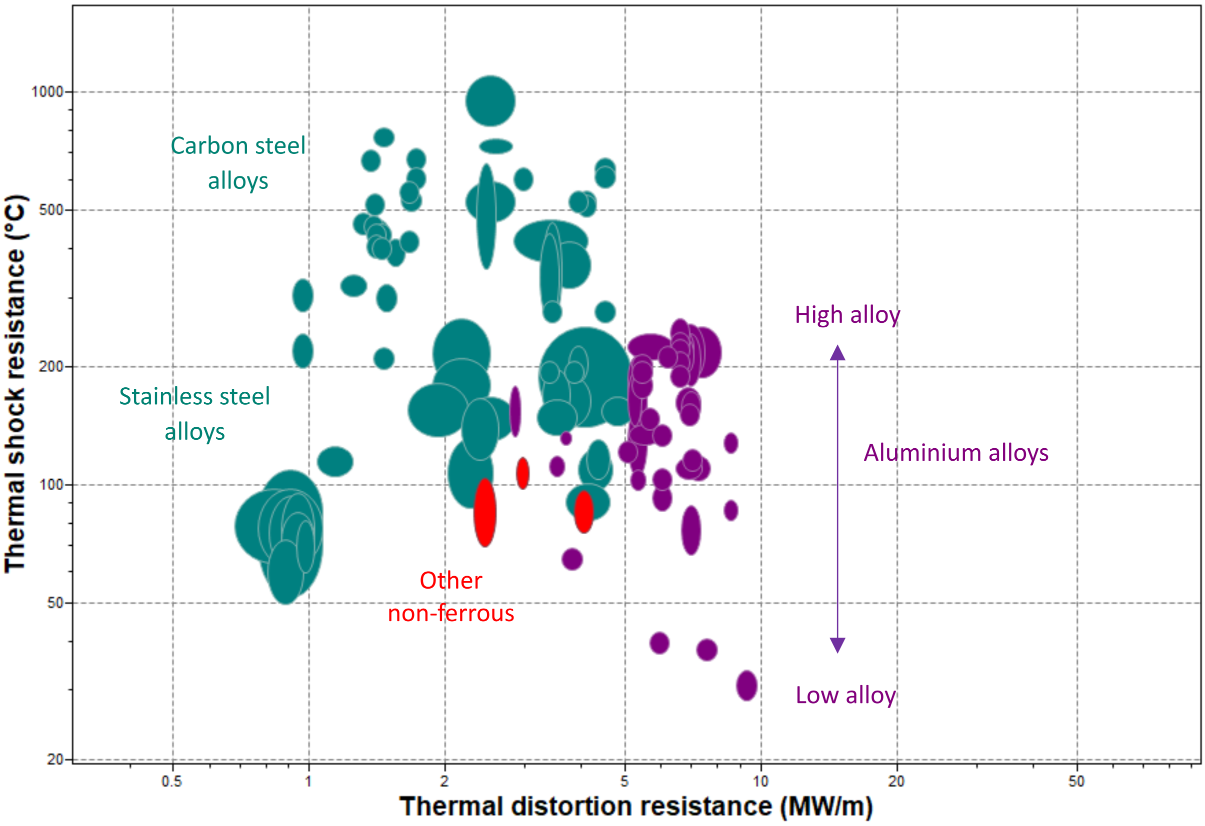


Figure 48 - Thermal shock resistance (TSR) versus thermal distortion resistance (TDR).

Thermal Distortion Resistance (TDR)

TDR is the ability of a material to resist the distortion induced by change of temperature. Heating up a material - in practise - almost never occurs on a uniform basis when exposed to a fire. Hotspots and cold spot are created and start pulling at each other due to a discrepancy in the aforementioned expansion rate. Aluminium alloys perform relatively well on distortion resistance, because they have a high thermal conductivity relative to thermal expansion coefficient. This results in the hotspots being evened throughout the material rapidly before it can start distorting, which can prevent thermal fatigue related disorders, like warping:

TDR = thermal conductivity / thermal expansion coefficient

Material	Thermal Distortion Resistance [MW/m]
Silicon carbide	24
Aluminium	7
Low alloy steels	3.5
Stainless steels	1

Albeit the TDR of aluminium is high - which is beneficial - its yield at elevated temperatures becomes fairly low, dropping 50% around 200 °C compared to room temperature (Granta, 2023). Therefore, a minimum thickness and stiff, uniform geometry is required to prevent warping and distortion (as discussed in the previous paragraph). Compared to aluminium, steel has a lower TDR but their yield is more stable at higher temperatures. Concludingly, as long as the bottom of the pan is thick enough and/or has an improved area moment of inertia, the thermal distortion should not pose a problem.

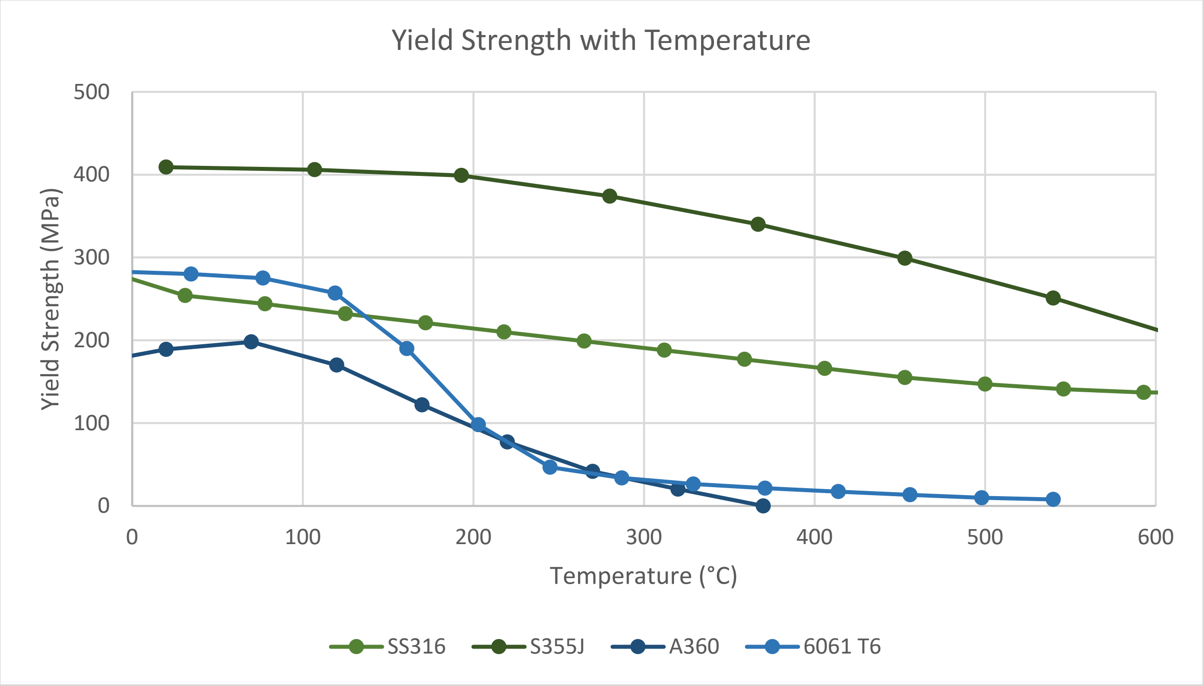


Figure 49 - Yield strength changes with temperature of 2 steel alloys (green) and 2 aluminium alloys (blue).

Thermal fatigue & thermal cycles

This paragraph assesses the thermomechanical durability of the pan over prolonged periods of time. The thermal fatigue describes the effect of heat over prolonged periods of time on the mechanical properties of the material. Thermal cycles describe effect on the material of iteratively heating-up and cooling down. This is one of the most uncertain topics of this project, according to metallurgical experts, long term predictions and behaviour of materials are extremely difficult to predict. The only way to do this is via an experimental approach or by learning from already conducted experiments.

However, this is difficult due to the unconventional nature of this project: this usage scenario is not common and examples are difficult to find. However, plenty of research has been conducted regarding the effect of thermal fatigue on the common 6xxx-series aluminium alloy, so this research is used as a benchmark instead. Heating aluminium (or metals in general), leads to a reduction of the following mechanical properties that are relevant for its structural integrity:

- Hardness
- Yield / tensile strength

The impact is assessed by the following research:

- A study by Kadhim & Kamal (2018) researched the thermal fatigue of aluminium alloy 6063 under variable stresses. At room temperature, the fatigue strength of the sample was determined at 90 MPa and this reduced to 85 MPa at 150 °C. This is a 5,2% reduction. The fatigue life (number of cycles) is reduced by 23% at 150 °C compared to room temperature.
- Hussain et al. (2016) studied the effect of temperature on the fatigue life behaviour of aluminium alloy 6061. The fatigue strength coefficient drops from 652 MPa at room temperature to 509 MPa at 200 °C. This is a 22% reduction.
- Sadak (2015) researched the effect of thermal cycling on the hardness of aluminium casting alloy A320. By repetitive heating to 300 °C, the hardness decreased from 50 to 37.6 Brinell after 20 cycles (25% reduction). This remained constant after the following cycles. At a heating temperature of 100 °C, the hardness remained constant.

Although the mechanical properties decrease significantly, there are no signs that thermal fatigue and cycling leads to terminal degradation of the material. However, the fin temperatures are measured at maximum 300 °C, this could be different depending on user scenario. For example, a temperature of 500 °C will result in a 99% reduction of hardness, coming close to the melting temperature, making the aluminium as soft as clay. Concludingly, looking at the research available combined with the expert input and the multiday pilot tests, there is no need to assume that aluminium in combination with a heat resistant oxide layer would not be durable enough to withstand the heat of the kitchen stove. However, long term effects need to be monitored during prolonged usage periods to be certain of the thermomechanical effects.

Chapter 3: Manufacturing

The client has the request to have a concept that is easy to scale, cost-effective to produce and has a form of resilience incorporated into the production process to prevent production errors. First of all, the choice of material is of utmost importance when selecting a production process, since not all processes are suitable with certain materials. For example, steel cannot be die-casted into a steel die because the die will melt. Secondly, in deliberation with the material choice, a production process has to be selected which might require pre-processing steps. Lastly, any post-processing and surface treatments are discussed.

3.1. Materials for manufacturing

As discussed in the previous chapters, the choice of material is one of the most important variables in this project. It affects a multitude of variables, like food safety, ergonomics and thermal behaviour. Most importantly, the material determines how the product can and cannot be made and what the coherent implications of a certain production process are, like wall thickness, weight and thermal performance. Resulting Chapter 2: Thermodynamics, the alloys suitable for manufacturing are selected based on general usage in similar components, processability, availability and suitability for the purpose.

			General		**Mechanical**			**Thermal**
Material			**Density**	**Price**	**Youngs**	**Yield**	**Hardness**	**Melt point**
			[kg/m3]	[eur/kg]	[Gpa]	[Mpa]	HV	[C^o]
Ferrous	Wrought	Stainless steel	7,800	2.60	200	500	300	1,400
		Carbon steel	7,800	0.60	210	300	140	1,400
	Cast	Cast iron, gray	7,200	0.28	140	220	285	1,300
Non-ferrous	Cast	Aluminium	2,700	1.80	75	260	115	640
		Copper	8,940	5.00	130	190	70	1,100
		Magnesium	1,800	2.10	45	215	90	650
		Zinc	6,800	2.30	100	190	120	430
	Wrought	Aluminium (age-hardened)	2,700	3.10	75	330	130	580
		Aluminium	2,700	1.70	70	160	130	620
		Magnesium	1,950	1.90	45	410	135	650
		Zinc (pure)	7,150	2.15	110	150	45	420

The following table assesses the same subset of materials on their processability and durability against different potentially aggressive substances. The numbers indicate the suitability with a given process or substance.

3 = excellent, 2 = accepted, 1 = limited, 0 / blank = not recommended

	Processability					Durability				
Material	**Casting**	**Forming**	**Machining**	**Welding**	**Soldering**	**Acidic**	**Alkaline**	**Salt**	**Oils**	**Alcohols**
Stainless steel	2	1	1	3	3	3	3	3	3	3
Carbon steel	2	3	2	3	3	0	3	1		2
Cast iron, gray	3	1	3	0	1	0	3	1	3	2
Aluminium	3	3	3	3	2	0	0	2	3	2
Copper	3	3	3	2	3	0	1	3	2	3
Magnesium	3	2	3	3	2	0	3	2	3	3
Zinc	3	2	3	3	3	0	1	1	3	2
Aluminium (age-hardened)	3	3	3	3	2	0	0	2	3	2
Aluminium	3	3	3	3	2	0	0	2	3	2
Magnesium	3	2	3	3	2	0	3	1	3	3
Zinc (pure)	3	1	3	2	3	1	3	2	3	2

A strong preference for aluminium is established in the previous chapters due to its good thermal behaviour and light weight. The above information stipulates the advantages of using an aluminum alloy, for the following reasons:

- Low density, making the final product relatively light weight.
- Especially cast-aluminium is relatively affordable.
- High yield strength compared to other non-ferrous counterparts at elevated temperatures (like magnesium), making it more resistant to warping.
- Excellent processability rating according to Granta. This can be explained along three material properties of aluminium:
    - relatively soft, thus good to form;
    - stiff, light and thermally conductive, making it easy to chip and machine;
    - low melting point and high fluidity, making it very well castable.

The downsides of aluminium can be found in its lower durability in harsh environments, such as:

- Low hardness, making the product prone to scratching. Therefore, an abrasive resistant surface treatment is required.
- The given service temperature will be exceeded by the temperatures that the pan will be exposed to. As described in chapter ‘Thermal mechanics’, this should not pose a problem since the pan is not structurally burdened. However, long term effects might affect the material of the pan, leading to deterioration of the surface of the material. Therefore, a heat resistant surface treatment is required.
- Compromised durability to limited resistance against potentially aggressive substances. Therefore, a chemically stable surface treatment is required.

The second most favourable material option is a ferrous material, like cast iron or steel. Choosing a ferrum-based metal would solve all the aforementioned durability problems that come with aluminium. However, it offers problems in the domain of processability. The main setback of using a ferrous metal is its high melting point (around 1,200 C^0) and tough mechanical properties. This make it difficult to get the material into the right shape, especially the desired complex and thin-walled shape. This results in only a few possible processing options with each their distinct disadvantages due to emerging complexities. On the other hand, the fact that ferrous metals are so tough and have a high melting point make them incredibly suitable for the given application of a frying pan in a harsh environment. Therefore, it is important to include steel as a material option for manufacturing.

Comparing steel and aluminium on relevant parameters gives the following discrete output:

	Aluminium				**Steel**			
	-2	*-1*	*1*	*2*	*-2*	*-1*	*1*	*2*
Thermal durability		🟧						🟩
Chemical durability		🟧						🟩
Mechanical durability		🟧						🟩
Processability				🟩		🟧		
Price			🟩				🟩	
Weight				🟩		🟧		
Thermal conductivity				🟩		🟧		
Thermal behaviour				🟩		🟧		
	6				**3**			

2 points are assigned if it completely satisfies the requirement, 1 point if it positively satisfies the requirements, -1 point if it dissatisfies the requirement and -2 points if it crucially dissatisfies the requirement.

Concludingly, it is clear that aluminium scores better overall. Especially given the fact that aluminium can potentially be surface coated to alleviate its durability concerns. However, if the processability challenges of a steel part can be tackled, the two materials come at equal foot step. The following chapter discusses potential processability options for both materials.

For a full overview of materials and their characteristics, go to Appendix[i] *I. Materials.*

3.2. Main shaping processes

The shape of the pan is depended on three main factors: as a starting point, there is the shape that dictates the thermodynamic performance. It is altered by the requirements of the chef which improve usage convenience. Lastly, the pan is further dependent on the constraints of manufacturing. The dependence of manufacturing creates an interplay between choosing the right manufacturing method on the one hand (which method can meet the given requirements) and design for manufacturing on the other hand (how can the pan be designed such that it can be manufactured best).

General Criteria

The previous chapters have given a set of constraints that need to be respected and will be highly influential when selecting eligible manufacturing processes. To start off, the weight of pan will be limited for a given size (diameter of 26 cm), as well as the volume of the pan that dictates the amount of material that is put to purpose. This material (volume needs to take the shape thin-walled fin structures in a special arrangement. The modelling in chapter 2 thermodynamics show that the maximum wall thickness for steel is 2 mm and for aluminium 3 mm. The main geometric requirements are:

Variable	Requirement
Weight	≤ 1.600 g
Wall thickness	≤ 3 mm aluminium, ≤ 2 mm steel
Ratio fin height/thickness	≥ 4
Ratio duct depth/width	≥ 4 *(the negative of the fin)*

Fortunately, there are no strict requirements for tolerances, dimensional accuracy and surface roughness required. The information in ISO 2768 ‘Basics of General Tolerances’ and ISO 8062-3 ‘Geometrical Product Specifications (GPS) - Dimensional and geometrical tolerances for moulded parts’ that manufacturers work with apply, unless noted otherwise.

From a viability perspective, the process should also be scalable, cost-effective and robust. The following requirements are valid:

Variable	Requirement
Production costs at 10,000 units	≤ 50 euro / unit
Viable batch size range	10,000 - 100,000 units / year
Pre-production investment costs	≤ 150,000 euro

As a rule of thumb, the production costs are ought to be 25% of the selling price to increase the chance for a profitable business. The client has investigated a sales price of 200 euros as desirable, given that the product performs as claimed (see *Chapter 1: Product Experience*). This results in a maximum production cost of 50 euros per unit. Furthermore, the client has the ambition to scale up from a 1,000 unit ‘launch batch’, to a 10,000 unit batch size to become profitable. The 10,000 unit batch size is therefore the reference batch size for design for manufacturing. Lastly, the client has approximately 100,000 euro pre-production investment budget available to setup the production line that can be scaled to 10,000 units annually or more in the future.

The production of the core of the pan consists of two main function groups that need to be fulfilled:

1. Create the main shape, also referred to as the core, which has the fins, captures heat and evenly spreads it throughout the pan;

2. If the core is made out of aluminium, a protective layer needs to be added to the product to prevent scratching and aluminum leaking into the food.

Main shaping processes are selected based on the following criteria within Granta (2023):

Material compatibility	Ferrous + non-ferrous
Shape	Solid 3D
Mass range	0.5 - 2 kg
Economic batch size	1,000 - 100,000 units
Range of section thickness	1 - 3 mm
Max. costs at 1,000 units	100 euro

A slightly more lenient selection range is taken to prevent the 'on edge' processes to get sorted out by the filter. The following processes are selected with Granta:

Machining	Milling
Deformation	Forging
Powder metallurgy	Pressing and sintering
Casting	Sand casting
	Investment casting
	High pressure die casting
	Ceramic shell evaporative mold casting
	Semisolid casting

The only process added is milling. Milling is not filtered in by Granta because it is not officially a main shaping process and the price range could not be honoured due to an inestimable cost range of the process: it differs tremendously where, how and what is being milled. Other processes are researched outside the Granta database, online and in literature. The above selection is unanimous and comprehensive among the sources used.

From the selected processes, ceramic shell and investment casting are removed because their price range remains high, even at higher batch sizes of 10,000 - 100,000 units.

What remains is the following selection:

- Milling
- Forging
- Pressing and sintering
- Sand casting
- High pressure die casting
- Semisolid casting

Explanation and insights in the above processes can be found in Appendix H. Manufacturing Processes.

The above shaping processes are measured against 6 important parameters, and either comply (Yes), not comply (No) or are uncertain/partly satisfy (Maybe).

	Sand casting	**HPDC**	**Semisolid casting**	**Forging**	**Machining**	**Press-sintering**
Wall thickness 2 mm	N	Y	Y	M	Y	M
Geometry & size	Y	Y	M	Y	Y	M
Quality	Y	Y	Y	Y	Y	M
Both ferrous & non-ferrous	Y	N	N	M	Y	Y
Production costs < 50	Y	Y	Y	Y	N	Y
Batch size 10,000	M	Y	Y	Y	N	Y
No additional layer required	M	N	N	N	M	Y

From the processes researched, press-sintering offers remarkable competitive characteristics. It is one of the only production processes that is able to produce complex and thin-walled parts from steel. The only two other processes that can also get steel into an intricate shape are sand casting and machining. However, they are respectably too rough and costly for the given purpose. Press-sintering does offer these characteristics, but manufacturers and engineers working on press-sintering indicate that the process seems not suitable for producing the concept of the pan as proposed: it is too big in size and press sintering creates highly brittle parts. Further research and development is required to see is this process is feasible.

Despite the fact that steel is a durable material, both literature, field and expert research indicate that it is very hard to get steel into the desired - thin-walled and complex - shape. Therefore, the decision is made to discontinue with steel and continue with aluminium as the core material. Looking at the main shaping process comparison table, HPDC ticks all the boxes if we ignore the request for steel processing. This is the process for continuation.

3.3. Bonding

A variety of pans on the market consist of multiple layers to enhance durability and performance. When the inner material is not durable or food safe - like aluminium or copper - the outer most layer is often of protective nature and needs to be bonded to the core. Since aluminium is a preferred core material, finding a way to bond two layers is paramount. The main bottleneck is the loss of thermal conductivity between the layers if a poor bond is established. A few methods have been researched:

- Casting
- Diffusion bonding
- Epoxy

The in-depth analysis regarding these methods can be found in Appendix P. Bonding of dissimilar metals.

It is found that neither of these techniques are desired, because they:

- Are too complex / risky
- Require further research and development
- Are not suitable for the given application

Although promising options, they are at the moment not cost effective solutions since they require further research and resources, which is not desired by the client, NeoStove. Therefore, a set of less complex options is proposed in the next paragraph.

3.4. Surface treatment

Instead of adding another sheet material to the core, the existing surface of the core can be treated such that an protective layer emerges. A variety of surface treatments exist:

- Coating
- Plating
- Oxidizing
- Spraying

The surface treatment should adhere to the following requirements, which are more strict than the core material itself since they operate on the boundary layer of the heat source:

Variable	**Requirement**	
Hardness	> 130 HV	Scratch resistance
Thickness	> 25 µm	Abrasion resistance
Thermal shock resistance	> 200 °C	
Maximum service temperature	> 500 °C	

Furthermore, the surface treatment should be food safe, impact proof (low brittleness) and cost-effective given the batch size. Furthermore, the coating should not be a thermal shield, but rather be thermally conductive and enable an efficient heat transfer. Although a wide variety of treatments are selected, it should be compatible with aluminium.

The following surface treatments are selected:

Surface treatment	**Base material**
Vitreous enamelling	Silica glass
Anodizing / oxidation	Aluminium oxide
Electroplating	Zinc
Polymer powder coating	PTFE
Flame spraying	Combination of ceramics (i.e. silica)

Further explanation and insights in the above surface treatments can be found in Appendix J. Surface Treatments.

The above surface treatments are compared against the following parameters:

- Mechanical durability (hardness Vickers, wear rate + thickness)
- Thermal durability (thermal shock resistance + max service temp)
- Non-stick (metal / ceramic / polymers)
- Heat transfer efficiency (thermal cond. + surface thickness & structure)

Since one of the biggest failure reasons for a frying pan is the wearing out of the surface treatment, the mechanical durability and tribological properties are from paramount importance to make the pan a success. For mechanical durability, a combination between hardness, tested wear rate and coating thickness is used.

A selection of coatings are compared in Appendix O. Wear rate of surface treatments.

The coatings are rated on the discussed parameters. +2 points are assigned if it completely satisfies the requirement, +1 point if it positively satisfies the requirements, -1 point if it dissatisfies the requirement and -2 points if it crucially dissatisfies the requirement.

	Enamelling				**Oxidation**				**Electroplating**				**PTFE**				**Ceramic**			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Mechanical durability			🟩				🟩				🟩		🟧						🟩	
Thermal durability				🟩			🟩				🟩			🟧					🟩	
Non-stick			🟩				🟩		🟧							🟩			🟩	
Heat transfer efficiency	🟧							🟩				🟩		🟧					🟩	
	2				**5**				**2**				**-2**				**4**			

The high performing options are both within the ceramic family (oxidation and ceramic), but are applied through a different process. Within both processes, there is a large band width between a satisfactory and unsatisfactory application. Therefore, close collaboration with the manufacturer and a meticulous approach is advised to achieve the coating quality as desired.

Oxidation offers higher thermal efficiency compared to ceramics. This might not seem crucial given that the layer is relatively thin. However, if we compare low conductive frying surfaces like PTFE and enamel with highly conductive ones like carbon steel and aluminium oxide, we see that chefs have to increase the burner power to achieve the same Maillard effect: although the pan is hot, the PTFE acts as a tiny insulation layer between the food and the pan. Therefore, having a more conductive frying surface can be the difference between high and low burner setting for the chef.

Chapter 4: Findings

This chapter concludes the analysis of the previous chapters Product Experience, Thermodynamics and Manufacturing.

4.1. Product experience: conclusion and requirements

Product experience is about how the chef interacts with the pan given the kitchen environment. This interaction can be broken down into two main categories: primary usage and secondary usage.

Primary: cooking

- Ergonomic grip to allow for good control over the pan for cooking
- Low weight to reduce strain on the chef
- Smoothly curved inner frying surface that allows for tossing food around and does not stick to the food

Secondary: convenient usage

- Convenient storage: eyelet for hanging, a universal sizing and angled sides that allow for stacking multiple pans on top of each other;
- High handle to prevent hot handle and clash with surrounding pans
- Curved bottom fins that ensure a stable position on a wide variety of stove tops, enable sliding and do not fall and jam between the grates of the stove
- Forcus on durability to elongate lifespan, material and surface properties that can withstand:
    - Mechanical stresses like drops, warping, scratching and abrasion
    - Chemical stresses like aggressive cleaning substances and acid foods
    - Thermal stresses like high tepmeratures and thermal shock events

4.2. Thermodynamics: conclusion and requirements

The pan needs to have a certain level of thermal performance and thermal durability. Performance wise the pan should be fast, stable and spread the heat evenly:

- Heat-up time to 200°C within 200 seconds on 2 kW stove power
- Cool-down time under 2 minutes to 150°C

These requirements can only be honoured by a pan with a maximum wall thicnkess of 2 mm for steel and 3 mm for aluminium.

- Total heat capacity of minimum 500 J/K to foster heat stability, this corresponds with at least 600 grams of aluminium or 1000 grams of steel.
- Thermal conductivity should be as high as viably possible to enable even heat distribution and prevent cold spots in the pan. Tests has shown that the thermal conductivity of stainless steel (15 W/m.K) is low to enable a fast pan. Therefore, the minimum is set at ~30 W/m.K (alloy/carbon steels).

In terms of thermal durability, the main problem that experts foresee is the exposure of the material to repeated thermal shocks. Especially frying pans in the kitchen are prone to thermal shocks of typically 100 to 160°C. Therefore, the material should have a TSR of at least 130°C to prevent degradation and distortion over time.

4.3. Manufacturing: conclusion and requirements

Within the domain of manufacturing, three main branches are discussed that are relevant for establishing the frying pan as desired: choice of material, main shaping process and surface treatment.

Material
Steel is durable, but difficult to form within the required fin structure given the limited wall thickness of 2mm. The availablility of suitable main shaping processes that can form steel in the required shape are scarce and costly. Aluminium is less durable, but performs significantly better on the other parameters like thermal performance and manufacturability. Therefore, the choice is made to advance with aluminium. An alloy that conforms the production process has yet to be selected.

Main shaping process
A selection of processes have been studied. High pressure die-casting outperforms the other options based on the required parameters. It is cost-effective, scalable and offer the possiblility of creating complex thin-walled shapes. Furthermore, aluminium is well-suited for HPDC.

Surface treatment
Since the combination of high pressure die casting and aluminium, a surface treatment has to be selected that fits both usability, thermodynamic as process related requirements. Aluminium lends itself excellent for the oxidation process that deposits a ceramic protective layer onto the surface, called alumina or aluminium oxide. There are a variety of methods for depositing this layer onto the aluminium, like anodizing and other oxidation methods. It creates a hard integrated layer that is grown into the aluminium. It offers scratch, abrasion, thermal and chemical protection as required. Furthermore, it prevents galvanic corrosion on the interface of the steel handle attachment.

For the full list of requirements, see Appendix B. List of requirements

Chapter 5: Design for Manufacturing

Hence a well-grounded selection is made for material, surface treatment and production process, the pan requires finetuning to be best suitable for the manufacturing process, and at the same time satisfy the requirements assigned in the Product Experience and Thermodynamics domain. Design for manufacturing is covered by 5 main topics:

1. Overall product shape
2. Dimensioning
3. Die design
4. Material selection
5. Post-processing

5.1. Production Process Overview

First, a sequential overview of the manufacturing process needs to be established. Hence, the sub processes can be identified to foster a systematically approach to DfM, and helps estimating the total production cost in the next chapter. The manufacturing can be divided into 4 sub stations:

1. Casting
2. Anodizing
3. Handle attachment
4. Packaging & shipping

Between every station, transport may occur if different parties are responsible for a different operation. Besides, a quality control is advised after every station to ensure the desired quality of the part, before it continues to the next one. This can prevent extra costs and uncertainty in the supply chain.

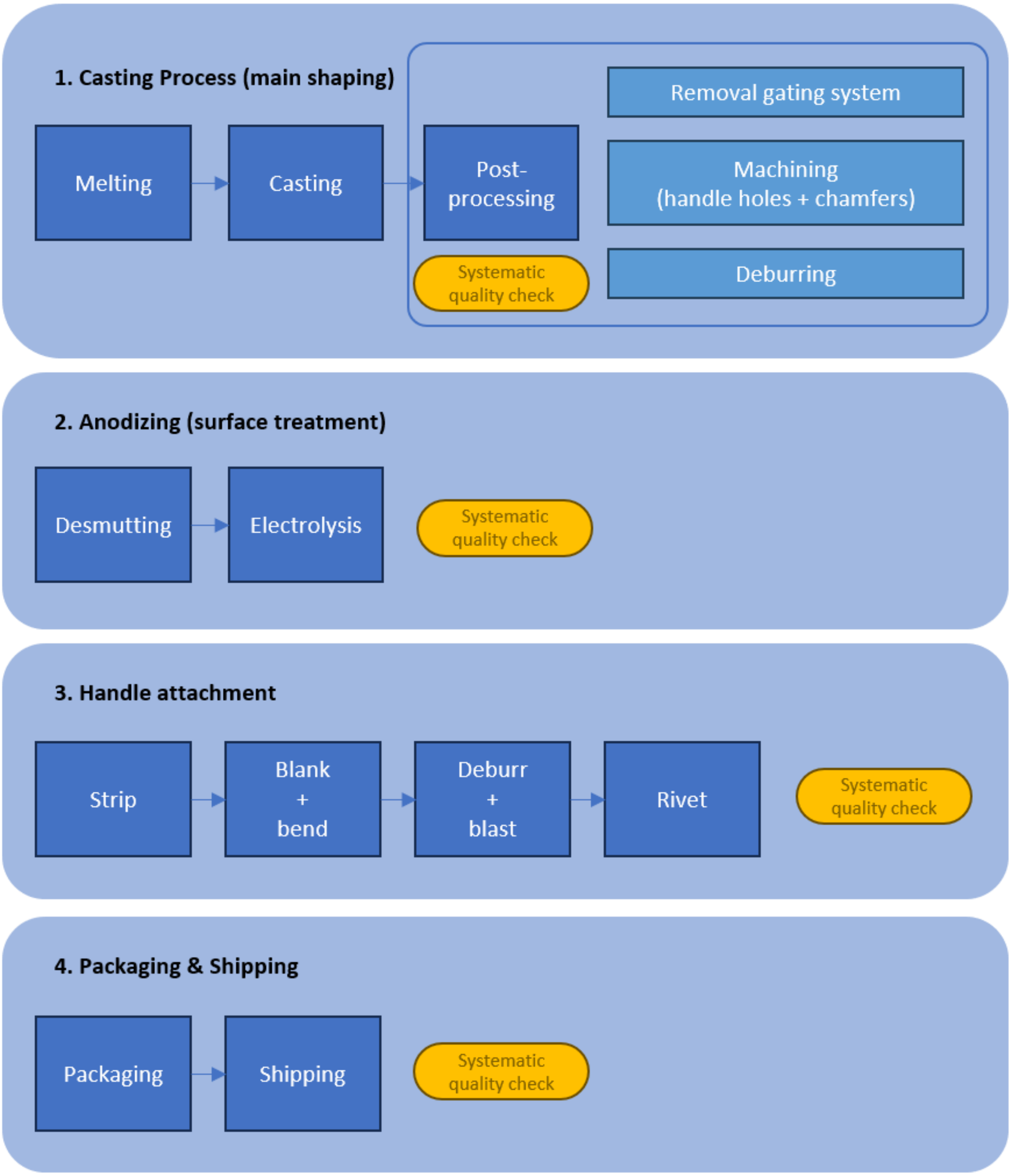


Figure 50 - production process overview.

Since anodizing, making a handle, attaching a handle, packaging and shipping are rudimentary operations, they will not be explained in further detail (see Overview of the Final Design, Handle production: blanking and bending). Information regarding the surface treatment can be found in Appendix J. Surface Treatments.

5.2. Overall Product Shape

To enhance the castability of the product, the overall geometry is from utmost importance. The fins of the pan can be used in its advantage by having it functioning as flow channels for even and fast filling of the die. To enable proper casting operation, a set of rules apply:

- Uniform wall thicknesses
- Releasing shape with drafted surfaces parallel to the ejection direction
- Sufficient and symmetrical ejector spots for ejector pins

The model is very well suitable for die-casting, since the main shape is already releasing from itself (Figure 57). Besides, the biggest cavity is parallel to the parting surface of the die. This enables unobtrusive and efficient filling of the cavity, resulting in better casts.

From an early design stage, models are repeatedly discussed with casting experts to see if casting would be an appropriate way forward. Although the production process of casting seemed very promising from the start onwards, it was not yet clear at the beginning what the final method would be. The general concepts of the pan, 3D printed models (Figure 58; Figure 59) and the prototypes are discussed with an independent casting expert and 3 foundries to verify and improve castability. Besides, a casting simulation is executed with one of the models (steel, 2mm wall thickness (Figure 60; Appendix K. Casting Simulation Report). As can be seen in this figure, the centre block (where all the fins meet in the middle), takes a long time to solidify and causes more shrinkage due to the relatively high volume concentration. In this case, the rule of 'uniform wall thickness' is not abided, which might negatively influences the cast. This is an example of a feature that required optimization.

Both experts, manufacturers and the simulation report indicate that the model of Figure 49 is well-suited for casting, given that some minor dimensioning adjustments were implemented. This will be discussed in the next paragraph.

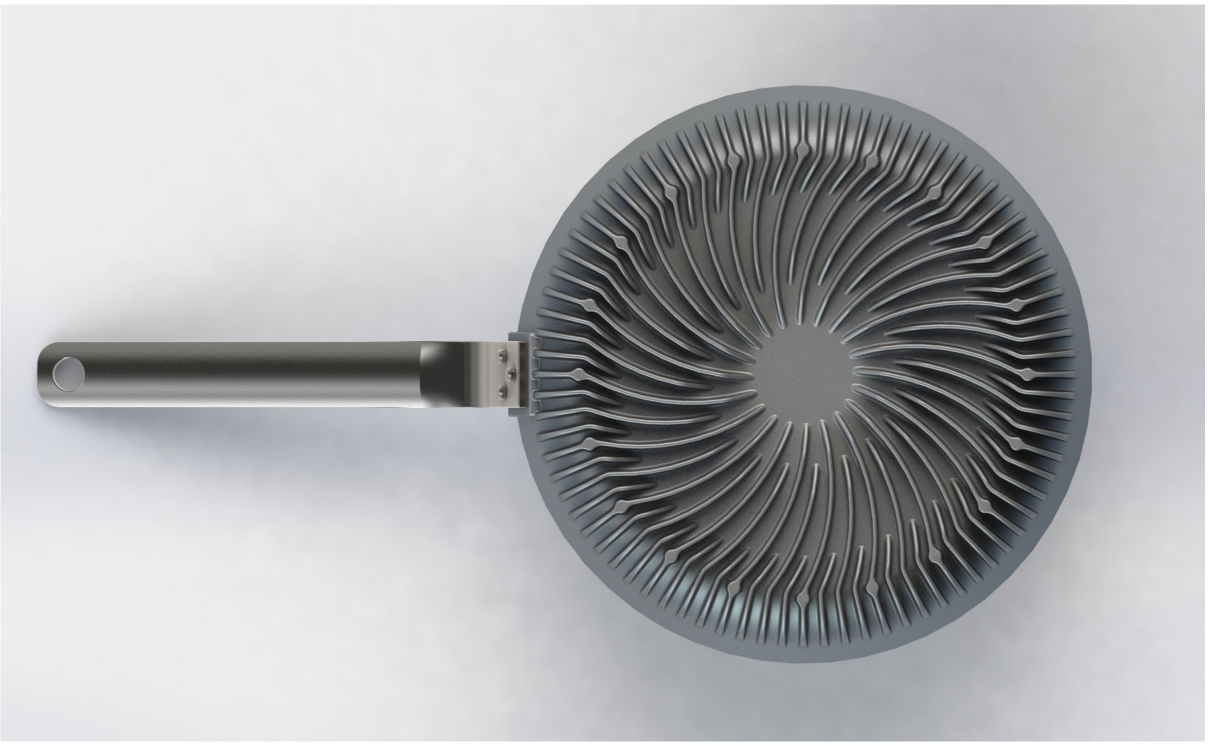


Figure 51 - bottom view of V3. Ejector spots are placed amid the 20 long fin sections.

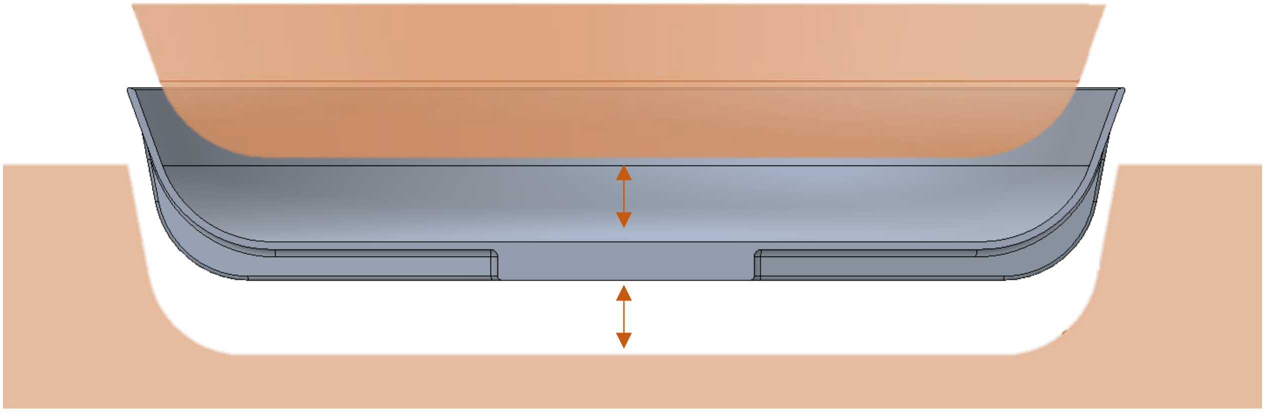


Figure 52 - section view of the CAD model of prototype 2, with the possible die-parts in orange.

Figure 53 - 3D printed PLA model that was made prior to prototype 1 production.

Figure 54 - 3D printed PLA model that was made prior to prototype 2 production.

Temperatures

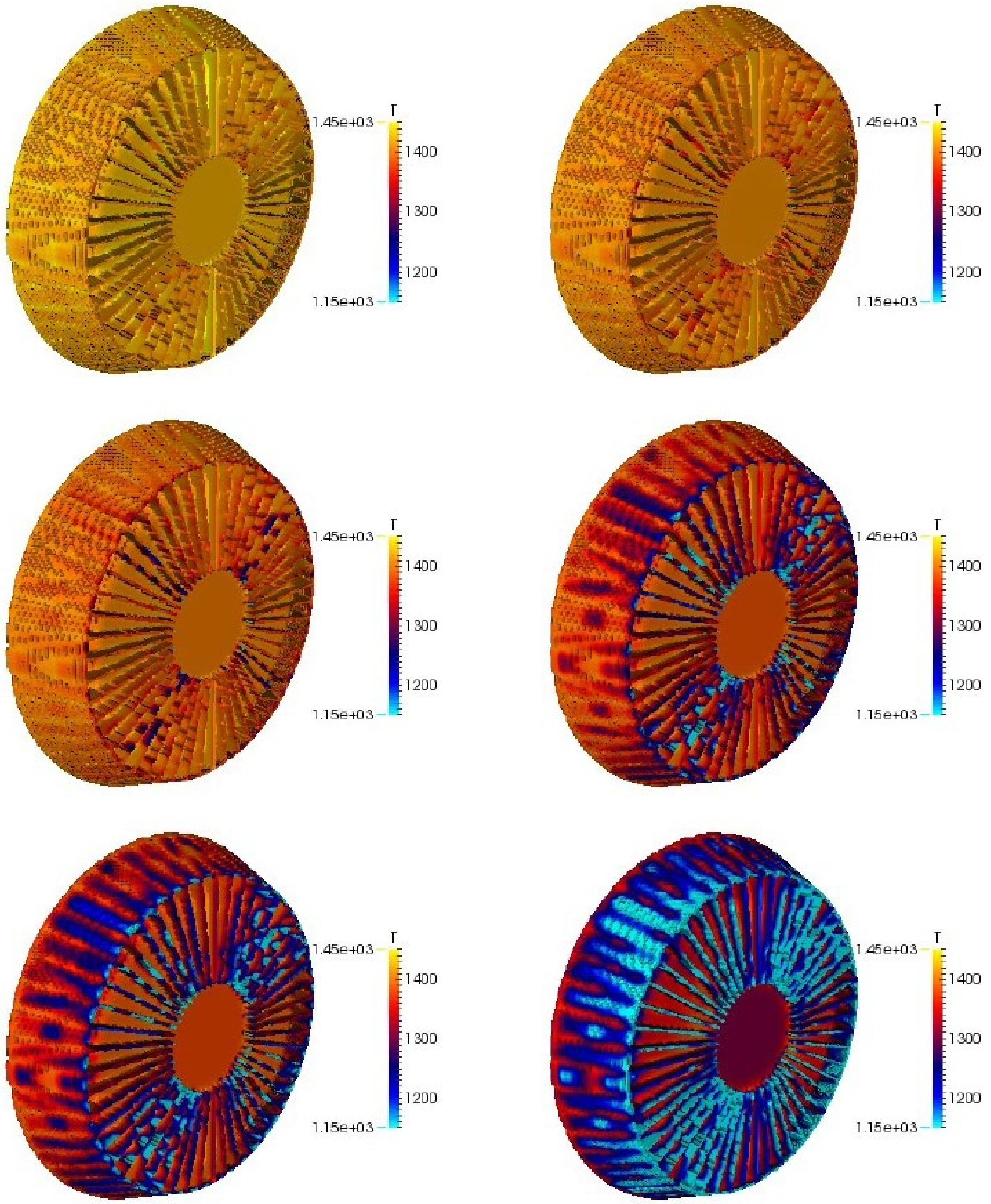


Figure 55 - casting simulation: cast temperatures at 10%, 25%, 50%, 75%, 90% and 100% of the solid fraction.

5.3. Dimensioning

The devil is in its details. It is commonly understood that a lot can be gained by part optimization for casting: both in cycle time, material usage as well as general product quality. Design guidelines have been collected from manufacturers websites, expert input and online literature ((*DIE_CASTING_DESIGN_GUIDE_TIPS_REBRANDED_AW_SG*, n.d.; *Think High-Pressure Casting*, n.d.; Wang et al., 2022). The most important ones are:

A. Radii and fillets should be similar to the local wall thickness or at least ½ of the wall thickness, to prevent stress concentrations at sharp corners and allow for easy flow around the corners which enables smooth filling of the die;
B. The only region where a sharp corner is a must, is at the interface of the parting line between the two dries. Therefore, efficient placement of the parting line is crucial;
C. Additionally to radii and fillets, rounded corners at the intersection of ribs and flanges are desired;
D. Draft angles (outside surface) should be 1-2° for an aluminium cast, to enable smooth opening of the die and ejection of the part. This also reduces friction and wear during these processes and elongate lifetime of the die;
E. Draft angle (inside surface) should be 2x the angle of outside surface, to prevent interlocking of the part caused by shrinkage. Shrinkage level of aluminium parts given the pan size is approximately 1%.

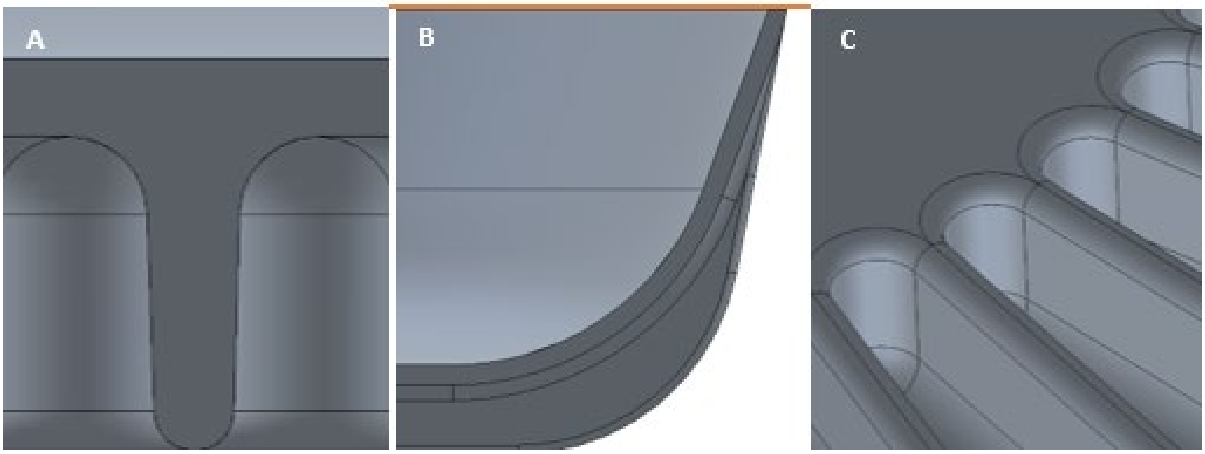


Figure 56 - A) section view of fin, B) section view of the side of the pan, C) close-up of fins merging at the centre block.

Guideline		Figure
Point A radii and fillets	The radii and fillets are the maximum possible size throughout the model. The radii at the end of a fin is ½ wall thickness (R=1mm) and the fillets and the start of the fin is equal to the wall thickness (R=2mm).	A
Point B sharp corners at parting line	The corner at the parting line is an untreated sharp corner that aligns with the parting line (orange). Corner can be chamfered during post-processing.	B
Point C round corners	Corners are completely tangent to at the transition.	C
Point D & E draft angles	The draft angle should be 2 degrees, since the fins are all facing each other (1 deg is not enough due to shrinkage). This is not incorporated in the machined prototype 2.	A

5.4. Die Design

The die design simply consists of a negative of the product, split up in two by a parting line to enable the die to open and eject the casted part. However, determining the orientation of the product within the die, where the parting line will be and how the gating system works requires some thought. Especially the latter might be a responsibility for the manufacturer in question, however, it is beneficial as a designer to already incorporate some casting principles into the design, to prevent major pivots later on in the process leading to additional costs. The die consists of multiple parts that are crucial to understand for effective die design:

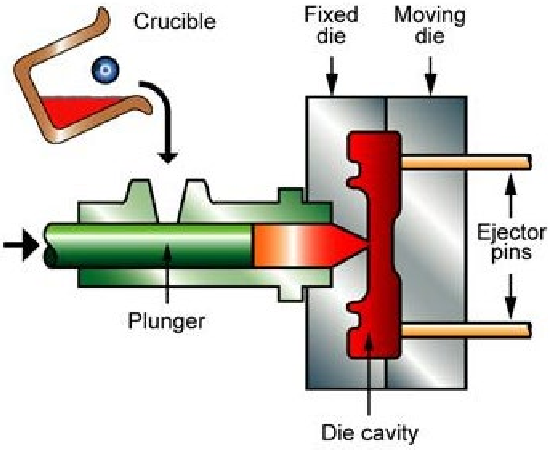


Figure 57 - high pressure die casting process (Granta, 2023).

	Part	Function
	Plunger and shot chamber	Melted metal is poured into the shot chamber, whereafter it is shot into the die by the plunger/ram.
	Cavity + gating system	The cavity is the negative of the actual product. The gating system is a system of channels that allow for efficient and even filling of the cavity.
	Fixed die	Half of the die that does not move. Generally, the shot chamber is attached to this side, together with some other crucial components that are rather not moved for complexity reasons.
	Moving die	Half of the die that does move to let the part being ejected after solidification. This moving die part needs several tons of pressing force to close and properly seal of the cavity, otherwise casting defects such as flashing may occur (material between the parting surface of the dies).
	Alignment pins	Pins to align the dies, basically the rails along which the dies can slide.
	Ejector pins	Pins that eject the part out of the machine when it is solidified.

The gating system of a die consists of multiple parts with each its own function, in chronological filling order:

	Part	Function
1	Sprue	This is the main entrance of the die, where the metal from the shot chamber enters the die.
2	Runner	Channel that connects the sprue to the ingate(s) of the cavity.
3	Slack catcher	The first part of the molten metal often brings some slack and impurities along. This will populate in the slack catcher, preventing it to enter the cavity
4	Ingate	Entrance channel to the actual cavity

5	Cavity	This is the actual negative of the part to be casted
6	Overflow	The part of the cavity that is filled last often has the highest porosity and casting defects. The overflow basically moves this problem to somewhere outside of the cavity.
7	Chilling vent	Exhausting residual air/gas from the inside of to the outside of the die.

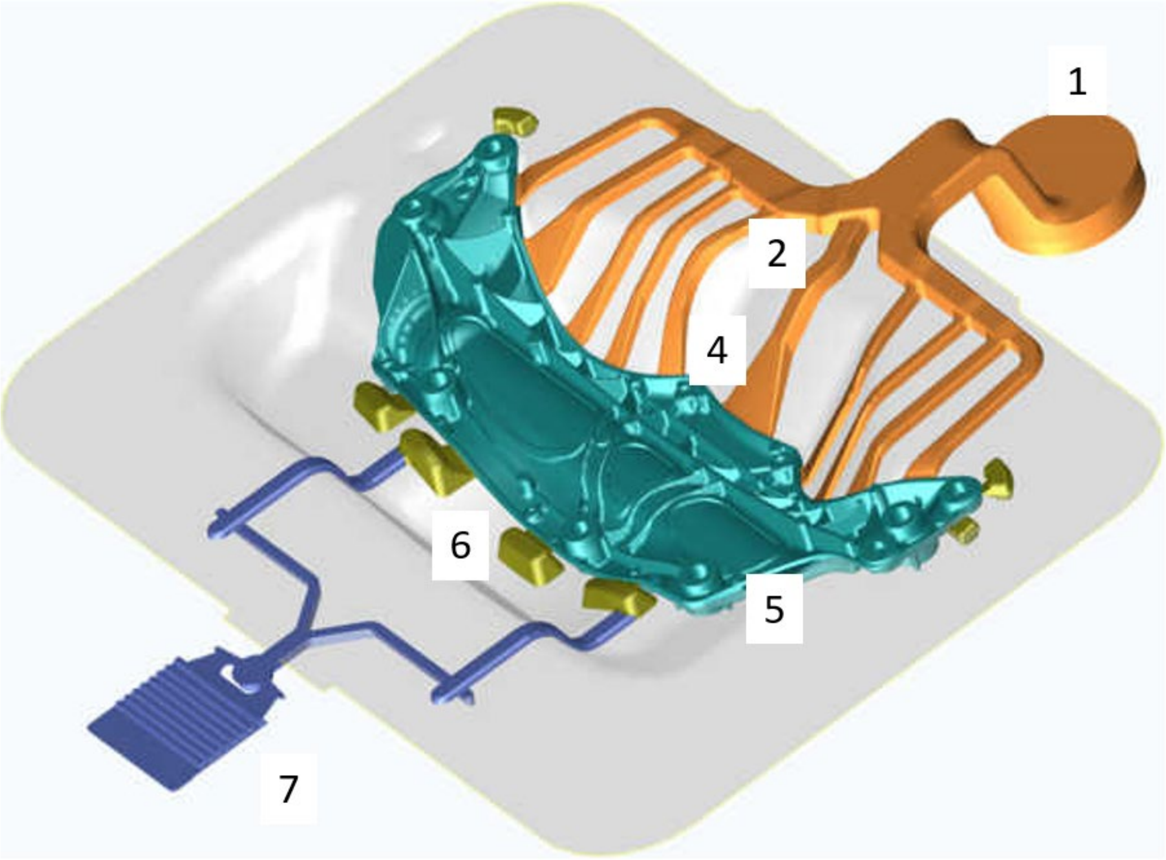


*Figure 58 - gating system visualized (*HPDC Gating System Design*, 2023)*

The basic anatomy of the die has to be understood for effective product and die design. To reduce the chance for casting defects, it is advised to comply with the following guidelines:

- Design gating system in a way that enables symmetric and even die-filling;
- Foster unobstructive flow from ingate to overflow;
- Minimize travel distance from ingate to overflow;
- Effective placement of parting line to reduce model complexity;
- Simplicity is robustness, reducing complexity will safe costs. Therefore, the aim is to have no sliding parts other than the moving half of the die.

Lastly, there are two general setup for the HPDC machine:

- Horizontal machine (conventional)
- Vertical machine

Horizontal machine is the most common setup due to its simplicity, convenient ejection of the part and accessibility for the operator. However, it also has its limitations, such as offset injection location and part orientation. The vertical machine requires a more complex setup, but offers bottom-up injection resulting in higher quality castings with lower porosity (Good et al., 2017). For both machines, a gating setup is designed:

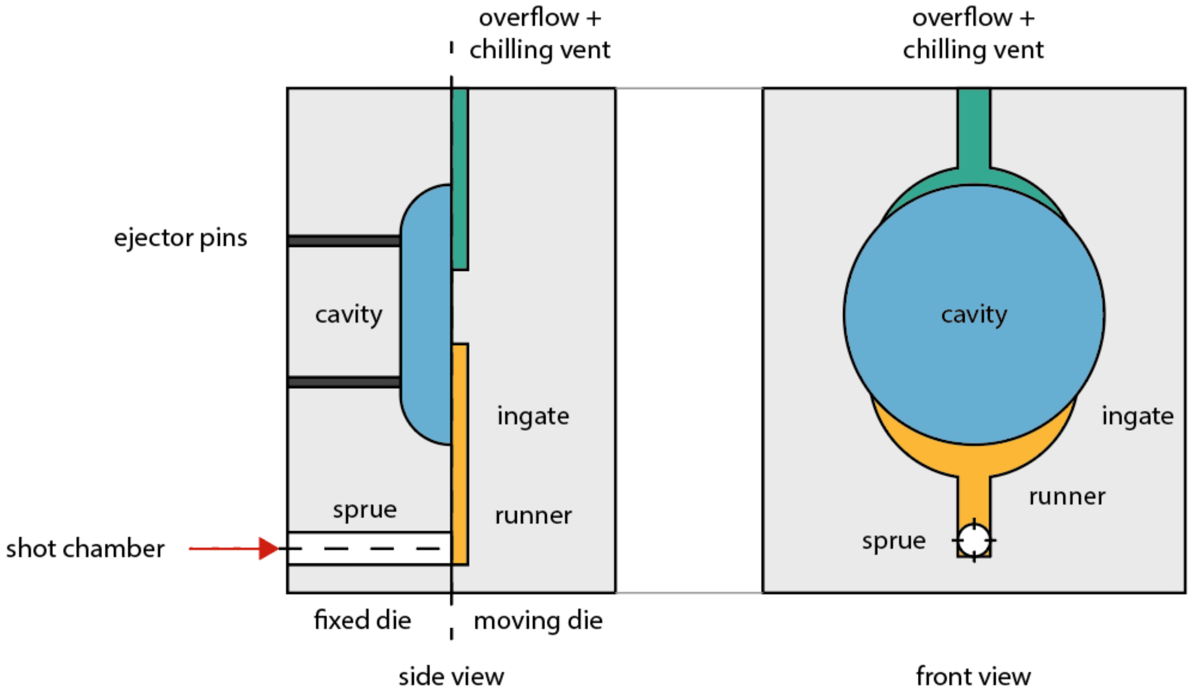


Figure 59 - die layout and gating system setup for horizontal machine.

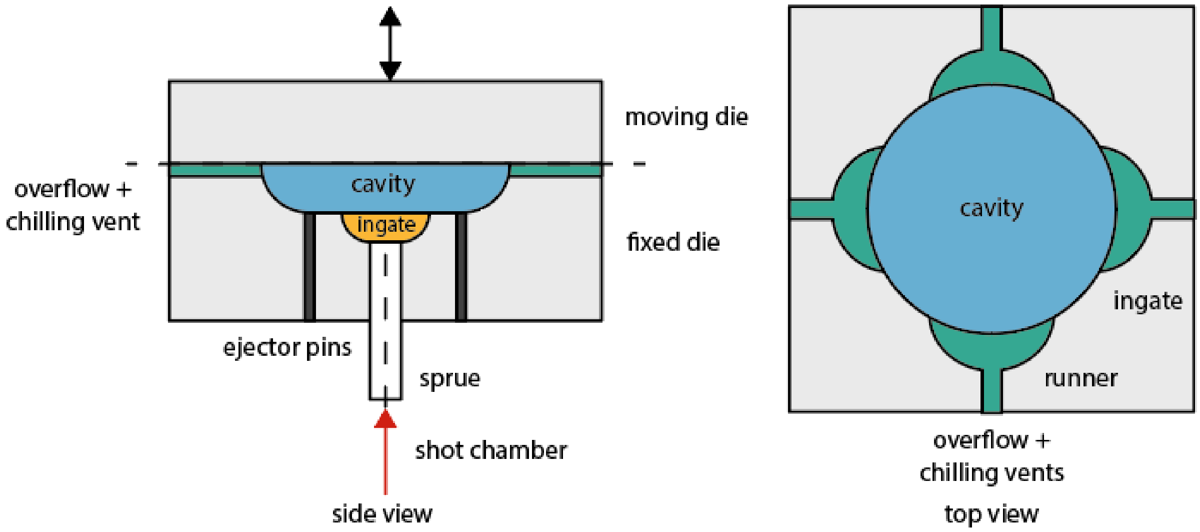


Figure 60 - die layout and gating system setup for vertical machine.

The die layout from Figure 64 and Figure 65 can be explained along the casting sequence:

1. Shot chamber, red arrow
2. Sprue, white
3. Ingate, yellow
4. Cavity, blue
5. Overflow channels + chill vents, green
6. Die opening direction, black arrow
7. Ejector pins, dark gray

In a computer aided 3D model, the horizontal setup could look like this:

- Left: fixed die (transparent) with sprue at the bottom
- Right: moving die with ingate at the bottom and overflow at the top
- Casted part in between

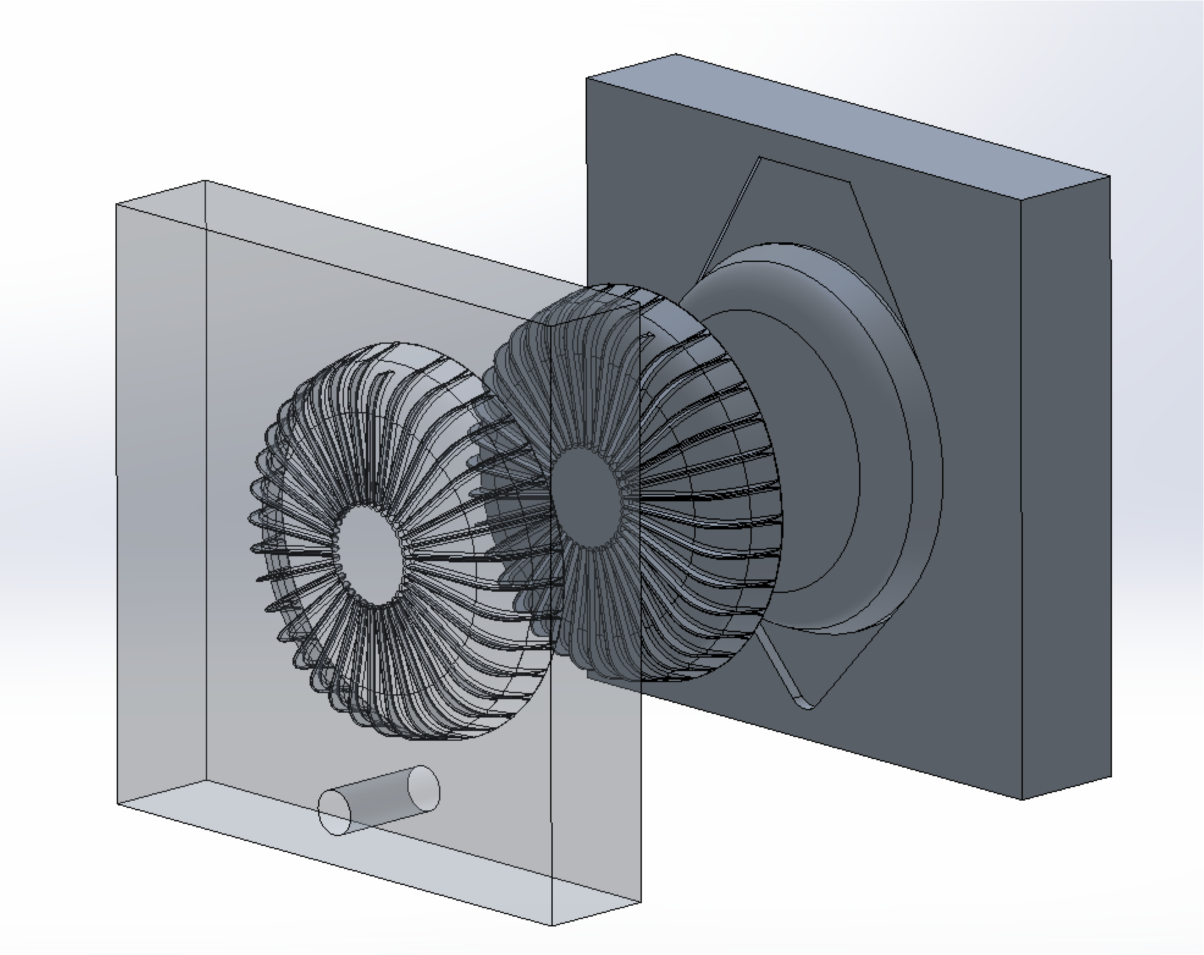


Figure 61 - CAD model of horizontal machine die setup.

5.5. HPDC alloy selection

A suitable high-pressure die casting alloy has to be selected that satisfies a wide range of requirements. Over 200 aluminium casting alloys exist, each with their distinct qualities to fit a certain purpose. For clarity, the Aluminium Association distinguishes 9 groups which are based on their main alloying element with and each have their distinct benefits and drawbacks.

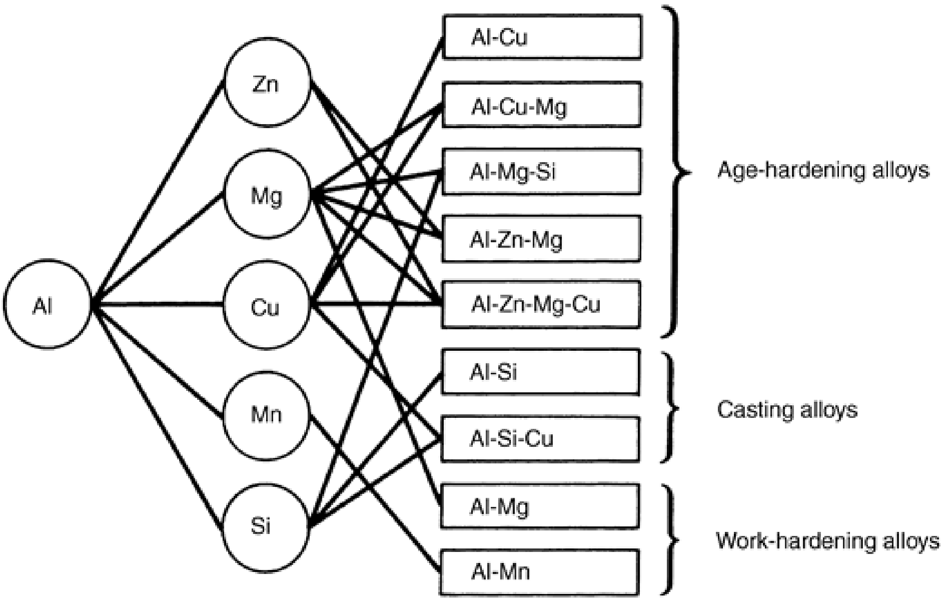


Figure 62 - general division of aluminium alloys by processing method (Davis, 1998).

Casting series	**Main alloying element**
100-series	Pure aluminium
200-series	Copper
300-series	Silicon, with added copper and/or magnesium
400-series	Silicon
500-series	Magnesium
600-series	*unused*
700-series	Zinc
800-series	Tin
900-series	Other

The relevant alloying elements are discussed below. Data from the ASM International Metals Handbook (Second Edition) is consulted (Davis, 1998) combined with online sources and an expert article (Runge & Chesterfield, 2023).

100-series: pure aluminium (>99,50%wt)
Pure aluminium is rather soft in unalloyed form (low hardness, low strength), therefore alloying elements are added to enhance material properties. These are the effects of the main alloying elements in cast aluminium:

200-series: copper as main alloying element (0-4.5%wt)
Copper is used as an hardening agent to improve strength, hardness and thermal resistance. This is highly beneficial for the product. If we look at the material selection list, most alloys are either 200-

or 300-series containing copper. A side effect of copper is that it negatively influences the anodizing process, therefore it is advised to reduce the copper content where possible.

400-series: silicon as main alloying element (5-22%wt)
Silicon increases fluidity, which benefits processing parameters like die-filling capacity, anti-soldering to the die and resistance to hot-cracking. Therefore, silicon casting alloys are highly desired, especially by the manufacturer. Furthermore, silicon improves stability of the material at higher temperatures and slightly increases strength. Setbacks of using silicon are increased brittleness at higher contents and that it does not react to the anodization process, reducing the effect of anodizing. Again, it is advised to reduce the silicon content where possible: ideally below 7wt% (Runge & Chesterfield, 2023). This contradiction requires extra attention when selecting the right alloy in consultation with the manufacturer, to prevent any processing difficulties or casting defects.

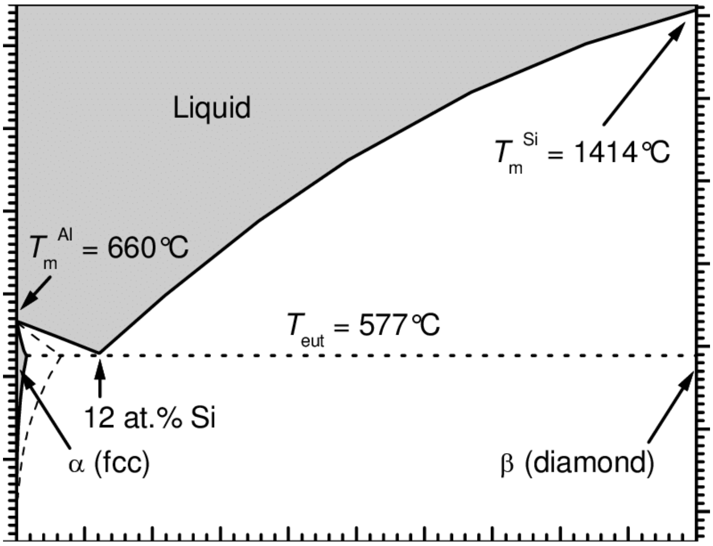


Figure 63 - Eutectic phase diagram of the AlSi alloy.

500-series: magnesium as main alloying element (0.3-1%wt)
Magnesium creates stiff and light parts with excellent corrosion resistance. Furthermore, it enhances heat treatability and enables precipitation hardening. However, it troubles processing parameters like die-filling capacity, pressure tightness, resistance to hot-cracking and anti-soldering to the die. Besides, it reduces the ductility and thermal shock resistance. Magnesium alloys are used in marine applications.

700-series: zinc as main alloying element (0-5%wt)
Zinc tremendously increases the strength of the alloy and improves thermal shock resistance. The 700-series with added zinc are one of the strongest aluminium alloys. The downside are that 700-series are difficult to cast and that high zinc contents compromise anodization.

Furthermore, alloys can consist of secondary elements that are either added in small amounts or are impurities to the alloy:

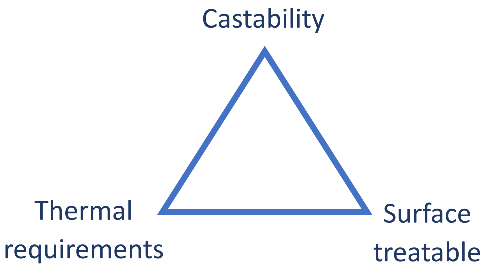
Iron makes the alloy harder are more heat resistant, but it negatively influences anodizing. Alloy designations with a preceding letter 'A' have a reduced iron content (e.g. A360 compared to the similar 360 alloy).

Manganese can be added in small amounts to modify the microstructure of the alloy to increase castability and make the alloy easier to anodize.

Chromium, titanium, calcium, sodium, strontium, antimony and phosphorous can be added in different scenarios to control the microstructure and improve fluidity for enhanced castability. They can also improve anodizing effect of the alloy.

To make the selection, we are looking for a material with a high aluminium content to allow for effective surface treatment. On the other hand, the material needs to comply with the thermal requirements of chapter 2, and needs to be well suitable for casting. This might sound contradictive, but some casting alloys are not preferred for casting. The following triad of requirements emerges:

- Thermodynamic requirements, where thermal shock resistance (TSR) is the main bottleneck;
- Good castability, ideally a dedicated high-pressure die-casting alloy;
- Low alloying content, i.e. high aluminium content, to foster oxidative surface treatment;



In practice, there is no alloy that could meet all the demands due to physical constraints. This is a typical scenario of ‘pick 2 out of 3’:

- High silicon content makes the part castable and thermal resistant, but less surface treatable.
- Low silicon content, with for example increased magnesium content makes the part surface treatable, but less thermal resistant.
- Alloys that are both thermal resistant and are excellent surface treatable are not dedicated HPDC alloys

The following high-performance die-casting alloys have been selected, that satisfy two or more of the above topics:

Material designation		**Alloying elements**		
Commercial	**ANSI/AA**	**Si**	**Mg**	**Cu**
A13	A413	12	-	-
43	C443.0	5	-	-
A380	A380	8.5	-	3.5
383	383	10.5	-	2.5
384	384	11	-	3.8
390	B390.0	17	-	4.5
A360	A360.0	9.5	0.5	-
218	518.0	-	8.0	-

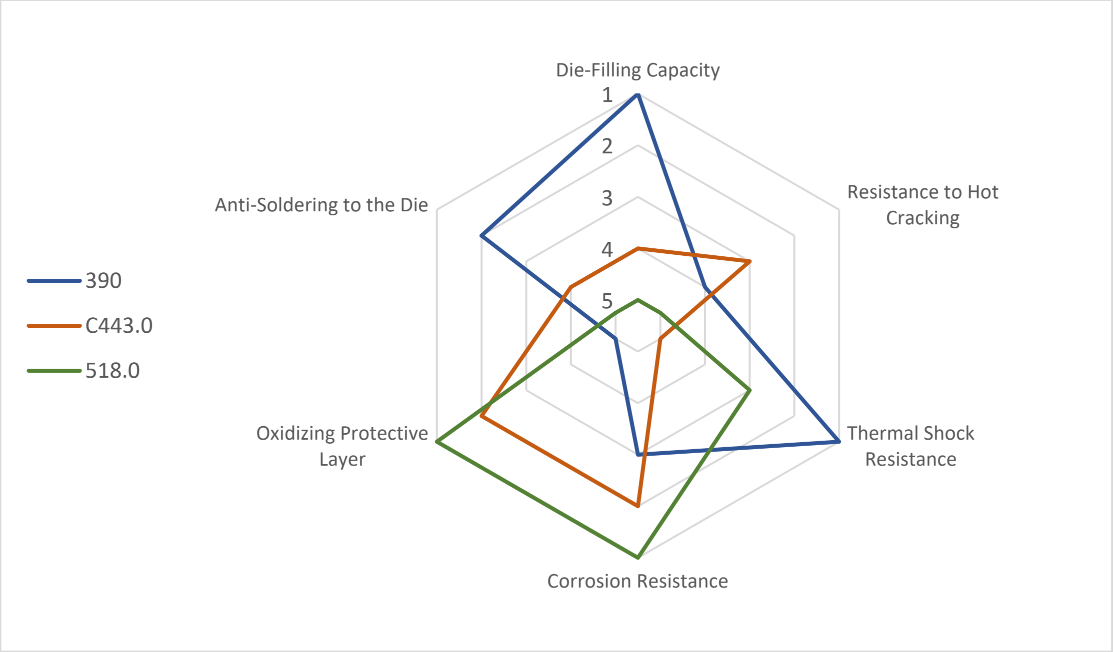
The aforementioned alloys are scored from 1 (ideal) to 5 (least ideal) on the following properties (MESinc, 2023).

Group	Property	Coherent Variable
Processability	Die-Filling Capacity	Fluidity [φ]
	Anti-Soldering to the Die	Solidification range [dT]
	Resistance to Hot Cracking	Strain to failure [%µstrain]
Durability	Oxidizing Protective Layer	Wt% of copper, zinc, iron and silicon
	Strength at Elevated Temperatures	Yield at temperature [MPa]
	Corrosion Resistance	Reaction to environmental substances

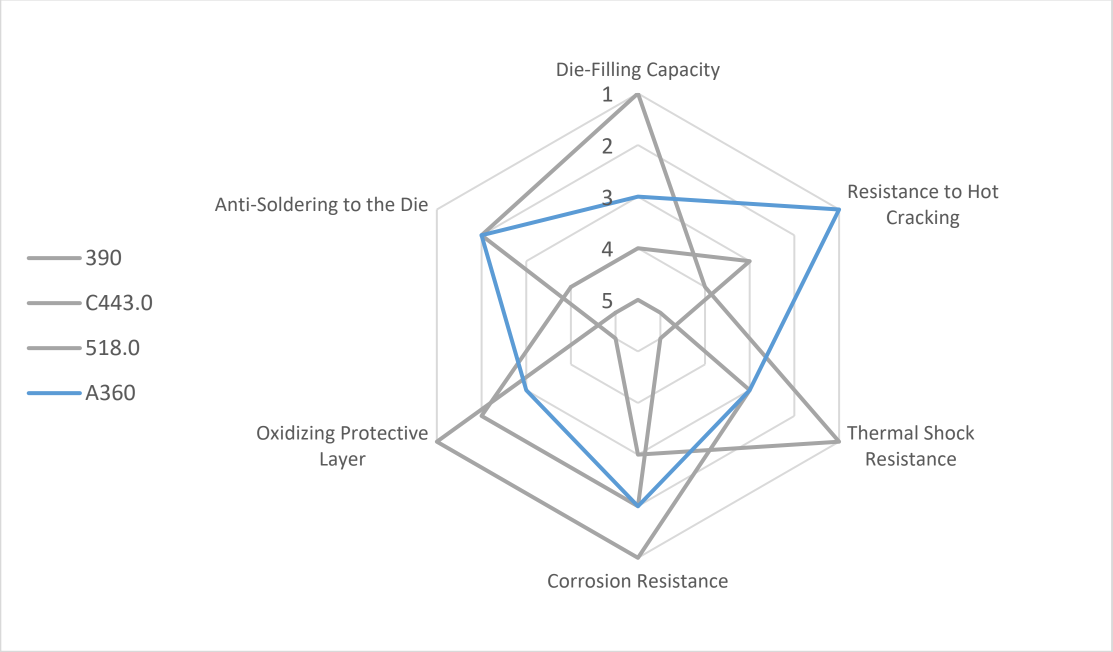
ANSI/AA:	413	C443	A380	518.0	A360	383	384	390
Si	12	5	8.5	-	9.5	10.5	11	17
Mg	-	-	-	8.0	0.5	-	-	-
Cu	-	-	3.5	-	-	2.5	3.8	4.5
Die-Filling Capacity	1	4	2	5	3	1	1	1
Anti-Soldering to the Die	1	4	1	5	2	2	2	2
Resistance to Hot Cracking	1	3	2	5	1	1	2	4
Thermal Shock Resistance	4	5	3	3	3	3	3	1
Corrosion Resistance	2	2	4	1	2	3	5	3
Oxidizing Protective Layer	4	2	3	1	3	3	4	5

From these alloys, a top 3 is made, with each their different specialty:

- 390 has excellent heat resistance due to high silicon and copper content;
- 443 has good oxidation possibilities, due to low silicon content;
- 518 has excellent oxidation possibilities, due to no silicon content and added magnesium.



Additionally, A360 is an overall high performance casting alloy, that performs well on most areas:



From this data, a simplified decision model (Harris profile) is made:

	360				390				443				518			
	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2	-2	-1	+1	+2
Castability			🟩				🟩			🟧			🟧			
Anodizing			🟩		🟧							🟩				🟩
Thermal resistance		🟧						🟩	🟧						🟩	
	+1				+1				-1				+1			

Based on this outcome, there is no clear preferred material. It is important to note that this is a theoretical research - although based on practical implications - but the data is merely measured in points and numbers, not in actual outcome. Therefore, it is advised to discuss the above materials with a selected manufacturer to come to the best result. Probably, practical test are required to see if a material genuinely responds to a certain scenario as claimed. To verify this, the following tests can be performed:

- Verify with manufacturers if the above alloys combined with the proposed shape are good castable or not and what the coherent implications of the alloys are. It is important to understand why it is or not, and what design or process parameters can affect the castability;
- Anodize material samples and look at appearance and test for abrasion resistance and hardness of the applied coating.
- Expose material samples to increasingly thermal shock conditions and note when they start to warp or crack.

Only after these tests are performed, a well-substantiated decision can be made regarding the exact alloy composition.

5.6. Post-processing

After casting, the part requires post-processing before it can be oxidized. The step are:

1. Removal of gating system, either via manual grinding or with a blanking die;
2. Tumbling
3. Drilling/blanking holes for the three-point rivet attachment;
4. Any necessary post-machining operations, e.g. to smoothen blanked edges;
5. Deburring of sharp edges

After the part is checked for casting defects or other imperfections, it can continue to the oxidation process. Before the oxide layer can be applied, the part has to be desmutted first to clean the surface and remove the natural oxide layer which can prevent growth of the artificially grown oxide layer during electrolysis oxidation. Furthermore, desmutting can also help removing any alloying element residuals on the surface, to prevent these substances affecting the oxidation process in a negative way. After anodization, the handle can be attached. Size 5 (mm) solid steel mushroom head rivets will be used, in accordance with DIN 662. Lastly, the part has to be packed and shipped.

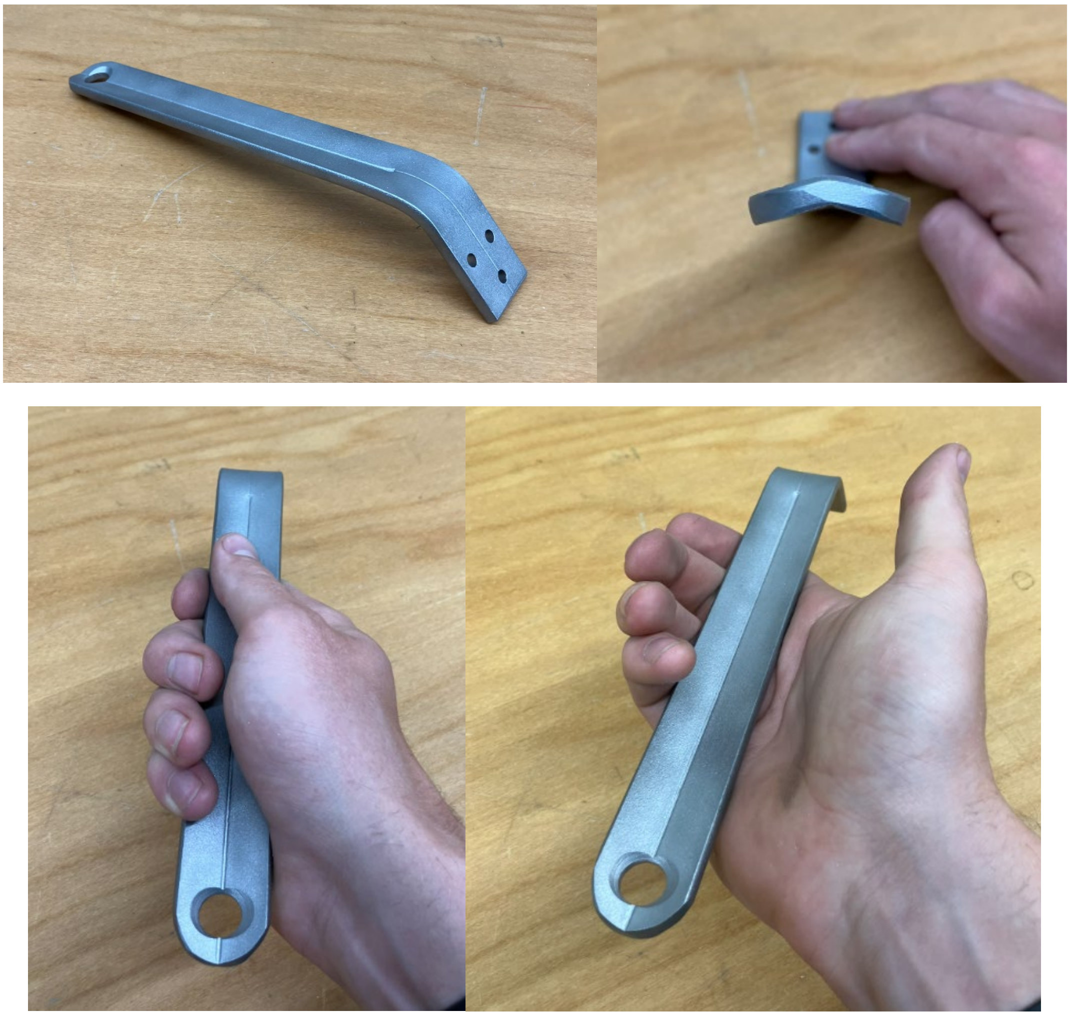


Figure 64 - images of hand with the handle.

5.7. Production cost estimation

The production costs will be estimated along the four sub processes (Figure 56):

1. Casting + material
2. Anodizing
3. Handle + attachment
4. Packing + shipping

An estimation is executed for two scenarios: a high cost scenario, where the higher end of estimations is taken based on rates in the Netherlands, and a low cost scenario where the lower end of estimations is taken based on rates in China.

For both scenarios, the following assumptions are established:

- Batch size is 10,000 pans;
- Pre-production investment costs are spread over the given batch;
- The machine size required is 800t;
- The material costs are deemed equal for China and the Netherlands
- The labour rates differ a factor 5, based on 2023 wage comparison (Qian Zhou & Zoey Zhang, 2023)
- The anodizing costs are based on the quotation from a Dutch anodizing company (Dutch Anodizing B.V.). The anodizing costs are divided by three for China.

For a list of consulted manufacturers, see Appendix C. List of interviewees.

The labour and machine rates used are, in euro per hour:

	Netherlands	China	
Labour rate	65	13	*Based on average 2023 industry rates*
Engineering rate	120	24	*Based on average 2023 industry rates*
HDPC machine rate	135	90	*Based on Custom Part Net default rates and knowledge gather from manufacturers.*

Two methods are used:

- Custom Part Net Cost Estimator tool
- Granta EduPack database method

Custom Part Net Cost Estimator tool, costs per unit in euro.

	High cost	Low cost
	Netherlands	China
Casting	21.873	11.498
Trimming	2.733	0.546
Deburring	1.834	0.367
Anodizing	12.49	8.33
Handle	7.5	2.5
Assembly	3.015	0.804
Packing	2.417	1.983
Total	**51.862**	**26.025**

Granta EduPack method, costs per unit in euro.

	High cost	Low cost
	Netherlands	**China**
Casting	22.500	8.330
Trimming	2.733	0.546
Deburring	1.834	0.367
Anodizing	12.490	4.163
Handle	5.000	5.000
Assembly	4.661	1.061
Packing	4.000	1.000
Total	**53.218**	**20.467**

The full cost estimation with an outline of all subprocesses can be found in Appendix L. Cost Estimation.

Concludingly, the production costs for the producing in the Netherlands (high cost scenario) are estimated around 50 euros per pan, equal to the set requirement. However, production costs in China are estimated at half the price, 20 euros per pan (low cost scenario).

Research Question 3
To answer research question 3 regarding viability: can the production costs be low enough to enable profitability? Yes. Definitely in an industrial and low cost country like China, and potentially also in a more costly country like the Netherlands. It is advised to move production to a low cost area (like APAC) when most production related risks are tackled, since producing overseas can also bring difficulties along.

5.8. Return on Investment

To bring the business case more alive given the information gathered, a return on investment comparison for the target user is made between a conventional frying pan and the proposed prototype. It is good to mention that a conservative-realistic scenario is worked out. Overly optimistic scenarios can jeopardize the business case due to their fragile foundation. The following assumptions are made to establish the comparison:

Assumption	**Value**	**Unit**	**Source**
Gas costs	1.37	*eur / m3*	*Market gas price, Netherlands, August 2023*
kWh per m3 gas	10.55	*kWh*	
Stove power	10	*kW*	*Typical stove that chefs use for frying*
Operational hours per year	600	*hours*	*2 hours per day for 300 days*
Operational product lifespan	600	*hours*	*equal to 1 year of cooking*

Gas costs are taken at the time of writing in the Netherlands (August 2023). One meter cube of gas embodies 10.55 kWh of energy. Operational hours are the hours that the pan is actually frying on the stove. This typically happens on a 10 kW stove to ensure enough power to create the Maillard effect and a high productivity. It is assumed that a conventional pan requires on average 60% of full power (6 kW) and the NeoStove pan requires half of it, since it is at least twice as efficient (3 kW). The operational lifespan of both the pans is set at 600 hours. Although the prototype is designed to be more robust, actual data for elongated lifespan is not 100% sure. In this scenario, the lifespan is equal to one year of cooking. In high foot-traffic restaurants, e.g. those of major hotel restaurants that are open throughout the year, the usage hours can double (1200 hours), theoretically halving the lifespan of the pan to six months. The two pans compared:

	Conventional	NeoStove	
MSRP	30	200	*euro*
Lifespan	600	600	*hours*
Net thermal efficiency	20%	40%	*%*
Required stove power	6	3	*kW*
Costs per hour	0.78	0.39	*euro / hr*

The sales price of the conventional pan is set at 30 euros, which is on the lower end of what restaurants pay for their medium sized frying pans. Although it is fairly low, it makes sense since the pan is seen as a disposable item. NeoStove has the preliminary aim to sell their pan for 200 euros. Restaurant owners have indicated that - given the savings of 50% - this is a price they are willing to pay (theoretically). Since no sales have been made, this is not yet proven in practise. The cost savings of this scenario are extrapolated over 600 usage hours and plotted in Figure 62.

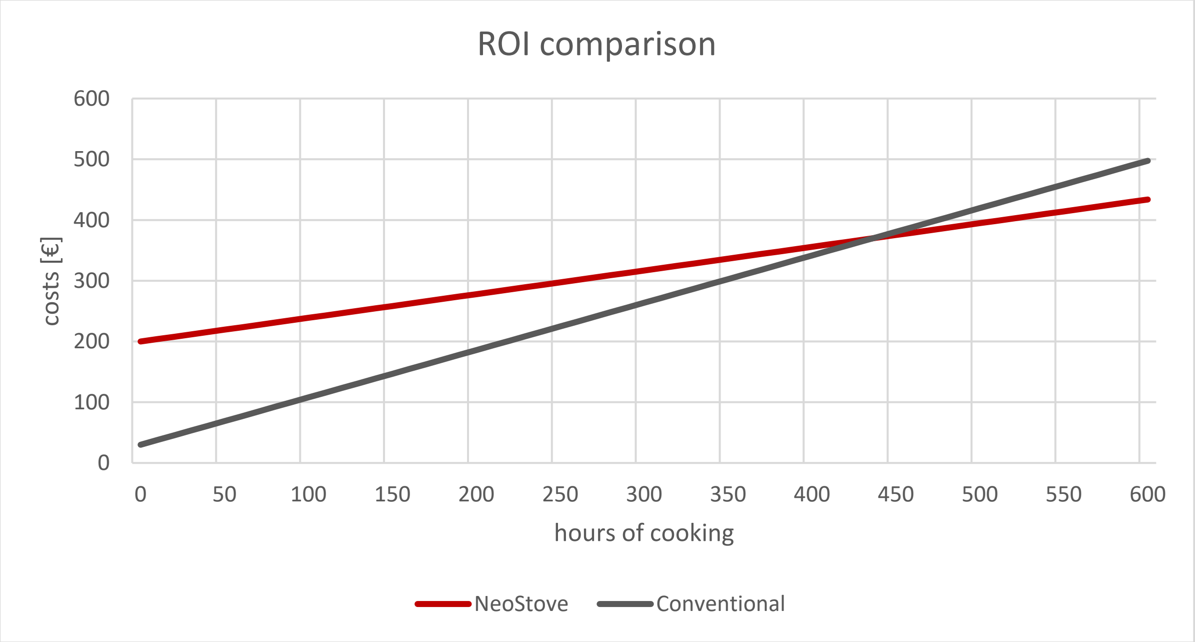


Figure 65 - operational cost comparison between a conventional pan and the developed concept.

The ROI compared to a conventional pan emerge after approximately 440 hours of cooking. This is long, close to the lifespan of the product. Therefore a set of suggestions is made to improve the ROI, hence increasing the viability of the proposition:

- Reduce sales price
- Increase thermal efficiency
- Increase lifespan of the product

Especially the latter are obvious and are the main challenge throughout this project: higher efficiency and elongated lifespan. Although one could tweak their calculations, it is important to truly substantiate potential monetary gains. The thermal efficiency gain should be monitored over a prolonged period of time with an accurate flow meter. The lifespan should also be tested and assessed over a prolonged period. Both of these parameters can drastically influence the ROI, and so the success of the innovation. Three additional scenarios are drawn up given the aforementioned suggestions:

A. Reduce sales price from 200 to 150 euros
B. Increase thermal efficiency from 40 to 60%. Prototype 1 (V1) has showed that this is possible
C. Increase operational lifespan from 600 to 900 hours

The comparisons for the three scenarios against the conventional product are shown in the following three figures. Two things are important to take note: 1) the point at which the lines intersect: hrs to ROI, and 2) difference in costs at the far end of the graph: cost savings at EoL.

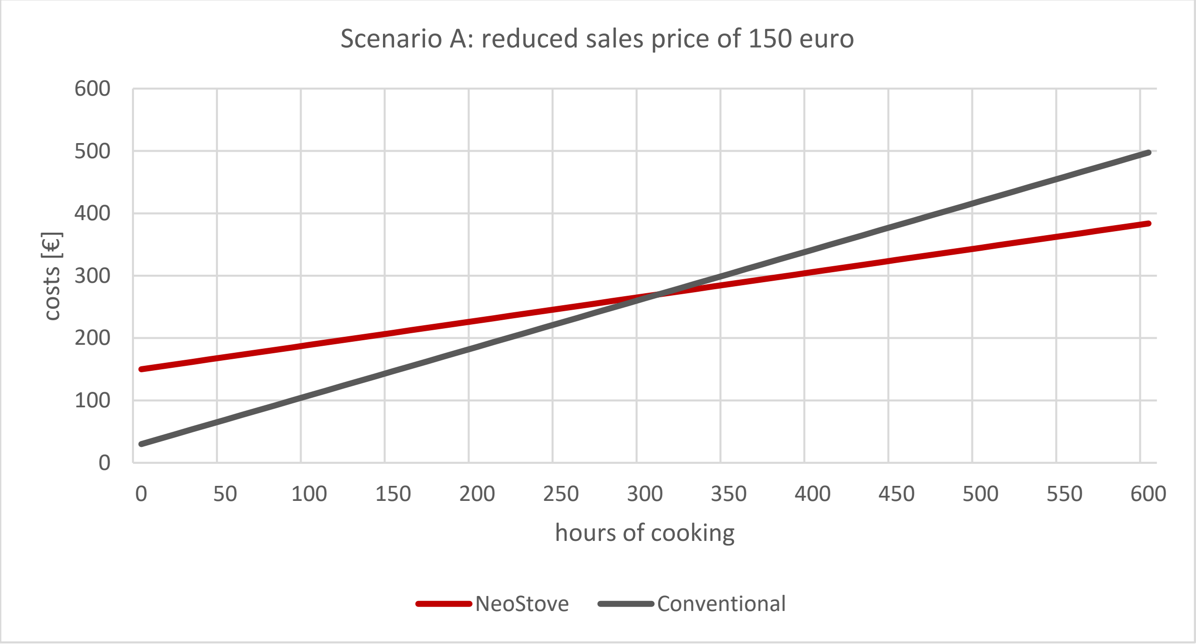


Figure 66 - scenario A: reduced sales price of 150 euro.

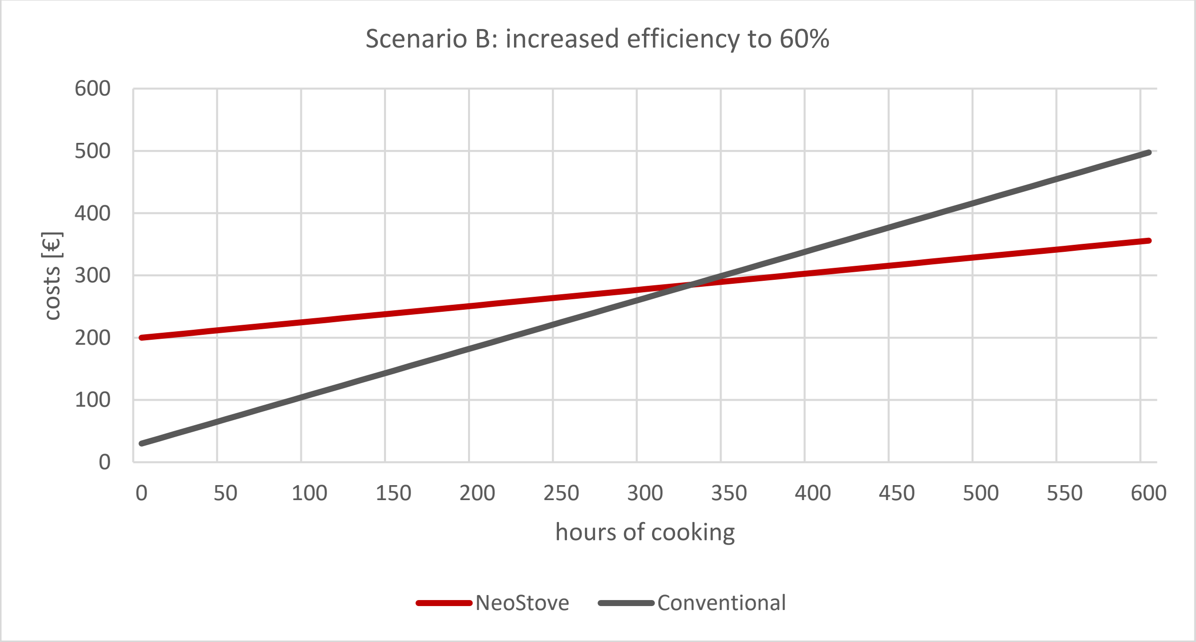


Figure 67 - scenario B: increased thermal efficiency to 60%.

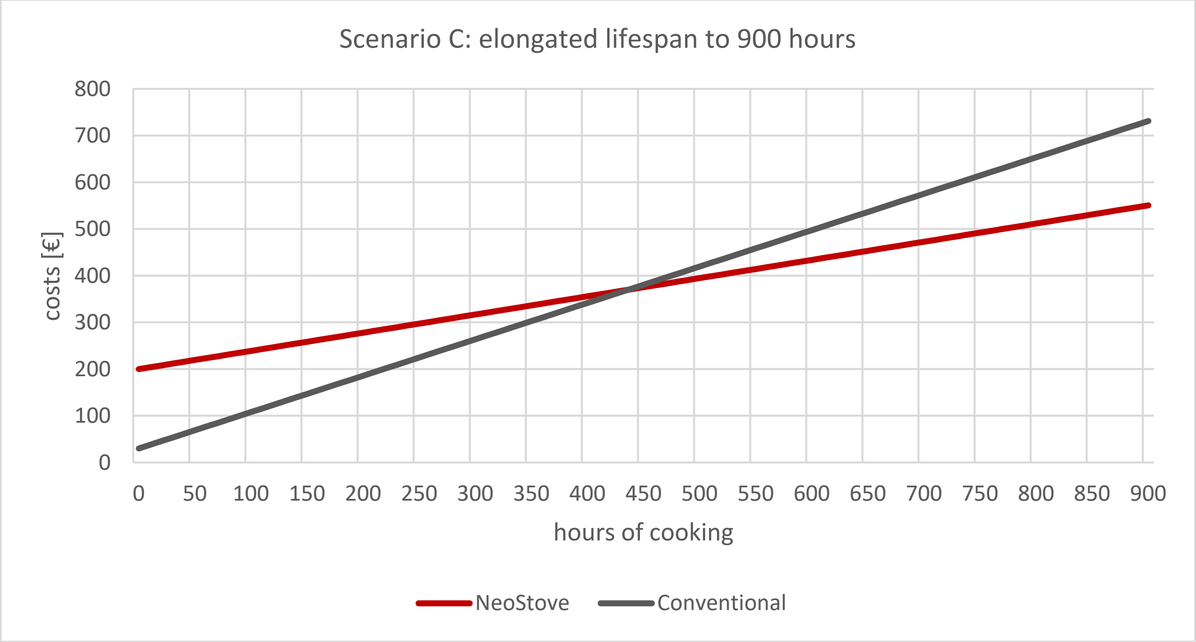
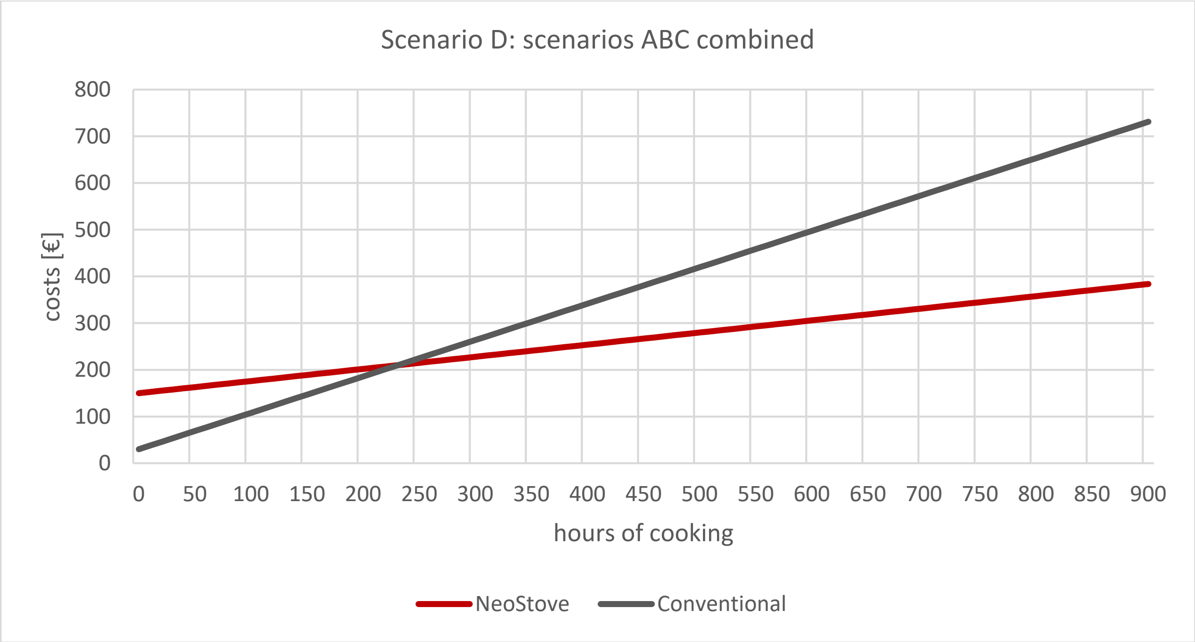


Figure 68 - scenario C: elongated lifespan to 900 hours.

Lastly, the three scenarios combined:



ROI and net cost savings compared for the given scenarios:

	1	2
	ROI [hrs]	**Net cost savings at EoL [eur]**
Base scenario	430	64
Scenario A: *reduced MSRP to €150*	310	114
Scenario B: *increased efficiency to 60%*	330	142
Scenario C: *increased lifespan to 900 hrs*	430	181
Scenario D: *ABC combined*	230	347

The net cost savings are estimated between 64 and 192 euros for the first year. This is not a major contributor given the high cash flows in a restaurant. However, if all pans are replaced with more efficient counterparts, and if NeoStove can validate a scenario similar to scenario D, thousands of euros can be saved on a yearly basis.

A final remark has to be made for the gas costs, which is set at €1,37 per m3 for the calculation. Naturally, this is both a dominant and volatile variable. It is a main driver for the viability of the innovation, which was not possible a few years ago with lower gas prices. The new pan saves 50% on cooking costs. This is 34 cents per hour in absolute terms, and would be more given a higher gas price. How the gas price develops over time is an uncontrollable variable but a determining factor for the success of NeoStove.

5.8. Sustainability

The core proposal of the frying pan is to reduce gas consumption. From a business perspective, this save costs. From a sustainability perspective, this reduces the emission of greenhouse gasses like CO2. However, the embodied energy and emissions during production of the pan should not be neglected. If production makes up a large part of the emissions, the whole sustainability effort could fail to succeed, like what we see with the emerge of some luxurious electric vehicles: the embodied energy of production is so high, that it can barely compensate over its operational lifetime. In that regard, a prompt sustainability analysis is performed, comparing the new prototype against two conventional frying pans, to see if the sustainability effort can be justified.

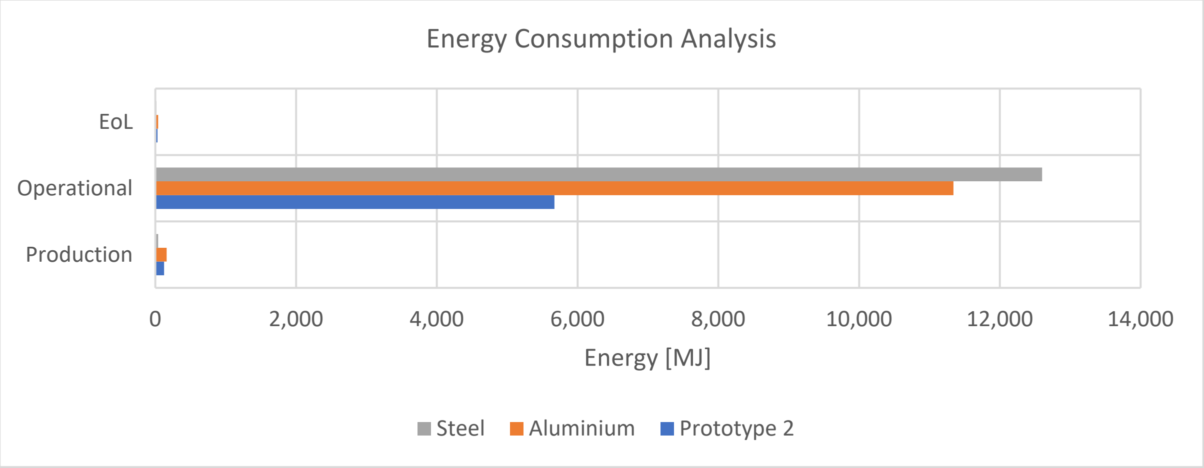
	Prototype 2	**Conventional frying pan**	
Material	aluminium	aluminium	steel
Alloy	390	390	S235J
Coating	aluminium oxide	PTFE / ceramic	No coating
Manufacturing method	HPDC	LPDC	Deep drawing
Gross material weight [kg]	1	1.3	2
Lifespan [years]	2	1	5

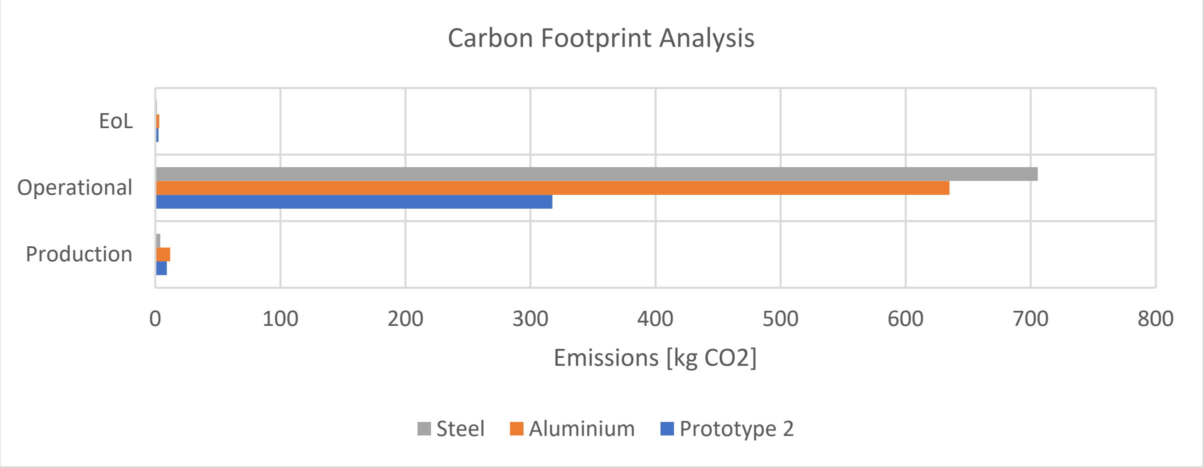
Three main stages are distinguished within the life cycle assessment:

- Production stage
    - Material primary production
    - Main shaping process
- Operation stage
    - Energy usage
    - Carbon emissions
- End of life stage
    - Recycling & disposal energy

The following assumptions are made:

- The handle and other secondary production processes are not incorporated because they are deemed similar among the pans. Therefore, only the core material and the main shaping process are compared;
- Yearly impact is calculated. For production and EoL, the embodied energy/emissions are divided by lifespan to penalize less durable products;
- For materials, the 390 alloy is used for the aluminium pans and the S235J alloy is used for the steel pan;
- The aluminium pans are casted and the steel pan is deep drawn, in accordance with typical production processes for these type of pans.





Although the production related emissions of the prototype might be slightly higher, the majority of the impact is made throughout the operational phase. Therefore, we can conclude that the pan makes a positive contribution to the environment and the reduction of greenhouse gasses. Nevertheless, keeping an eye on additional sustainable design and production practises is always desired, therefore the following points are addressed:

- The pan is optimized for durability, to enable a longer lifespan compared to conventional aluminium pans in the kitchen (2 years vs. 1 year);
- Aluminium is one of the most recycled materials in circulation (Granta, 2023). The typical grade 390 alloy saves respectively 38% and 36% on embodied energy and CO_2 footprint for primary production compared to the virgin grade (Granta, 2023). Therefore, it is advised to go with a typical recycled grade where possible;
- A durable aluminium oxide coating is emerged via the anodizing process. This offers excellent durability, increasing the lifespan of the pan compared to PTFE counterparts. Furthermore, where PTFE can contain PFOAs and other pollutant substances, anodizing uses the base metal to grow a protective layer which can be easily recycled. Other coatings can drastically impede the recyclability of the aluminium underneath (Subudh K., 2010);
- Instead of disposal and recycling at the end-of-life, the pan can be re-coated after it wears off and being used for another 2 years. Re-anodizing is very well suitable for already used pans, as the desmutting can remove all kinds of clutter from the surface before a new coating is applied. However, the question is whether this is a viable service.

To improve:

- The anodizing process is relatively environmental friendly due to the growth of a natural oxide layer without the presence of potent substances. However, the content of the sulfuric acid bath itself can be pollutant to the environment when disposed in an irresponsible manner by the manufacturer. The discussed PEO/MAO process on the other hand, makes use of a non-pollutant solution. Nonetheless, power required during this process is 30 times higher (Krishna et al., 2006; Mora-Sanchez et al., 2021), leading to higher energy consumption. If this process can be powered in a sustainable manner and is industrially available and affordable, it could be a promising alternative to anodizing;
- Although production in APAC area is more affordable, both social and environmental sustainability of production practises in the region are under scrutiny. The EU is implementing a sustainable product policy and ecodesign to prevent products with unethical origin enter the European market (European Commission, 2023). Close collaboration and tracking of the full supply chain are advised to enable responsible and sustainable production to comply with future sustainability policies. Furthermore, shipping from APAC to Europe, even by sea, increases carbon footprint and increased chance for supply chain disruption, compared to a local alternative.

Chapter 6: Project Conclusion

A conclusion can be established by answering the main research question and its 6 sub questions.

1: What should the product characteristics and requirements be such that it aligns with the desires of the target user?

The product requirements should align with the usage of the chef in a commercial kitchen environment. The requirements can be split up in three main groups: primary usage, secondary usage and durability. Primary usage requirements cover topics like optimized shape for frying and thermal behaviour. Secondary usage requirements all the other sub processes that are not frying, like the optimisation for storage, cleaning and user ergonomics. Furthermore, the pan requires a certain level of resistance to chemical, mechanical and thermal wear to elongate the lifespan of the product, increasing the energy-saving impact it can make.

2: How can the desired thermodynamic characteristics be translated into robust and practical features?

The thermodynamics of a frying pan have to be understood. The domain is split up in two focus groups: design for thermal behaviour and thermal durability.

Thermal behaviour consists of a set of parameters that may contradict each other. Therefore, a balance is found to enable desired cooking characteristics. The total heat capacity of the pan causes heat stability and should be >500 J/K to do so. Optimized characteristic length improves thermal efficiency and heat volatility, where both a faster heat-up (<120 [s]) and cool-down time (±120 [s]) is desired according to the chefs, to reduce waiting times and increasing productivity. Lastly, heat distribution caused by thermal conductivity of the material results in an even frying of the food. The material that outcompetes other materials and complies with these requirements is aluminium. In terms of dimensioning, the most important requirement that results in a geometry that complies with the above requirements is a limited wall thickness of ≤ 3 [mm].

Thermal durability determines the longevity of the pan: the microstructure of a material is affected at elevated temperatures and repeated heat cycles. Especially thermal shock events can pose a problem for the pan, therefore a material property called thermal shock resistance (TSR) should be above 130°C. Only a few aluminum alloys comply with this requirement. Steel alloys comply better and have higher thermal durability. The renewed geometry increases the stiffness of the pan with a factor 5 ($I=235mm^4$), reducing the chance for warping, which is one of the main end-of-life reasons for a frying pan. It is advised to not reduce the wall thickness below 2 [mm] for structural reasons, even though it might increase thermal efficiency.

3: How can the product comply with the established requirements and be mass-manufacturable?
Material choice is one of the most important factors of this project. It determines weight, thermal behaviour, thermal durability and processability of the product.

Aluminium is excellent processable material, which is beneficial due to the shape complexity required. Steel is less processable because it is a tougher material with a higher melting point, which makes it more difficult to form, also at elevated temperatures.

The product requires complex thin-walled fin structures. Only a few metal shaping processes can achieve this. The choice is made for high pressure die casting (HPDC) due to its excellent form freedom, scalability and cost-effectiveness. Steel is not suitable for HPDC, so the choice is made for aluminium. Due to the lack of thermal durability of aluminium, an additional surface treatment is required. A process called anodizing creates a hard oxide layer on the surface of the aluminium, making it more scratch, abrasive and thermally resistant.

4: How should the manufacturing be setup to ensure a robust and cost-effective process?
HPDC in itself is a quite robust process if the constraints are respected. Therefore, HPDC guidelines and design for manufacturing are applied, such as selecting a set of appropriate die-casting alloys (A360, 390, 443, 518) and implementing stable dimensions (uniform wall thicknesses and 1-2 deg. draft angles), which improve castability, reduce die-wear and increase resilience of the process.

5: Do the production costs compared to willingness to pay offer perspective for a profitable business?
Two production cost scenarios are calculated and compared: first, a high cost scenario with production in the Netherlands, where production costs are estimated to be 50 euro per pan. Secondly, a low cost scenario with production in China, where production costs are estimated to be 20-25 euro per pan. This is equal or below the anticipated 50 euros. This offers perspective for a profitable business given the willingness to pay of 200 euros.

6: How much are users willing to pay for the product and how is this affected?
200 euros, if the product works as claimed, given the presented gas savings of 50% and a lifespan of at least 2 years. If the gas savings or its lifespan are lower, the WTP naturally reduces, linearly with the savings to achieve the same ROI. The proposed concept (V3) has a hard anodized surface treatment which exact lifespan is unknown, but estimates are 1 year. Hence, it is advised to lower the MSRP or upgrade the surface treatment.

Research question: is it viable to enter the market with a more efficient and user friendly frying pan for commercial kitchens that inhibits the right characteristics for series-production?

Yes, but the following topics require further research:

- Thermal fatigue and longevity;
- Exact wear and durability of surface treatment;
- Optimization for thermal efficiency within the boundaries of manufacturing, HPDC in specific.

This will be covered in the next chapter, ‘Discussion’.

Chapter 7: Discussion

Summary

The pan is feasible for production, aligns with the desires of the target user so a subsequent market entry is viable.

Interpretations

This means that if the client (NeoStove) supports the design outcome and a suitable production partner is found, the detail design phase for production can start. This is followed by the making of a die and subsequent production runs.

Implications

If the design outcome along with coherent material and production process is assessed as suitable, investments need to be made. Although multiple check-ups and iterations by dedicated experts will be executed, much is at stake. The invested capital will not come back once it is spend, even if the design or the manufacturer fails to deliver. The caveat here is that manufacturers might be biased towards their own production process, increasing the change for a positive advise on a potentially doubtful project. Although this project is executed with a focus on trustworthiness, precision and competence combined with the support of multiple trusted sources to substantiate the design, some uncertainties still exist.

Limitations

Not all alloys proposed meet the strict thermal resistance requirements to prevent thermal fatigue and warping. However, plenty of other pans have materials with worse thermal durability properties, and still manage to remain unaffected over time. Because these requirements are not always met, the thermal durability of the proposed pan might be compromised, but its impact is difficult to assess.

We have learnt that the kitchen environment can deplete frying pans within several months, amongst others due to the unavoidable abrasion of its coating. Although the anodized oxidation layer is one of the hardest coatings available, its exact abrasion resistance under prolonged usage periods is unknown. Experimental research and theoretical mechanical properties indicate that the aluminium oxide layer should hold up well over time, but its practical lifespan remains unknown.

Calculations, experiments and pilot tests are executed to establish an insight in the cost savings for a given user. However, these tests are either in a controlled environment where the effect is difficult to track. Practical and long-term gas savings have not been established yet, which are crucial to convince potential customers.

Recommendations

To tackle the unknown of thermal fatigue, three rather resource intensive methods are proposed:

- Accelerated testing in controlled lab environment using X-ray and micro-spectrophotometry to assess microstructural change;
- Long term testing via prolonged pilot tests;
- (beta) Launch and monitor long term effects or wait for customer complaints;

To assess the durability of the anodized oxide layer, the following methods are proposed:

- NEN-standardized wear-resistance test (*NEN-EN 12983-1 General Requirements*, n.d.);
- Long term testing via prolonged pilot tests;

- (beta) Launch and monitor long term effects or wait for customer complaints.

To further substantiate exact cost savings, a set of use cases can be built together with launching customers. By installing a flow meter to the stove, the situation before and after usage of the more efficient pan can be assessed. It is important to ensure a reliable and comparable testing environment. This will give realistic input on the practical cost savings.

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