Technical University of Delft

3mE

Mechanical Engineering

Track High Tech Engineering

Literature Review

on

SYNTHESIS METHODS FOR FRAME DESIGN

STUDENT:
Stan van Egmond

SUPERVISOR:
Prof. Ir. Hans Goosen

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Chapter 1

Introduction

Many machines, vehicles or mechanical designs in general consist of a multitude of parts working together. For these parts to work harmoniously, they need to be strung together somehow. More often than not, a main frame of some sort supports all components and keeps them in place. This frame acts as the spine of the design and can take many shapes. When considering vehicles we see that cars have chassis, ships have hulls and bikes have frames. When expanding the spectrum we also see that computers have casings, buildings have support structures and organisms have skeletons or shells.

These structures have no other purpose than to position and support all other parts while being able to take all the loads that the object may encounter. Since this central structure either directly or indirectly influences all parts, designing it well can benefit the entire system. Although the essence is simple, designing a good structural basis often proves to be difficult.

Mostly, the parts that are to be integrated into a system are set in their shape and size. Of course, the designer has a choice as to which parts they want to implement. Nevertheless, those parts will not adapt to the rest of the design in terms of mounting solutions or layout. Therefore, it is up to the designer to place that component into the system.

This means that the placement must come with an adaptation of the frame to the part. Sometimes a subframe may offer a solution but that would concern a similar design problem. Anyway, as the parts will not change significantly, the frame must be flexible in terms of shape, size and layout to make the system work. This inherently comes with a lot of design freedom, which is useful to design a working frame but makes it difficult to assess what the best possible frame may be.

Oftentimes, a frame is good when it is light but stiff, costs little and is easy to manufacture. Ultimately though, what makes a frame, or any design for that matter, good is rather subjective. Naturally, it is possible to rate different designs based on certain criteria and a numerical outcome would show which design is the better one. However, this only shifts the subjectivity to the creation of those criteria and how they are weighed. So in the end, a design is only good if it does what it is intended to do and those intentions may be arbitrary. In other words, there is no fundamentally optimal design since what makes a design good depends on its use case and the wishes of a designer/customer.

These wishes can be of a non-mechanical nature. A good-looking design is something that could very well be wished for by a client, whereas an engineer may find that irrelevant and would rather focus on other aspects of the design. A design that looks better may impede other properties such as stiffness or weight. So in the eyes of the client, the good-looking design may be better, but the engineer prefers the stiffer or lighter design.

This already tells us that normal wishes from different types of people can quickly conflict and also shows that there is no fundamentally good design. Therefore, pursuing a fundamentally optimal design would be futile and a waste of energy. It has to be accepted that every design to some extent comes with compromises.

If there is no optimal design and every design comes with compromises, then the task of the designer is to generate the best compromise for all requirements and wishes that may be set for the design. This is no easy feat, as mechanical designs typically have multiple requirements and functions. These will, more often than not, counteract each other and impose trade-offs. Oftentimes there are properties that need to be minimized - cost, mass, emissions - and properties that need to be maximized - stiffness, speed, durability. This need for both minimization and maximization is what imposes trade-offs. One example would be that increasing the stiffness of a structure comes at the cost of also increasing the mass of that same structure. This relation between mass and stiffness is very direct and easy to grasp mentally.

When more properties come into play and the design problem is larger than just optimizing stiffness, the relation between these factors becomes less clear. How does ease of manufacturing influence the stiffness of the structure? There is no clear answer as this would be different for every design. Therefore, the engineer steps in and does the work needed to find out and changes the design accordingly.

To help the engineer do his work, it would be beneficial for them to have a clear overview of the design. When a design becomes complex, it will be harder to see how all parts and properties relate to each other. A systematic approach would then aid the designer in creating the most optimal design. This systematic approach already exists in the form of design methods. This aid to the engineer may be especially useful for chassis and frames, as nearly all designs have one. An efficient method for frame design could then collectively save resources, such as time for engineers, material and production effort.

1.1 Initial Outset

The proposed goal of the thesis this literature review is for was improving the chassis of the Lunar Zebro, a small rover intended to operate on the moon. Improving that chassis would be a very specific design case, as space applications have very different criteria than non-space ones.

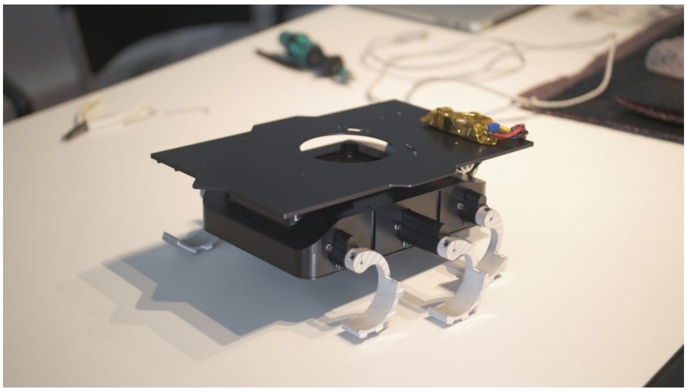


Figure 1.1: The Lunar Zebro

Using the Lunar Zebro as the main design case, it would be interesting to develop a method to systematically implement components into structures to enhance those structures. For example, batteries that improve the rigidity of the frame they are placed in[12], or stressed engines as used in Formula One. The main idea is to utilize the stiffness of components that are going to be used anyway, to increase the stiffness of the main frame. In return, this would result in less material being needed to achieve the desired stiffness, saving resources.

Generating this method and applying it to the Lunar Zebro would not only improve the Lunar Zebro but also benefit future designs, extending the usability of the thesis outcome. On top of that, a good method would not only benefit the design performance and material usage, but also the resources needed to come to the final design would decrease. This could be the time engineers spend on analyzing the problem, creating solutions and evaluating them.

To conclude, is it possible to create a design method to integrate parts into frame-like structures in order to improve the specific stiffness of a system?

Chapter 2

Frame Design

2.1 Chassis

Before any general method on anything regarding frame design can be composed, first the frames have to be understood. In other words, what information is already out there on design solutions, synthesis and analysis of frames and chassis?

2.1.1 Design Solutions

A recurring theme within literature on chassis design is the catalog style explanation of different design types of design solutions for creating a chassis. Each type of solution has its own strengths and weaknesses, which are thoroughly explained in the literature which for this mainly consists of books[4].

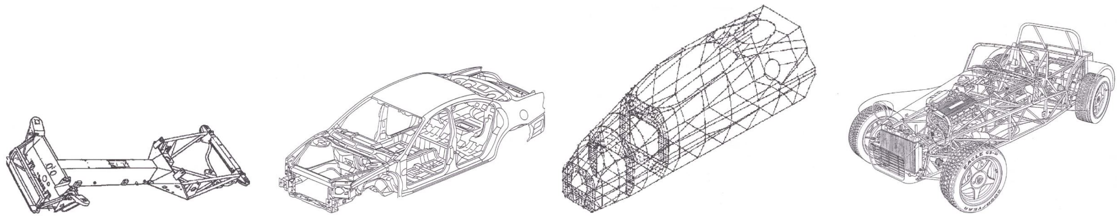

(a) Backbone chassis (b) Body in white (c) Monocoque (d) Triangulated tubes

Figure 2.1: Different types of chassis as described in the catalog style literature

Naturally, after automotive engineers have collectively designed many chassis over the years, the solutions mentioned are there for a reason. On top of that, sharing knowledge about these solutions is important for new engineers. Surprisingly, the literature does not seem to mention when a certain type of solution may be chosen over another.

2.1.2 Chassis Analysis

As chassis are made to facilitate all components and carry all expected loads, they are exposed to a large number of analyses. Assuring that a chassis can actually withstand all possible loads is crucial, as it ensures safety and durability. Unsurprisingly, this also comes forward in the literature on chassis.

Analysing chassis-like structures can be done either analytically or numerically. The latter has the upper hand though, as computing power increases over the years and the former only works for simplified cases.

2.1.2.1 Analytical Analysis

An analytical method to evaluate a chassis' load-carrying capacity is the method of using simple structural surfaces [3]. These surfaces represent flat sections of a thin-walled chassis. The SSSs can only carry loads in their respective planes, meaning that to accommodate torsional or bending moments a box-like structure is needed. Therefore, when converting a chassis into its simplified surface model it should become evident whether that design can effectively support these types of loads.

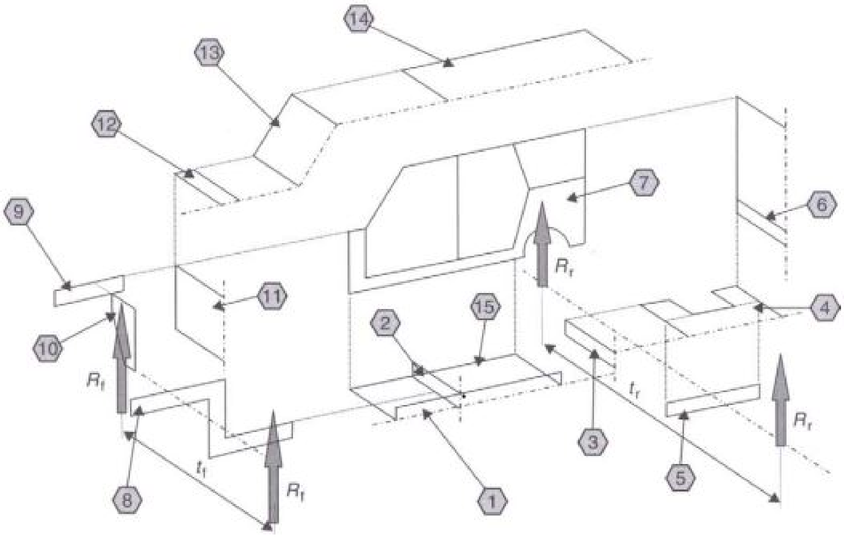


Figure 2.2: Caption

Beam theory can also be widely applied throughout chassis structures but will not provide any means to evaluate a chassis as a whole.

2.1.2.2 Numerical Analysis

A more modern approach to chassis analysis and evaluation are the numerical methods. One of them is the finite element method or FEM. This method divides any structure into smaller building blocks (the finite elements) by meshing it. Then the appropriate calculations are done on the elements regarding the forces, deflections and stiffnesses. It all comes down to solving the following equation;

$$\mathbf{KU} - \mathbf{F} = \mathbf{0} \tag{2.1}$$

As this is done for every element, the results can be assembled and the deflections of the entire structure can be visualized, showing the overall stiffness. This is FEM in a nutshell and naturally FEM itself is a complex field of research. The purpose of FEM here will be as an analytical tool to assess chassis performance.

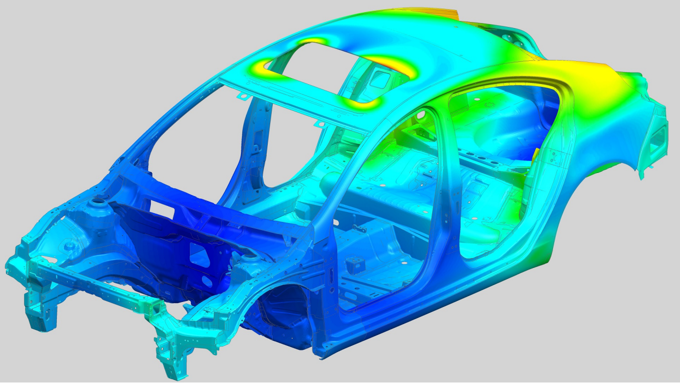


Figure 2.3: Example of the result of Finite Element Analysis on a car chassis

2.2 Approach to Frame Design

Demonstrating the types of design solutions available and providing tools to analyse them are not enough to synthesize new solutions. Naturally, knowledge helps in achieving adequate solutions. A good method, however, may be of equal importance.

What sets frame design apart from any other type of design is the level of integration. Frames are structures that often form one rigid piece, possibly after assembly, and have to integrate all other components. The frame has interfaces with all other disciplines, such as design, electronics, aerodynamics, ergonomics, etc. On top of that, frames usually are made from one type of material, limiting available production methods. The lack of moving parts or mechanisms within frames also makes frame design unique compared to many other mechanical design problems.

2.2.1 Part Integration

One way to improve chassis or frames would be by utilizing the stiffness that components within the structure already provide. Whether it may or may not be the purpose, all material objects have stiffness which theoretically can be used towards increasing the overall stiffness of a system.

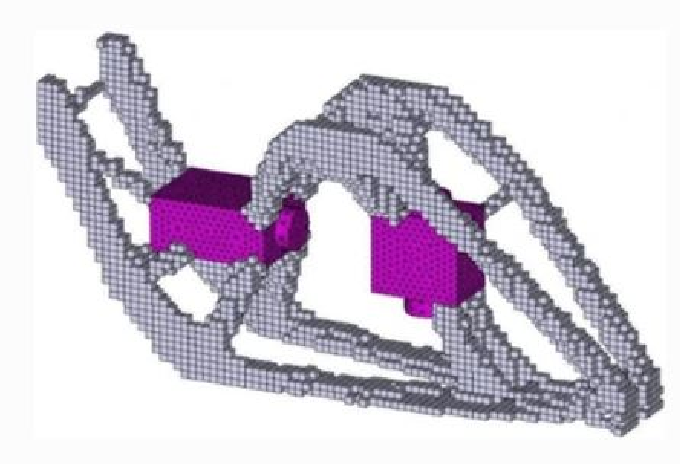
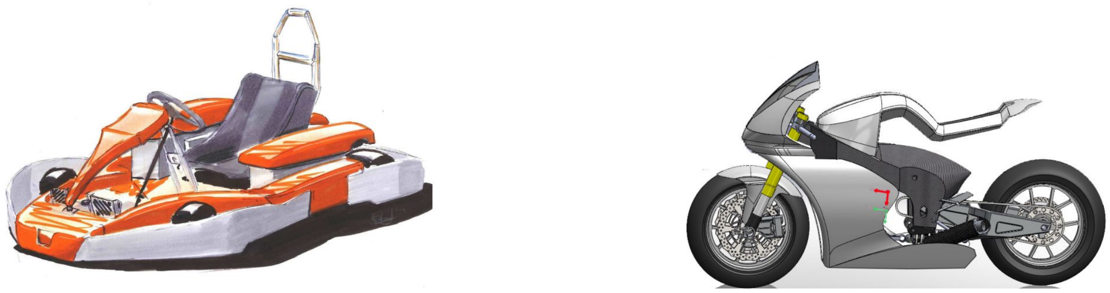


Figure 2.4: An example of topology optimization including rigid parts to increase overall stiffness.

This is already done in different cases, such as in Formula One or high performance road cars. These utilize the stiffness of the engine or gearbox to facilitate certain components and thereby decreasing the total weight of the car. In literature, there are some cases where an opportunity was found to apply this concept [22]. These, however, do not show a way to repeat this integration. Zhu et al have done work on applying this principle in topology optimization, but it is limited. [24]

2.2.2 Shape Design

As no approach to integrating parts into frame-like structures is retrieved from literature, a more general approach to frame design may be required first. When no external parts provide stiffness, any chassis or frame can only be improved by changing its shape or material composition. As the material selection is a design choice that usually is not iterated on, it will be left out of consideration when consulting the literature.



(a) Kart

(b) Moto2 motorbike

Figure 2.5: Examples of chassis which were primarily shaped by industrial design.

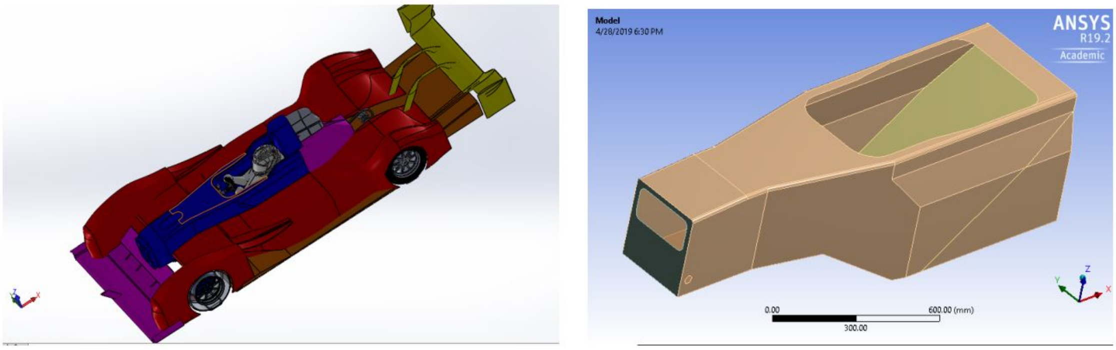
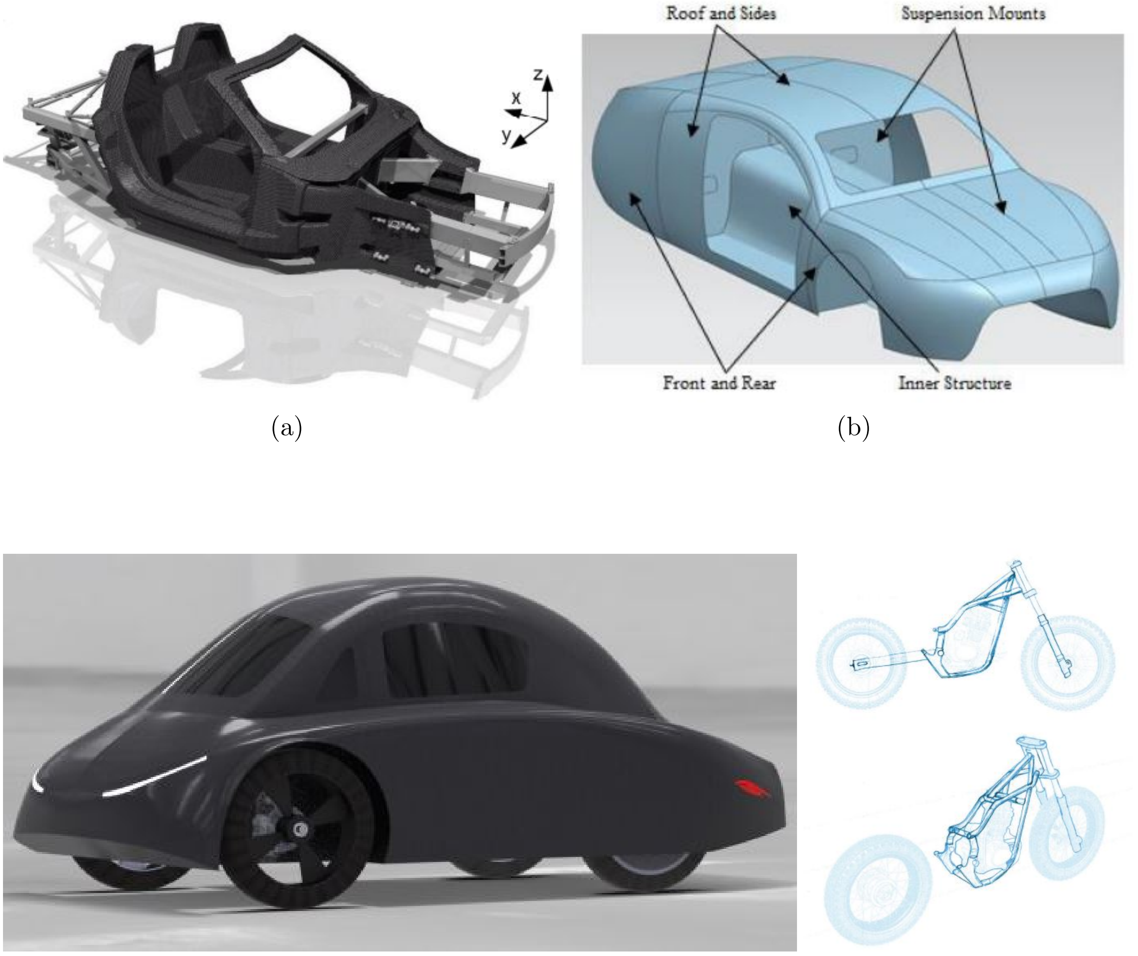


Figure 2.6: A chassis that was shaped by putting aerodynamics as the priority.

The shape of a chassis or frame does not start with stiffness or rigidity. An initial shape may be formed through industrial design [2] [19] when the aesthetic appeal is of importance, or through the aerodynamic performance when minimization of drag is relevant [14]. Only after this initial shape has been created and worked out into a model, attention is paid to the mechanical performance. From this point, multiple iterations occur, where FEM analysis and design adjustments alternate.



(a) (b)

(c) (d)

Figure 2.7: Multiple examples of chassis or frames where the initial shape design was created with no mention of how or why it is that exact shape, whatsoever.

On top of that, many pieces of literature do not mention or show how a certain design solution is reached. Oftentimes, a prototype or initial design is created 'from thin air' and then the authors dive into analysis and adaption, where the design is only altered slightly through optimizing properties [21] [23] [7] [13]. This begs the question of whether the chosen solution direction is the most optimal one.

2.2.3 Numerical Frame Design

Besides the existence of numerical analysis for frames or chassis, there are also numerical methods to (partly) generate frames or chassis. There are three 'levels' of numerical optimization techniques; size, shape and topology [11]. Size optimization needs a set shape of the overall structure and can then optimize cross-sectional area or shell thickness according to the loading. It leaves a lot of the design decisions to the engineer.

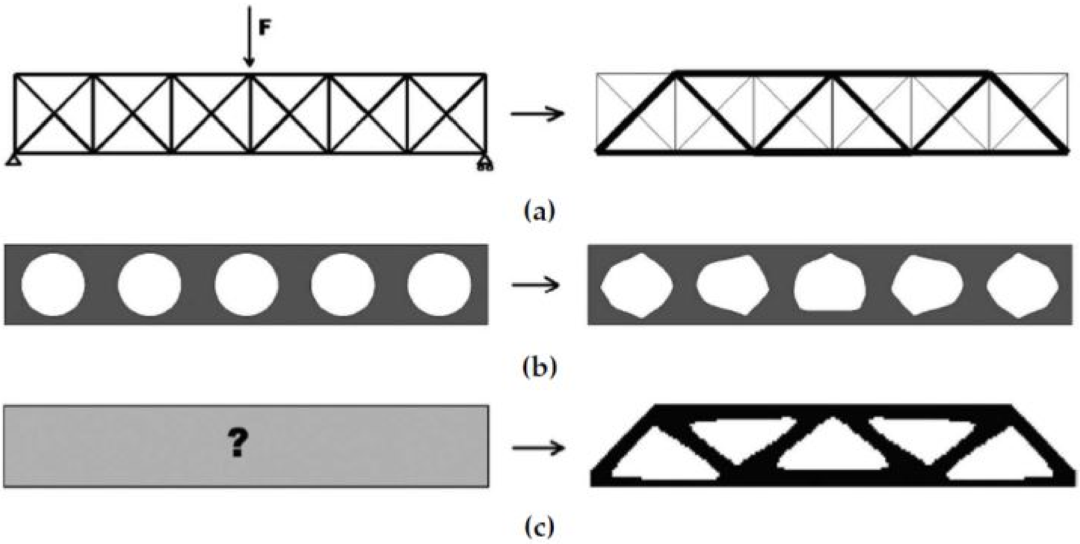


Figure 2.8: Sizing Optimization (a), Shape Optimization (b) and Topology Optimization (c) [11]

Shape optimization takes it a step further and can also change the geometry of parts, for example, cut-outs to lighten panels with minimal loss of stiffness. Topology optimization leaves only the boundary conditions to the designer and numerically calculates the optimal structure to meet those. What sets topology optimization apart from sizing and shape optimization is that topology optimization can synthesize an actual design whereas sizing and shape optimization are used to improve readily existing designs. Topology optimization can also be used to guide engineers toward a practical optimal solution. The theoretical optimal solution provided by the optimization may not be producible, so engineers may have to interpret this design and convert it to one that can be manufactured[18].

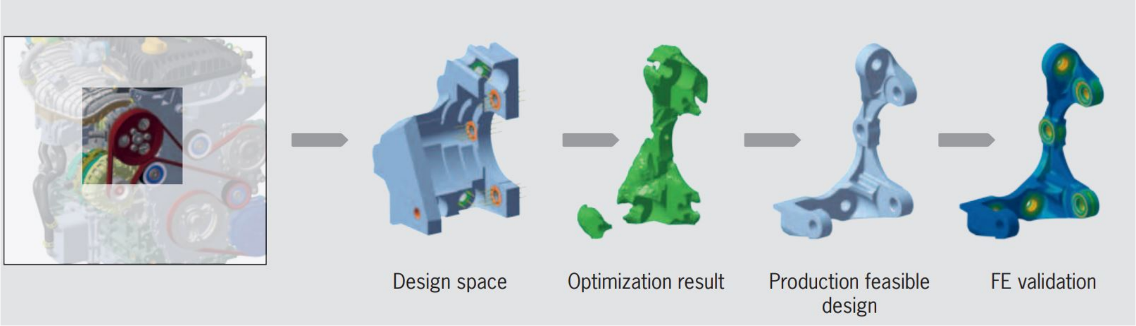


Figure 2.9: A part that is first optimized through topology optimization and then adjusted for manufacturability[18].

2.2.4 Intermediary Conclusion

The idea of integrating parts into chassis or frames in order to improve the stiffness is not new, but also not commonly applied, leaving a gap in the literature to enhance the availability of this application. However, for chassis design without the added complexity of integrating parts, there is also no proven method or approach. This raised the question of whether a general approach to design can be used at all.

Namely, many methods exist to guide engineers to their final designs, but why exactly these methods are helpful and how these methods came to be is not trivial. For these reasons it is decided that the direction of the literature review is altered into this world of varying design methods, approaches and philosophies.

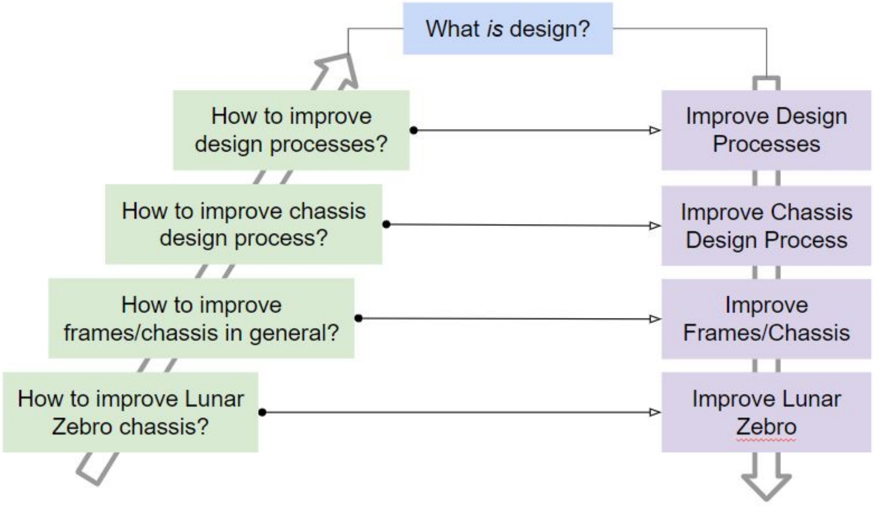


Figure 2.10: A visualization of the thought process behind deciding which questions to answer and why.

The idea behind this new direction is that in order to improve the chassis design process first it has to be considered how any design process may be improved. Then, if that can be done, all chassis including the Lunar Zebro could theoretically be improved. As going through all of the purple boxes in 2.10 in the final thesis will likely consume too much time, it is decided to focus on how to improve only the design processes themselves.

Chapter 3

Design in General

Design philosophy and methodology are constructs created by humans to better understand the nature of design and ultimately improve their use and outcomes. Many different perspectives on design have been voiced since the 1950s, as a need for a structured way of handling more and more complex designs became evident. Approaches, methods and philosophies about design are documented in books, papers and reports of congresses, highlighting different aspects of design on different levels of abstraction.

3.1 Design Process Models

The design process is often most clearly captured in a flowchart, showing all parts of the process as individual phases or steps and their order or sequence. Although these flowcharts may provide a handhold for designers to give them directions, they are not set up as guidelines or as a method. In other words, these models of the design process give an overview of what the activity of designing may look like but do not provide any instructions as a method would.

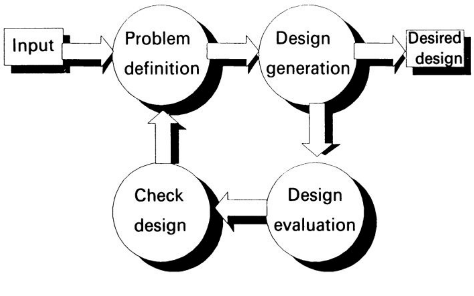


Figure 3.1: High-level model of the design process.

Bahrami and Dagli [1] initially show a very concise view of the design process in 3.1. Only four steps are set between the input (a fuzzy design problem) and the output (the desired design). While this chart does reflect all aspects of the process, it is too broad to extract a real sense of what goes on. Also, the output would fit better after the 'check design' box. Anyway, recognizing that this overview is too broad, Bahrami and Dagli have put forward a more detailed chart of what they call the general model of design.

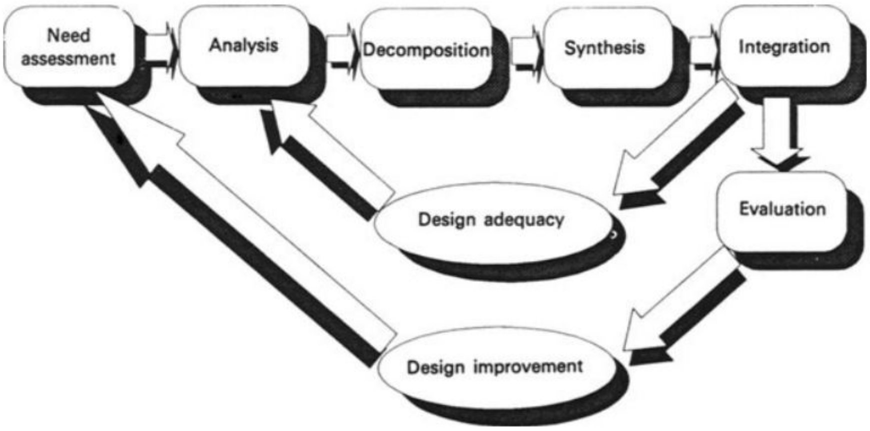
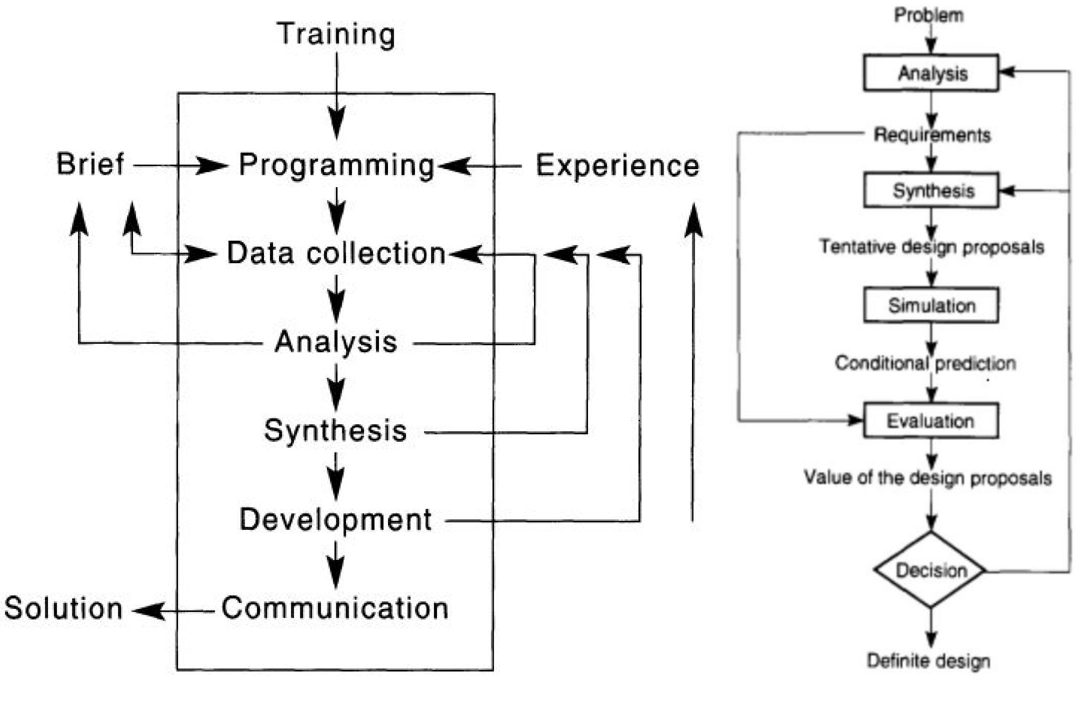


Figure 3.2: A more detailed model of the design process

As opposed to the compact visualization of the process, this overview gives a clearer image of what happens during a design cycle. Others have also tried to catch the design process in such a chart with a similar level of detail. As the interpretation of this process depends on the personal view on the matter or the design environment the different authors may be in, these models show some discrepancies between each other.



(a) Archers model[5]

(b) Eekels' model [8]

Figure 3.3: Design process models, similar but different.

3.2 What is Engineering Design?

As seen before, engineering design cannot be captured in one single method, approach or process model. This is also not needed as different types of design may require different tools. This is exactly the point and also the problem found in literature, when is method A beneficial and when is method B the optimal choice?

To answer this and other questions, one step back is taken to look at what design actually entails and what its place in society is. Especially the duality with science is a relevant topic. To answer this question of; ”what is engineering design?”, four subquestions are posed, each contributing to the final answer. The four questions are;

- Why is Design Needed?
- How are Engineering and Science Related?
- What are Synthesis and Analysis?
- How is Design Performed?

Arguably, other questions would also be relevant to answer what engineering design is, however, in light of the goal of this literature review, these particular questions may be more efficient.

3.2.1 Why is Design Needed?

First and foremost it must be clear that design and the need for design predate any methodology. Humans and some animals even are able to connect dots and form creative solutions to problems without the presence of any structured approach. These creative solutions stem from a specific need. Ultimately, this need comes from dissatisfaction with the current state of affairs. In other words, there is a driving force to change the current situation.

The feeling of this dissatisfaction does not have to be justified or objective, in fact, it is precisely the opposite. The subjectivity that each person has is the reason that there are so many different designs out there and also why it will stay relevant.

This variety in opinion can come from the cultural background a person has or how they have been raised, resulting in a specific set of values and norms. On the other hand, it can also simply come down to personal preference.

Summarized, engineering design is initiated by dissatisfaction with the current state of affairs. When this current state has to be changed and there is no explicit solution available, design is needed. For example, a kid using a chair to reach something on a high shelf is already a rudimentary form of design. The kid is not satisfied with the situation and wants the thing on the shelf, as that will satisfy them. Acquiring the thing is not straightforward as they cannot reach it, so a creative solution is needed. The kid utilizes the chair in a somewhat creative way and is then able to reach the thing, satisfying them.

3.2.2 How are Engineering and Science Related?

Engineering and science are two very interwoven subjects. They both need each other to advance and they also express many similarities. This creates the misunderstanding that engineering is merely a part of (applied) science and that engineering design is akin to scientific research. However, engineering and science show some fundamental differences, truly indicating that, although they complement each other, they are their own entities.

3.2.2.1 Process Comparison

First the similarities, according to J. Eekels the scientific process and the design process are isomorphic[8], they have the same layout and the same number of steps. Also the first step in both can be viewed as similar. Namely, the initiation for either is a problem. For scientific research, this problem is a gap in knowledge, the world of theory described as the mind by Eekels, about the physical world, the matter. In design, the problem lies in the physical world or matter. More specifically, the problem lies within the dissatisfaction with the matter, as discussed before. This dissatisfaction ultimately stems from value statements in the mind, which are said to be different than the truth statements (facts) captured in the mind, seen as knowledge.

Secondly, research has an observation step whereas design has an analysis step. The fundamental difference between these two is that observation outside-in and analysis inside-out. More clearly; during observation one observes the real physical world and tries to convert it to the theoretical world. During analysis, one does not have any physical object to observe but one can envision and investigate a mental image of a possible world. The ultimate goal is clearly realizing this possible world, hence the inside-out direction of thinking.

That brings us to the third step in design, which is synthesis. This is where one creates something new, changing the physical world. Unsurprisingly, the corresponding step in science changes the theoretical world. There it is done through induction, drawing a conclusion from a set of observations. This conclusion can be seen as an a posteriori photograph that captures one aspect of the observed reality. In contrast, synthesis is an a priori ‘photograph’ that encompasses the entire being of the design, which has to be realized.

Now, both in science and engineering, deduction becomes the mode of reasoning. In science, future phenomena want to be predicted. This prediction is deduced from present ones. In engineering, deduction is used as a tool for simulation. The first tentative design proposal is still an idea or mental image. To enact deduction, models have to be made that are logical of nature, often mathematical or based on material testing.

The fifth phase of the engineering design process is evaluation. Literally speaking, what is the value of the design and which value statements can be made? When the value is assessed, the final step in this process is making the decisions. Naturally, decisions are made throughout the entire process, hence the feedback arrow in the visual representation of the process. After the evaluation, it can be decided that the current design has to be improved or changed altogether, starting the process again.

The final two phases in scientific design are testing and then evaluation.Testing is done in the material world, to check whether predicted behavior corresponds with observed behavior. The result is a set of truth statements, which after evaluation, the final step, add to the collective knowledge.

3.2.2.2 Properties of Science

Cross, Naughton and Walker[6] argue that science has a set of attributes that make it attractive to project design on. The features of being rational, neutral and universal. They state that science and design are two separate entities. Design is said to be a technology, whereas science is based on fundamental truths.

> *"the scientific method is a pattern of problem-solving behavior employed in finding out the nature of what exists, whereas the design method is a pattern of behavior employed in inventing things of value which do not yet exist. Science is analytic; design is constructive."*

Although the distinction between science and design is stated multiple times, the urge for a 'design science' is clear. The qualities that science has; rationality, neutrality and universalism are desirable within the field of design. It would simplify the complex nature of design if there was a certain standard that could be used as a handhold for designers.

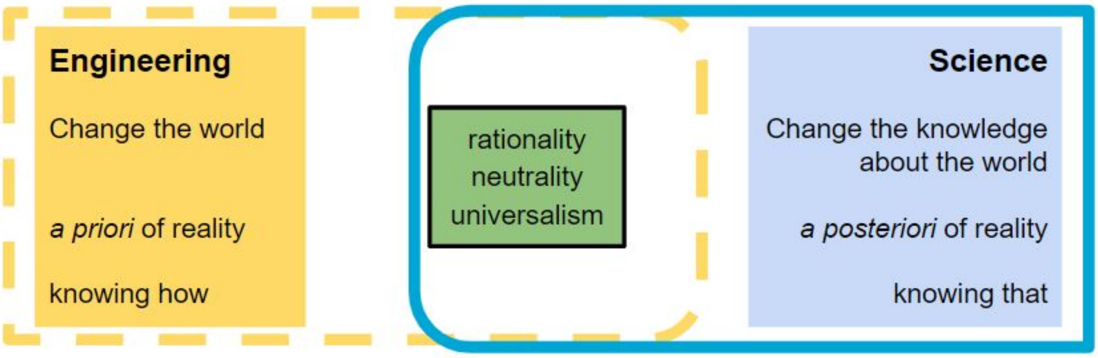


Figure 3.4: Engineering and science both have different characteristics. Some characteristics of science would be beneficial to the field of engineering.

Another way of putting it would be the need for an objective system or method to systematically conceive new designs or ideas. This does not mean that engineering design seeks to replicate the scientific method but it seeks to achieve the same values as science, as mentioned before. Also, viewing design as a technology is proposed. Technology is not as much the application of science, but the organization of resources in a way that enables complex solutions to be realized. A few key properties of technology are;

- Being directed toward practical actions and solutions for defined problems, whereas science is oriented toward understanding.

- Using knowledge that is not only scientific. Craft, design, organization and management are all fields that need to be employed in order for the technology that is engineering to work.

This way of viewing design implies that engineering and science are not similar and that engineering is of an entirely different category than science. The nonverbal thinking that contains visualization, images and abstract ideas are all part of designing, which are neither scientific nor literary. This human skill is poorly understood and inherently difficult to put into words. Therefore, it is a skill that is also difficult to convey in any shape or form. Oftentimes, this skill only grows with years of education and experience, not through text or video.

This is where the concept of tacit knowing or the skill of knowing how comes into play. The concept is that some things can be known but not told. This 'knowing how' is opposite the 'knowing that', the explicit knowledge which can be written down and transferred easily through media. The 'knowing that' is linked to science and the 'knowing how' to engineering and design, where the knowledge from science is very useful. It is even said that all of the explicit knowledge must be so integrated and grasped into the mind of a person so that it becomes 'forgotten' when performing the 'knowing how', which in this case would be the designing.

3.2.3 What are Synthesis and Analysis?

Akin to the comparison between engineering and science, synthesis and analysis can also be compared. Generally speaking, analysis is at the core of science and synthesis is at the core of engineering and design.

Synthesis is the combining, assembling or compounding of things such as parts and components but also ideas or processes. In other words, creating something new from what is already available. Generally, when synthesizing complexity increases, implying that synthesis is a process that requires a certain intelligent inspiration. Analysis on the other hand, is the exact opposite. Analysis is the detailed examination of something in order to understand it better. This can be done by taking it apart and breaking it into smaller pieces. The smaller pieces can be understood more easily and a structured overview can be made, which in turn provides understanding of the whole.

An important distinction between synthesis and analysis is their respective modes of reasoning.When reasoning from prepositions to a conclusion it can come in three distinctive modes; deduction, induction and abduction. Deduction is the most explicit mode of reasoning. When deducing, only one conclusion can be drawn from a certain set of premises, if A and B are present then C will happen. If one sticks a thermometer in water and it shows a certain temperature then it can be concluded that the water has that temperature.

Induction is less explicit, if A and B are present it is likely that C will happen. If one sees people outside wearing warm clothes, one might conclude that it is cold outside. There is some uncertainty involved with induction compared to deduction. Abduction reasons the other way around. With deduction and induction, the causes can be observed and the consequence is either certain or probable. With abduction, the consequence is observed and a possible cause is reasoned. This type of abduction is explanatory abduction. It requires certain knowledge to abduct the cause from a certain consequence; if one sees an unlocked bike near the entrance of a building they may conclude that someone was in a hurry to get to the building and in their rush forgot to lock their bike.

Aside from explanatory abduction there also exists innovative abduction, shortened to innoduction. Innoduction happens when a person takes and considers the current situation and manages to come up with something new using what is at their disposal. A simple example would be a kid using a chair to reach a spot they could not reach before. The use of the chair does not automatically follow from the current situation, its use needs some spark of creativity. This innovative spark can sometimes be observed in animals but for humans, it is part of daily life. These sparks to create solutions happen all the time, however, they are not guaranteed. Some people come to solutions earlier, some come to better solutions than others and some get stuck with the problem. This also applies to design. Oftentimes, the problems faced in engineering are far more complex than everyday problems, though. This is where the design methods come in. Using tricks, mental exercises and ways of working described in design methods the sparks of creativity can be reached more easily. The design methods are akin to flintstone, so to speak, and using them makes creating those sparks of creativity easier.

3.2.4 How is Design Performed?

When considering the models of the design processes, there is a common thread between all of them. Naturally, they all start with a problem of some sort. This problem stems from the dissatisfaction with the current state of affairs, as discussed before.

After this problem is stated, there is an analysis step. The problem is analyzed, taken apart, divided into subproblems and structured into functional requirements and wishes. Additionally, the current state of affairs is examined more closely. Solutions or partial solutions could already exist or the opposite could happen, where other problems need solving first. Also, indicators such as performance parameters could be set up, in order to be able to assess possible solutions later on. In short, this analysis step is of a preparatory nature.

As the preparation is done, solution creation can be started; synthesis. This is where the 'magic' happens, where engineers use their creativity and experience to generate ideas and concepts. Creating new things is at the core of design and engineering. Naturally, people are inclined to think of solutions before the initial analysis is done and that is normal. The rigorous separation between analysis and synthesis has been proposed, in order to avoid any form of bias toward any solution. However, this idea has been discarded by critics. Namely, it has been stated that every person will already have some bias on the basis of their previous experiences. Whether this bias comes forward during or before the 'official' synthesis is then irrelevant [**empty citation**].

After synthesis has been sufficiently done, another analysis step comes in. This time the analysis regards the created solutions and comes more in the form of evaluation. Design evaluation can be performed by using computational analysis techniques such as FEM, CFD or motion analysis, but also by simpler techniques such as scoring a design based on performance values.

As the design solutions have been evaluated, a decision has to be made. If the outcome of the design process is satisfactory, the design can be realized and finished. If that is not the case, the design process must be redirected to the first analysis step. Here the underlying problems that caused the unsatisfactory result can be identified and taken into account when entering the synthesis again.

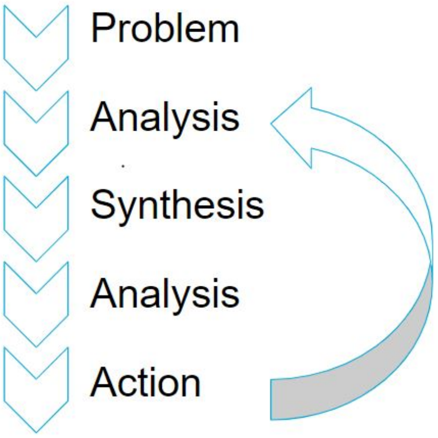


Figure 3.5: The essence of all design processes.

Although the steps are portrayed as sequential and linear, the design process is always iterative and circular. Besides, each step does not have a fixed duration, scope or level of detail. For example, if one feature of a design is not satisfactory in the eyes of the designer, they may identify what they do not like and change it into something satisfactory. This could be as basic as not liking the color of a part because it does not match with the rest of the system and changing the color, an action that takes a few seconds only. The other extremity is concluding that the design concept was wrong at a late stage and then deciding to go back to the drawing board, so to speak.

3.2.5 Design is...

Ultimately, design exists for the sole reason that people want to turn an unsatisfactory into a satisfactory one. This dissatisfaction is subjective and does not have to be justified necessarily. The means to achieve a satisfactory situation are innovation and design methods.

The way design is handled can be captured in different design process models, which all effectively boils down to the process visualized in 3.5. One of two key problems with design and design methods is the fact that synthesis or innovation is not guaranteed. That part of the process cannot be brute forced and therefore could be a potential bottleneck. Also, it is not clear whether certain problems require a different approach than others. An important question arises; Can method A be used to solve problem X more effectively than method B, C or D?

This question holds especially for the synthesis part of design, as the preparatory analysis mostly consists of setting up functional requirements and researching state-of-the-art and evaluation analysis often uses tools tailored to certain fields, such as CFD, FEM or testing. For synthesis, no general approach for everything exists and there is also no tailored tool. For these reasons, the direction of this literature is altered further, focusing on synthesis methods particularly.

Chapter 4

Design Methods

From the second half of the 20th century and beyond many different views have been shared on how a design process works and on how it should be performed. Methods, approaches and tools to aid the designer have been created and used.

Methods on the entire design process, such as the Pahl and Beitz method, exist[15] that for each step of the design process prescribe what action has to be undertaken. Not entirely surprisingly, a similar step-based guideline has been concluded from viewing how many different engineers approach problems and how they solve them [9]. These guidelines are valuable when some structure has to be applied to the entire design process but lack in sparking the designers' creativity.

On the other hand, there are also approaches to design, which do not necessarily prescribe a set of steps to be taken but a mindset that has to be practiced during the entire design process. Value engineering is one of these approaches, where all parts of the design are handled in such a way that minimal resources are used to achieve the goal. Other examples of approaches are;

- Design for Assembly
- Design for Manufacture
- Sustainable Design
- Modular Design

Then there are the tools, which come in two flavors; analysis and synthesis tools. Analysis tools help designers establish what problem they are dealing with and what they need from their design. The result of using these tools is a list of what design must comply with or what properties an ideal design would have. One example of these analysis tools is the MoSCoW method.

Then there are shorthand methods that can help designers with generating new and innovative ideas; the synthesis. These can be implemented into any design process during this synthesis phase.

4.1 Synthesis Methods

4.1.1 Reframing

Design problems can be stated in a particular way and in a particular frame. This frame could say something about what the product has to do, which is at the core of the design, but also about the environment, the type of people who interact with or within what time span, etc. The way a problem is framed influences the design. For example, an object designed for children or adults could manifest in different ways while their purpose may be the same.

The method of reframing [16] calls for setting an initial frame for the design problem that highlights relevant aspects regarding the context. Then a chart can be constructed with three columns. In the left column the aspect that changes is stated, the middle column contains the primary user goal and the right column holds the design implications that follow from the changed context. Supposedly, more 'provocative' context changes aid in reaching more innovative designs.

4.1.2 Concept Mapping

A concept map[16] is created in three steps. The first step consists of identifying the core taxonomy of the problem. Verbs and nouns that describe the context of the problem are put onto index cards. These include; 'people, places, systems, artifacts, organizations, actions, processes, methods, and other entities and activities'. This taxonomy then has to be prioritized by rearranging the cards into a certain hierarchy, which is subjective to the designer. Cards could also be arranged as 'parent' or 'child' cards. indicating subgroups within the taxonomy. Now, the concept map itself can be created with the index cards as building blocks. On a large sheet of paper the index cards can be laid out according to the hierarchy defined before, and connecting line elements with small pieces of sentences indicate the interrelationships between the elements.

Concept mapping can be a synthesis tool in itself but it is also proposed as an aid to any synthesis tool. Namely, it may help in increasing the understanding of the problem in a more visual manner.

4.1.3 Insight Combination

Insight combination [16] starts by identifying insights about the problem and problem analysis. The designer will write down observations within the gathered data and link them to a piece of their knowledge that is related, this is an insight. This link or insight may not be accurate, which is acceptable. The insight can be written down on a particular color of note card.

The designer will then identify design patterns within the field of their product or closely related fields. In what way have people created innovative designs? What changes did they make to their design? These patterns can be written onto different color note cards.

The now-attained note cards can be shifted around in the search for viable combinations. When a combination generates an idea then that idea must be written down as well. The method is in fact only a way to shuffle design solution patterns and design problems quickly and effectively, which can be fruitful.

4.1.4 Morphological Analysis

General morphological analysis (GMA)[20] starts with decomposing a complex problem into smaller problems that are easier to handle. Each part of the larger complex problem is given multiple solution options. This collection of subproblems along with their respective solutions are set against each other in a table, constructing the morphological field. Combining any set of solutions into a specific configuration theoretically yields a new design. This poses a problem however, as a morphological field constructed of five subproblems with four solutions each already creates over a 1000 possible design realizations.

Going through all of these configurations by hand is too much, so reducing this amount is the next step. This is done by *cross-consistency assessment* (CCA). The process of CCA is performed by comparing all subsolutions as pairs and assessing their compatibility. Evaluating these pair-wise relationships can reduce the solution space significantly and is also faster than evaluating all possible configurations. Namely, the number of parameter pairs grows quadratically instead of exponentially. For the example of five subproblems with four solutions each, a total number of 160 pairs have to be assessed. Still, a significant amount of evaluations but much more manageable, especially since pairs are assessed more easily than entire design configurations.

The morphological chart can now become an interactive model, where one or multiple subsolutions can be chosen as 'fixed' parameters and the availability of the other subsolutions will follow from the CCA. Importantly, for this to become truly interactive a computer model needs to be made that automatically goes through the CCA to show the possible configurations.

One advantage of GMA is that it rather objectively presents all feasible design configurations. Also the sheer amount of possible designs is a plus. Notably, the implementation of CCA prevents ill-posed solutions from entering the solution space, because performing the CCA becomes undoable when parameters are not defined well.

4.1.5 TRIZ

TRIZ or the theory of inventive problem solving, is the collective name for a large part of the work of soviet engineer Altshuller. Studying and evaluating patents in the former soviet union, he has created frameworks that can be projected onto designs in order to establish what has to be changed and how. Laws had been drawn up that, according to TRIZ, every good design has to comply with. Also, three methods to overcome creative difficulty or 'psychological inertia' were made, as well as a table that suggests solution directions for matching certain design parameters.

Laws

Altshuller defined his laws to design as logical trends in development, which can be either followed or breached. If any system breaches the laws, changes must be made to get back to the right path. Three types of law have been drawn up; static, cinematic and dynamic.

The first static law states that for a system to be whole it needs at least four main parts:

- a driving force or source of energy
- a transmission to channel the energy
- A working element that interacts with the intended part of the outside world
- a control element

Conditions are that each element must participate fully and that at least one of the first three parts must be controllable, otherwise the control element would have no function.

The second law poses that the flow of energy must be conductible, which holds no other meaning than simply saying that the input energy must efficiently be transported towards the output with minimal losses. The last static law says that all parts must somehow be coordinated considering their rhythm. Discrepancies between respective rhythms will inevitably generate energy loss and will deteriorate the performance of the system.

The fourth law, which is the first of the three cinematic laws, is described as the law of ideality, stating that the ideal system must be sought after, where the working capacity stays the same but parameters such as cost are minimized. The fifth law declares that all parts of the system must be developed at the same rate, as unequal development will increase the complexity of the system and thus inhibit progress. The third cinematic law (sixth altogether) tells that when a system has no further room for development it can transition to a supersystem. This also implies that when a subsystem becomes part of the supersystem it may take over functions from adjacent subsystems.

The two dynamic laws are different compared to the previous ones in the sense that a system will either follow law 7 or law 8. As these two laws are each other's counterparts, choosing between them should be obvious in the design process.

The seventh law regards the transition from the macro- to micro-level. Miniaturizing is a common trend within technical systems and for some systems, it may increase performance or efficiency. The eighth and last law proposes an '*increase in dynamics and controllability*', which comes with segmentation of the system in order to implement them.

According to Altshuller, every design must respect these laws and when one or more are being breached, the focus of the design process must lie on fixing that breach. Arguably, the explanation of the laws in [5] is rather vague, leaving room for interpretation and therefore also for misinterpretation.

Overcoming Psychological Inertia

Three methods follow from TRIZ that may help engineers arrive at improved designs. These can be described as mental exercises that help people think out of the box or at least from a different angle.

- The nine-screen method forces a designer to look at the system from different points of view timewise; past, present, future and at different system levels; subsystem, system and supersystem. Exploring any of the combinations will lead to new insights.
- The miniature people method allocates people whose roles are clearly defined to functions within a system. Viewing the functions in a system as tasks that have to be carried out by people allows a designer to see the system as an entity to be managed. This may help in understanding the roles of these miniature people and with that spot possible improvements or bottlenecks.
- Dimension, time and cost are three parameters that influence any design. Distorting these to their extremities to create hypothetical situations could trigger certain design solutions or decisions. Also, contradictions or inconsistencies could come to light sooner by forcing these perspectives.

40 Inventive Principles

The 40 inventive principles of TRIZ are 40 ways of handling a certain conflict within a design. These conflicts are between pairs of parameters that oppose each other and therefore a smart solution is needed to facilitate both. Within TRIZ 39 parameters have been formalized and for many perturbations one or more of the 40 inventive principles are applicable. The inventive principles are (perhaps purposefully) posed vaguely and lacking in any concrete guide toward a design solution. They do however give some direction to the designer and may prove helpful in reaching an effective solution sooner than without the help of this tool.

4.1.6 Design Principles

The design principles proposed by French [5] are advised solutions directions more than actual tools to spark creativity. That being said, if they aid the designer in finding solutions they could not have found otherwise, they will count as useful synthesis methods. Besides, French also argues that the most useful tool of all is insight, which can be developed through experience but also research and preliminary calculations and analysis. Five sample design principles are given which may be applied to a variety of engineering designs.

- Kinematic Design - Least Constraint; applying the minimum constraints possible to position or guide bodies will prevent unnecessary internal stresses. Parts may have to be less stiff, weight can be saved and also accuracy can be improved.

- Small, fast principle; using smaller parts that allow for higher frequencies (and therefore faster movement) can help in reducing weight while still achieving a certain level of performance.
- Matching; the practice of making sure that all parts match and perform together as a whole. A simple example would be attaching a very stiff rod to a weak joint, completely negating the stiffness properties of the rod. Matching these would need a stiffer joint so that the stiffness will actually contribute to the stiffness of the system.
- Flexures > Pivots > Slides; Flexures do not need lubrication, have no stiction and are free from wear (although they do have fatigue). This makes them a better choice in some cases over pivots and slides. The advantages of pivots over slides are that they are cheaper, easier to make, have no exposed working surface and generally have less friction. The main argument the author makes is that at least the consideration to improve any hinge towards flexures or at least pivots has to be made.
- Transfer Complexity to Software; Especially applicable in mechatronics, this principle argues that instead of aiming to make, for example, a motion system perfectly accurate, it may be less accurate and the errors can be corrected for in the software.

4.1.7 ACRREx

Abstracting, Categorizing, Reflecting, Reformulating and Extending (ACCREx) [10] is a systematic design synthesis method that can help designers get to new concepts and ideas. The method starts with abstracting existing designs and categorizing them based on one or more of their properties. Breedveld et al use the example of categorizing a car and bicycle into a four- and two-wheeled category, as well as a manual and motorized category. Filling in the voids in this matrix then leads to two new design options: a four-wheeled manual vehicle (a kart) and a two-wheeled motorized vehicle (a motorbike). Reflecting, reformulating and extending this matrix could then lead to categories with one or three wheels or a hybrid mode of power delivery. The number of wheels could also be reformulated into 'number of contacts with the ground', which would allow for introducing tracks or hovering as possible solutions.

Properly categorizing and formulating all properties and distinctions is at the core of ACCREx and then filling all the voids is what can make ACCREx powerful.

4.1.8 Brainstorming

Brainstorming was first formalized by Alex Osborn in 1957[17]. It consists of a group of people actively speaking their minds on ideas they have to solve a certain problem. The idea behind brainstorming is that as a group it is possible to work as a collective mind and increase the chances of finding an adequate solution. The four pillars of brainstorming are;

- Criticism is not allowed

- Wild and crazy ideas are encouraged, it is easier to tame ideas than to enrich them.
- Quantity is welcomed
- Combinating and suggesting improvements to other ideas is sought after

The idea behind this 'set of rules' is that a group will generate more and therefore better ideas than any of the individuals by themselves. Quantity is welcomed as it should increase the chances of finding good ideas. This quantity is ensured by sparking creativity through the second and fourth rules. The first rule is made so that rule two and four can be followed without inhibitions.

Many of the advantages of brainstorming come from the group element of this method. This can already be seen in rule four. Also, Osborn points out that sparking each other to come up with new ideas will lead to chain reactions of ideas. On top of that, he describes that friendly rivalry in finding good ideas will further lift the group members and motivate them to come up with better solutions.

4.2 Similarities

The discussed synthesis methods can effectively be put into three main categories. One category has methods that efficiently shuffle already existing solutions, the other type methods propose solution directions depending on the design problem and the last one forces the designer to look at the design from a different perspective so that they can develop new insights and come up with new solutions.

Methods falling under the first category are morphological analysis, ACCREx and insight combination. All of these ask for already existing solutions in order to come to new solutions, which are mostly new combinations of existing solutions. The caveat here is the unlikeliness of finding a truly new solution, although that depends on how the solution is viewed. At what point is a solution truly "new" and when is it "just" a combination of what already existed? This type of method can be caught under the term systematic methods.

In the second category, there are the 40 inventive principles from TRIZ and the design principles by French. These, instead of providing a path towards synthesizing something new, are more like reminders that say: 'Have you already seen this type of solution?'. They provide solution directions that are vague and often have at least one good example but may be difficult to convert to the designer's specific problem. Fittingly, these can be called the principle methods.

The last category is the one of intuitive methods, these provide a certain setting for the designer(s) to come up with new ideas on their own. Brainstorming, overcoming psychological inertia (OPI) and reframing fall into this category. Especially OPI and reframing are similar in the sense that force a different view on the problem to spark creativity. Brainstorming does this by physically creating a different setting, namely a group setting. These intuitive methods facilitate creativity while not enforcing existing solutions to be taken into account, which may suit designers.

Chapter 5

Research

5.1 Literature Gap

Within literature many different design and synthesis methods come to light. As described in the previous chapter, the way different methods approach help in synthesis varies significantly. This raises the question of whether one type of approach outperforms the others, or if it is down to the specific methods.

Importantly, a method is useless without a design case to apply it to. Even more so than synthesis methods, design cases vary from designing a chair to designing a spaceship. Scale, number of parts, materials, budget, time and many more factors can change from case to case. The chances that one single synthesis method outshines all other synthesis methods for this vast variety of design cases are minimal if not zero. Perhaps certain synthesis methods work very well for certain types of design cases.

The comparison of design and synthesis methods has not been carried out in literature. Besides, evaluating the outcome is often more important to authors than evaluating the method used. Also, no methods specific to certain problems have been identified, including chassis design.

5.2 Research Proposal

The gap in research that needs filling most is whether certain synthesis methods are significantly better than others when solving certain types of problems. This question can be answered by applying different synthesis methods to a particular design case and evaluating the quality and quantity of possible designs flowing out of those methods.

Initially, this can be done on one or multiple frame-related design cases, but other types of engineering problems are not excluded. Also, a rubric or evaluation chart will have to be set up to ascertain which elements of each synthesis method and their respective result are desirable. Only if this is done properly, a true comparison can be made. This part of the research will have priority and will be done first.

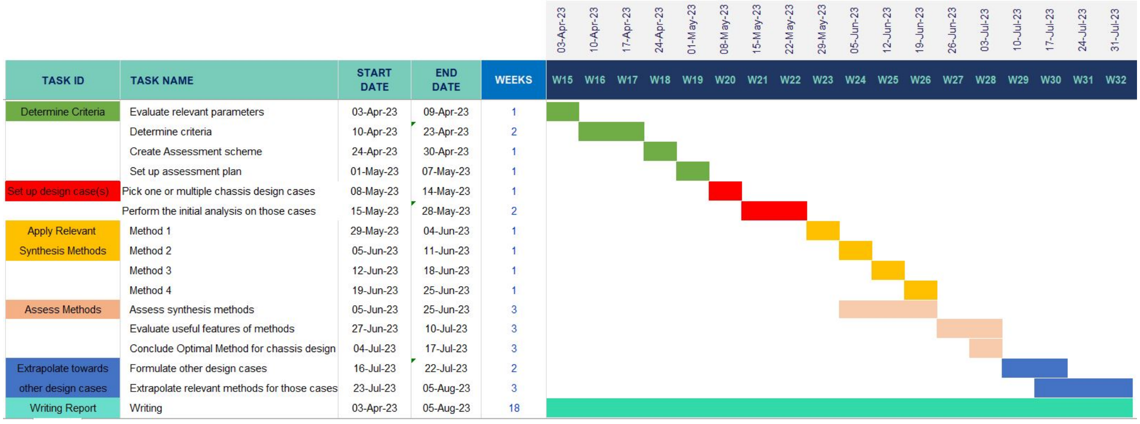
As stated before. methods are useless without design cases, therefore one or more design cases will be set up. As the focus lies on the synthesizing part of the design process, the initial problem analysis will also have to be done.

After multiple methods have been applied to multiple cases and a large number of different solutions have been generated conclusions can be drawn on the performance of the methods for different circumstances. This will be done according to the rubric that will have been made.

When the frame-related design cases have been fully evaluated and if the time is there, other types of design cases can be viewed as well. Either through sufficient experience in applying the synthesis methods or simply by applying them again, optimal synthesis methods for other types of design may be concluded.

5.3 Research Plan

A more detailed research plan can be seen in 5.1. The plan is to carry out most steps in a sequential fashion as certain steps needed dedicated preparation. As the project goes on, some parts can be done simultaneously, such as evaluation of methods while working with new methods.



					03-Apr-23	10-Apr-23	17-Apr-23	24-Apr-23	01-May-23	08-May-23	15-May-23	22-May-23	29-May-23	05-Jun-23	12-Jun-23	19-Jun-23	26-Jun-23	03-Jul-23	10-Jul-23	17-Jul-23	24-Jul-23	31-Jul-23
TASK ID	TASK NAME	START DATE	END DATE	WEEKS	W15	W16	W17	W18	W19	W20	W21	W22	W23	W24	W25	W26	W27	W28	W29	W30	W31	W32
Determine Criteria	Evaluate relevant parameters	03-Apr-23	09-Apr-23	1	■																	
	Determine criteria	10-Apr-23	23-Apr-23	2		■	■															
	Create Assessment scheme	24-Apr-23	30-Apr-23	1				■														
	Set up assessment plan	01-May-23	07-May-23	1					■													
Set up design case(s)	Pick one or multiple chassis design cases	08-May-23	14-May-23	1						■												
	Perform the initial analysis on those cases	15-May-23	28-May-23	2							■	■										
Apply Relevant Synthesis Methods	Method 1	29-May-23	04-Jun-23	1									■									
	Method 2	05-Jun-23	11-Jun-23	1										■								
	Method 3	12-Jun-23	18-Jun-23	1											■							
	Method 4	19-Jun-23	25-Jun-23	1												■						
Assess Methods	Assess synthesis methods	05-Jun-23	25-Jun-23	3										■	■	■						
	Evaluate useful features of methods	27-Jun-23	10-Jul-23	3													■	■				
	Conclude Optimal Method for chassis design	04-Jul-23	17-Jul-23	3														■				
Extrapolate towards other design cases	Formulate other design cases	16-Jul-23	22-Jul-23	2															■	■		
	Extrapolate relevant methods for those cases	23-Jul-23	05-Aug-23	3																■	■	■
Writing Report	Writing	03-Apr-23	05-Aug-23	18	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Figure 5.1: Step-by-step plan for performing the research with timeline (Gantt Chart Format).

Which methods exactly will be employed still has to be determined. At least one from each previously defined categories will be used. Also, the time it will take to perform synthesis may vary greatly. This could mean that all discussed methods may be applied, which would be beneficial to the goal of the research. The writing of the report, or at least keeping track of all the doings and findings will be done throughout the entire project.

5.4 Discussion

As frame design is so widely done, a lot of frame-like structures have been developed well. This could imply that the headroom for innovation is limited and therefore that the synthesis methods may not be as effective. In the event that that may occur, it is still a valid result and a conclusion can be drawn. However, if this comes up early in the research, some redirection might be needed so that the synthesis methods can still perform well, perhaps on different design cases.

Another important aspect is the vast application of numerical methods that help with generating chassis and frames, especially topology optimization. For single monolithic parts it will be hard if not impossible to beat this technique. For this reason, it will be important to focus the synthesis methods on the aspects that topology optimization cannot handle. This could be the allocation of space for certain parts or the boundary conditions needed for topology optimization. Also the integration with visual design aspects or ergonomics is something that will need a human touch.

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