Department of Precision and Microsystems Engineering

Comparing Design Synthesis Methods
A Study on Frame Design

S.J. van Egmond

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by

S.J. van Egmond

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Thesis committee:	Dr. ir. J.F.L Goosen,	TU Delft, supervisor
	Dr. ir. P. Breedveld,	TU Delft
	F.G.J. Broeren PhD MSc,	TU Delft

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Preface

This thesis is written to finalize my Master of Science in Mechanical Engineering with the specialisation of High Tech Engineering. Although the literature review had started with finding ways to improve the Lunar Zebro, I had ended up with something much more abstract and theoretical; design synthesis methods. Engineering is not only my field but also has become part of my hobbies, resulting in many small design projects at home. This led me to find something different for my thesis, something more high level.

I hope the knowledge I gathered during this theoretical thesis will be valuable throughout my career, as well as be valuable to others. I believe this thesis can be the start in helping young engineers find creativity and new solutions, making this report something more than just another file in the TU Delft repository.

I would like to thank my supervisor Dr.ir. J.F.L. Goosen for sharing his knowledge, expertise and his open mindedness. Many conversations were had, which not always concerned the thesis, yet did always bring something fruitful. At last I would like to thank my family for their support and all my friends for making my time at TU Delft unforgettable.

Stan van Egmond

Delft, 2023

Abstract

The Lunar Zebro is a small moon rover that needs an advanced chassis to endure the harsh environment that the moon brings. To arrive at a solution for such a frame or chassis creativity and hard work are necessary. Whereas hard work is a given, creativity is not and it may need a helping hand. Design synthesis methods, of which brainstorming is a basic example, aid engineers and designers with reaching better solutions. Currently, however, which method works best for a given scenario is unknown.

The purpose of this research is to determine which synthesis method works best for concept generation, with the focus lying on generating innovative solutions for frame design. A meta-method is created to evaluate the performance of different synthesis methods when applied to design cases. This meta-method consists of executing fifty case-method combinations, built up from pairing ten design synthesis methods with five design cases, which are focused on frame design primarily. The combinations are then evaluated using a self-made rubric.

In the end, it became apparent that different methods apply well at different stages of the design process and at different system levels. Some work well to orient, understand the supersystem and therefore have an positive yet indirect influence on the final outcome. Some work well to generate concepts, bring new ideas at system level. Others apply well after a concept is already generated, only being useful to improve subsystems.

Contents

Chapter 1

Introduction

1.1 The Lunar Zebro

The Lunar Zebro is a small rover intended to operate on the Moon. The six legged Zebro, which can be seen in Figure 1.1, would travel to and land on the Moon, after which it explores the surface for one lunar day, which is approximately fourteen Earth days [6]. The mission goal is to last at least until the lunar night, however lasting beyond is desired. Due to the hostile conditions space travel and the Moons surface bring, the Lunar Zebro needs a special frame that can deal with these conditions. Creating such a chassis for the little rover is no easy feat. A vacuum environment, extreme temperatures and fine Moon dust are all design challenges to overcome. Improving the frame of the Lunar Zebro would be a specific and difficult design case, as space applications have very different criteria than non-space ones.

When a chassis has to be improved, it generally means that it has to fulfill all its demands and requirements while being as light as can be. One way to do this is to systematically implement components into the structure to enhance the rigidity and strength of that same structure. For example, batteries that improve the rigidity of the frame they are placed in[11], 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

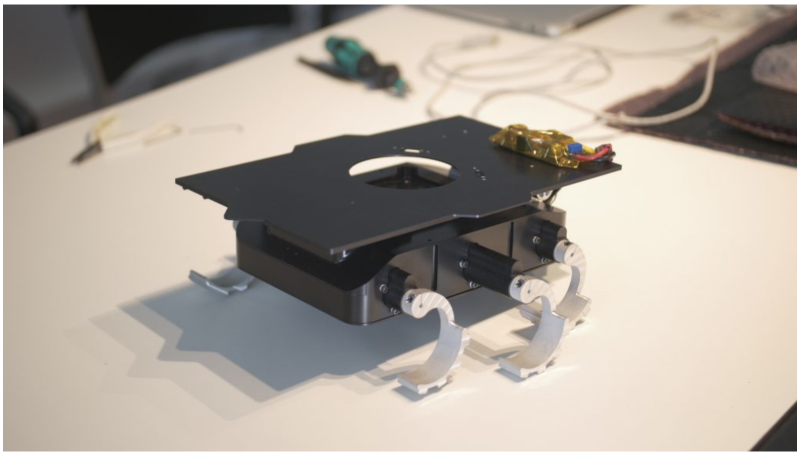


Figure 1.1: The Lunar Zebro

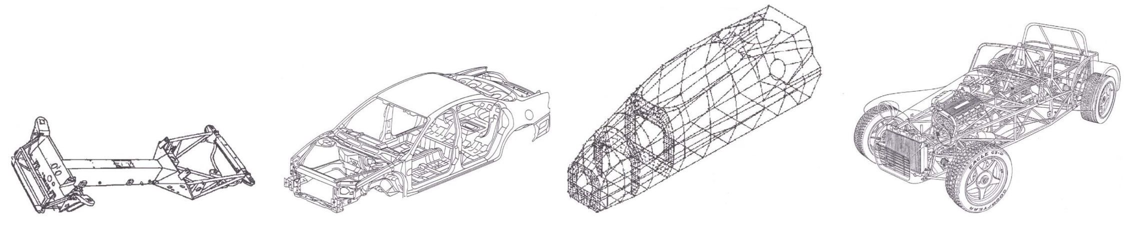
less material being needed to achieve the desired stiffness, saving resources and mass.

There is one caveat however, currently there is no systematic method to adequately implement parts into carrying structures such as frames and chassis. At the moment, it is done on a case to case basis, depending the on engineers' creativity and skill to find this type of solution. What is more, a general method to conceive chassis and frame concepts is also absent.

1.2 Chassis and Frames

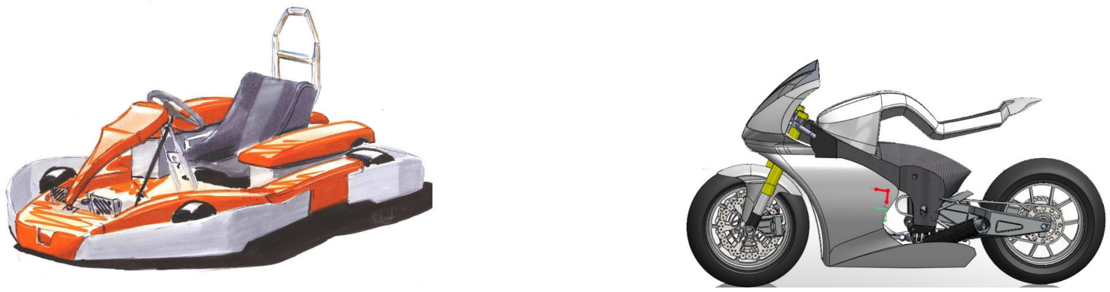
Before the chassis or frame design process is to be improved, naturally knowledge of them is of importance. What sets frame design apart from any other type of design is the level of integration. Frames are structures that often form one rigid piece, possibly after assembly, and have to integrate all 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.

Currently, chassis and frames are more evolutions of existing concepts rather than fundamentally new designs. The increasing availability of analysis and optimization tools continuously improves the carrying structures of various designs. Still, a concept has to be created and chosen before these tools can do their work. The existing concepts are easily found within the literature, yet when and how to choose the correct one is not mentioned. A number of these existing concepts is visible in Figure 1.2.



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

Figure 1.2: Different existing chassis concepts as found in the literature [4].



((a)) Kart ((b)) Moto2 motorbike

Figure 1.3: Examples of chassis which were primarily shaped by industrial design [3] [17].

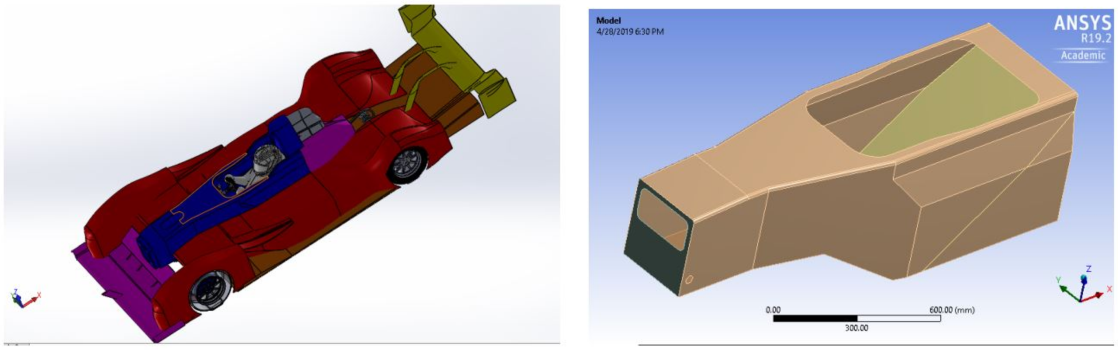


Figure 1.4: A chassis that was shaped by putting aerodynamics as the priority [12].

Nonetheless, there are some frame design techniques from the literate that are relevant to mention. Firstly, one technique lets the main chassis shape be determined by external factors such as industrial design (Figure 1.3) or aerodynamics (Figure 1.4). To then come to a structurally sound frame, normally one of the common chassis types is chosen and optimized. Four of those common chassis types are shown in Figure 1.2.

Another relevant technique is topology optimization. This technique uses a set of boundary conditions consisting of input loads, attachment points and a bounding box to find the optimal shape of a structure. In industry, this is used to guide engineers to an optimal design, as the direct result of topology optimization is often not easily producible. A visual overview of this process is shown in Figure 1.5.

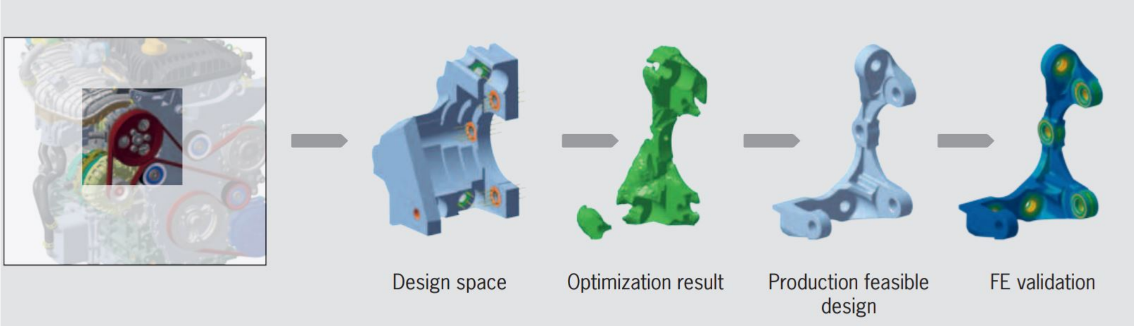


Figure 1.5: A part that is first optimized through topology optimization and then adjusted for manufacturability [16].

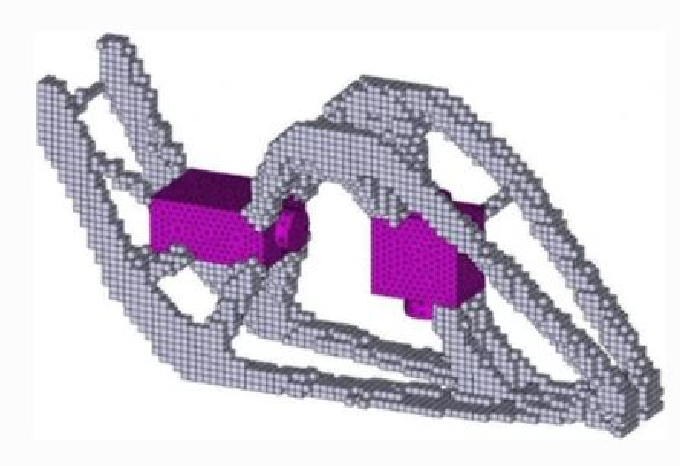


Figure 1.6: An example of topology optimization including rigid parts to increase overall stiffness.

Lastly, there is the integration of parts into the chassis as structural members. Of this, there is only anecdotal evidence such as the integration of the engine and gearbox in racing cars or parts of drones. Zhu et al. [19] have created an algorithm that can do this automatically, but it is still in early development and its application is very limited. One of their experiment results is seen in Figure 1.6.

1.3 Design Methods

As a general method to conceive chassis and frame concepts is absent, the goal of this research shifted from improving the Lunar Zebro to exploring what method works optimally for generating chassis and frames. Finding such a method would not only improve the Lunar Zebro but also benefit future designs, extending the usability of the research 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 is the time engineers spend on analyzing the problem, creating solutions and evaluating them.

Although the focus lies on finding a method that applies well to chassis and frame design, also in general there is a lack of insight in when and how to use certain design methods. Their performance in different scenarios is not documented, missing out on the possibility of picking the right method for the right design case.

Undoubtedly, knowledge of design methods and their place within the design process is also a prerequisite to improving frame design. First, the difference between design processes, approaches and methods will be discussed. Within the context of this research their definitions will be given and used accordingly throughout. Then the focus will lie on design methods, primarily the synthesis methods.

1.3.1 Processes, Approaches and Methods

Design processes, approaches and methods are three different things. Each entity covers a certain amount of the entire design. The design process is the most complete, covering the design from start to finish in an abstract manner. A design approach considers the intention of certain parts of the design, it is closer to a guideline. Design methods are mostly tools, that can be applied at various stages throughout the design process.

Processes

A design process is the entire set of actions that lies between the design problem and the final product. It is often depicted as a flowchart that capture all types of actions into a whole. These actions can be described as phases or steps that follow up upon each other in a certain sequence or order. Although performing the design process within these predetermined steps can provide structure, it does not specifically instruct the designer what to do exactly. Each step in the process is closer to a black box than a set of guidelines. Examples of this are the design processes as described by Archer [5] (Figure 1.7) and Eekels [7](Figure 1.8), which are similar yet different.

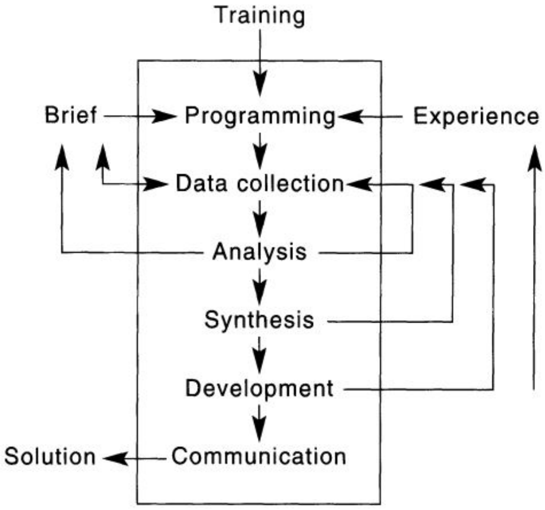


Figure 1.7: Archers model [5].

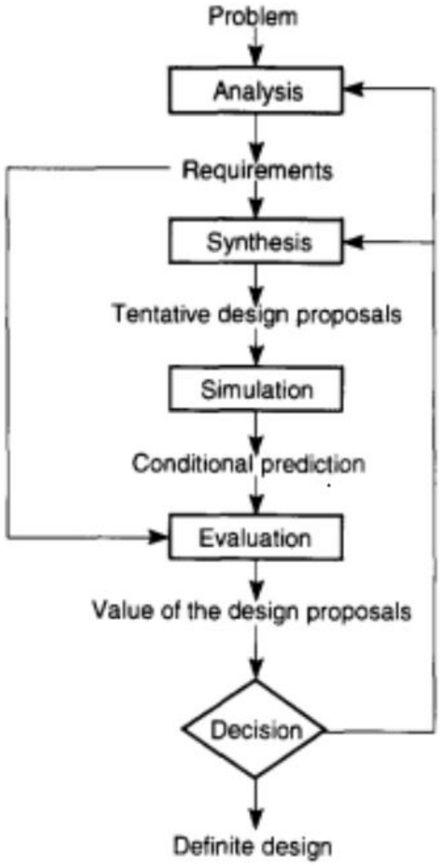


Figure 1.8: Eekels' model [7].

An exception to this is the Pahl and Beitz process [13], which consists of four steps;

- Task Clarification
- Conceptual Design
- Embodiment Design
- Detail Design

Each step has several substeps, further instructing what the designer has to execute. This extensive description of what to do in each phase of the design process can be beneficial, however, it does not help in generating ideas or concepts.

Approaches

An approach to design, also called design philosophy, says more about the intrinsic way a designer tackles the problem. There are no steps that are to be followed but rather a mindset has to be taken during the design process. If that mindset is actively practiced during the entire process, then the solutions will reflect that. An example of these design approaches is value engineering, where the aim is to use minimal resources throughout the design process. When properly applied, value engineering should reduce cost while maintaining quality and the reaching of deadlines.

To properly apply a design approach within larger projects, specific engineers are hired to enact them. In the case of value engineering this means having one or more engineers continuously looking for low cost alternatives to the current solutions or process steps. When the project size does not justify integrating extra people, the approach mindset can still be maintained by educating the engineers in its ways. The engineers are then encouraged to keep the approach in the back of their heads to come to better results. Besides value engineering. other examples of design approaches are: design for manufacture, modular design, design for assembly and sustainable design.

Methods

Methods, on the other hand, go one level further and give the designer instructions on how to perform certain steps. Mainly for the problem analysis, design synthesis and design analysis there are a variety of methods available. Arguably the most widely known synthesis method is brainstorming, where one or multiple people use dedicated time and space to generate ideas by simply popping up ideas and expanding them. An examples of a problem analysis method is the MoSCoW method [9], which helps with prioritizing design requirements.

Methods are more instructive than processes and approaches. They give clear steps on what to do and how to do it. Methods could be described as tools rather than guidelines. Instructions on how to solve a Rubik's cube is an example of a method. Naturally, the Rubik's cube can be solved by merely trying and experimenting, yet applying a method to solve it makes the endeavour much more manageable and reachable. What sets a method apart from a manual is the fact that method is applicable for a variety of scenarios whereas a manual applies only to one. A manual to solve the Rubik's cube requires a starting point where all the colored squares are in the exact point as where the manual begins. A method to solve the Rubik's cube is indifferent to the current state of the cube, as it can help solve any configuration.

Analysis and Synthesis

Methods for design analysis can be either analytical, numerical or experimental [8]. Analytical analysis involves classic calculations which can provide fully accurate results. Unfortunately, analytical methods can only be applied to simple or simplified cases. Experimental methods consist of real life testing, using sensors such as strain gauges to measure the behaviour of a prototype. This type of analysis is expensive and can only be done when prototypes are readily available.

Numerical methods can represent real life complicated problems without the need for physical testing. This makes them very suitable for analyzing designs. The results of numerical analysis must however be validated and are subject to assumptions made in creating the model. Nonetheless, numerical analysis is the most used design analysis method during the design process.

The design synthesis is of a different nature than the problem and design analysis. 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. Whereas deduction and induction can be achieved through pure logic, these are associated with analysis. Abduction requires a certain creativity or intelligence and is therefore associated with synthesis. When innovative solutions are desired the mode of reasoning becomes innovative abduction or 'innoduction', a term coined by Roozenbrug [5].

1.4 Methods within the Design Process

As seen before there are multiple ways to represent the design process, of which two examples are shown in Figure 1.7 and 1.8. Although each model may have its variations, there are certainly also similarities. Across all process models there is one common sequence that can be found, as shown in Figure 1.9.

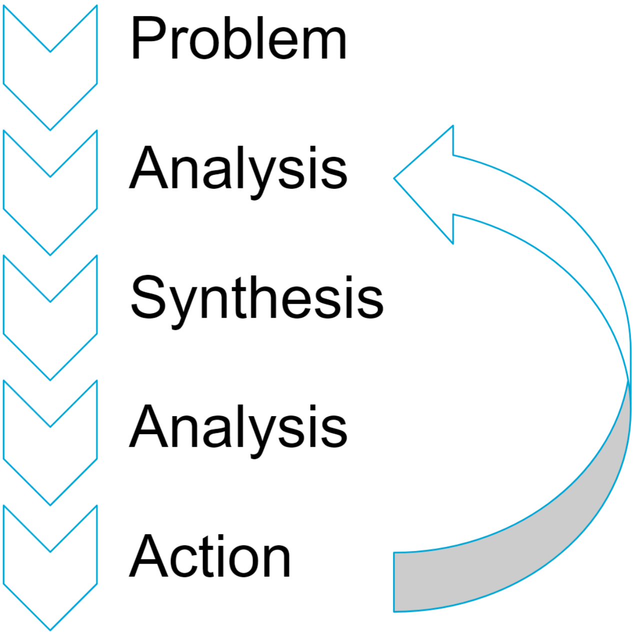


Figure 1.9: The core of the design process model.

Each design starts with a problem, originating from dissatisfaction with the current state of affairs [2]. This problem is then analyzed, often transformed to a set of requirements through a problem analysis method. Then solutions are created, requiring creativity and the aforementioned 'innoduction'. These solutions are then exposed to the design analysis. The last step, the action, then either results in proceeding with the design and create it, or deciding that there are still problems with the design. These problems will then be analyzed again and the synthesis of solution starts anew.

The synthesis is the crux of engineering, as without new solutions there would not be any innovation. Synthesis can be achieved through creative thinking by itself, heavily depending on the engineers intrinsic problem solving skills. Synthesis methods could aid any engineer by sparking their creativity and finding solutions they would not have found by creative thinking itself.

1.5 Goal of the Research

Currently, there are various was to synthesize solutions in the literature. Unfortunately, there is no information on how well these syntheses perform by themselves or against each other. Furthermore, it is also not known what the ideal time is when to apply certain syntheses throughout the design process.

The field of mechanical engineering is too broad to consider as a whole. Therefore, the focus will lie on the field of frame and chassis design. As also performing the entire design process is too large, only the design synthesis step of the process is considered, as this is the crux of engineering. Moreover, problem and design analysis are already well evolved whereas design synthesis is not well represented in literature.

The focus on both chassis and frame design and design synthesis methods results in the following research question;

"Which design synthesis method is optimal to improve frame design or the frame design process?"

Chapter 2

Design Synthesis Methods

Before the research question can be answered, it must be known what synthesis methods are available. Within the literature a total of ten relevant design synthesis methods were found. Each method claims to help in generating new and innovative ideas.

2.1 Categories of synthesis methods

The found synthesis methods can effectively be put into three main categories. One category has methods that efficiently shuffle already existing solutions. The second type of method proposes solution directions depending on the design problem. 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 [18], ACRREx [10] and insight combination[14]. 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[1], the TRIZ laws [5] and the design principles by French [5]. 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 [15], overcoming psychological inertia (OPI)[5] and reframing [14] 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 [15]. These intuitive methods facilitate creativity while not enforcing existing solutions to be taken into account, which may suit designers.

The remaining synthesis method is concept mapping [14], which does not fall into any of these categories. This could be because its use for synthesis is more indirect. The concept map relies on creating an understanding of the whole by piecing together all relevant parts of the design problem. As said by Kolko, it may aid any other synthesis method, which is logical for a method that mainly produces insight rather than concepts.

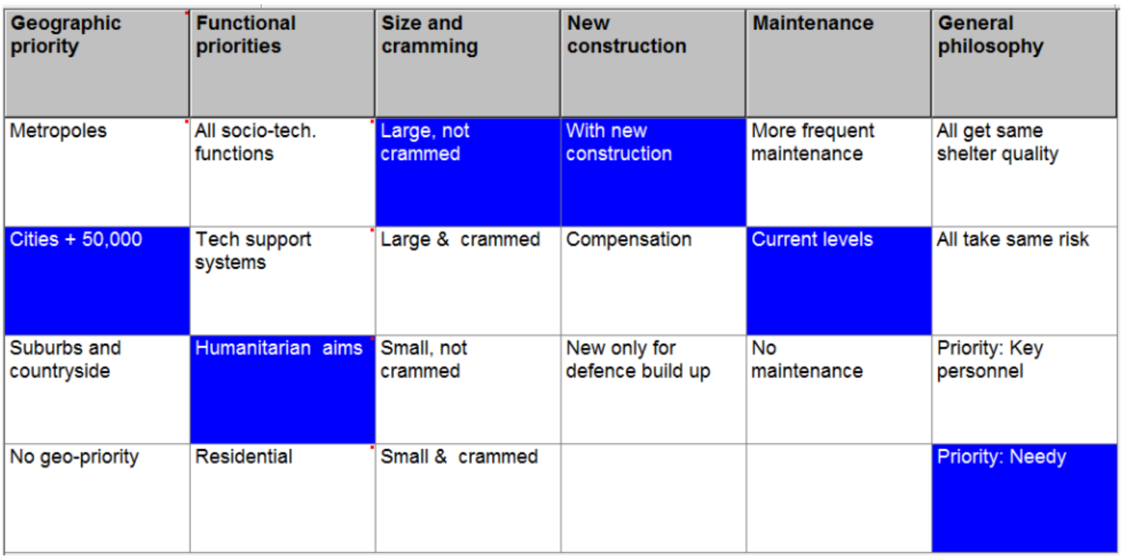
Notably, three of the mentioned methods stem from the larger design process called TRIZ. The theory of inventive problem solving, or TRIZ, is the collective name for a large part of the work of soviet engineer Altshuller. Studying and evaluating patents in the former soviet union, he has created frameworks 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; the TRIZ laws. Also, three methods to overcome creative difficulty or 'psychological inertia' were made (OPI), as well as a table that suggests solution directions for matching certain design parameters, the 40 inventive principles.

2.1.1 Morphological Analysis

General morphological analysis (GMA)[18] 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.



Geographic priority	**Functional priorities**	**Size and cramming**	**New construction**	**Maintenance**	**General philosophy**
Metropoles	All socio-tech. functions	Large, not crammed	With new construction	More frequent maintenance	All get same shelter quality
Cities + 50,000	Tech support systems	Large & crammed	Compensation	Current levels	All take same risk
Suburbs and countryside	Humanitarian aims	Small, not crammed	New only for defence build up	No maintenance	Priority: Key personnel
No geo-priority	Residential	Small & crammed			Priority: Needy

Figure 2.1: An example of General Morphological Analysis [18].

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. An example of a GMA-chart can be found in Figure 2.1.

2.1.2 ACRREx

Abstracting, Categorizing, Reflecting, Reformulating and Extending (ACRREx) [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. This example is shown in Figure 2.2. 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.

Distinguishing the working principles behind existing solutions and properly categorizing and formulating them is at the core of ACRREx and then filling in all the voids is what can make ACRREx powerful. In the end this results in a tree that gives an overview of all the possible solutions. An example can be seen in Figure 2.3.

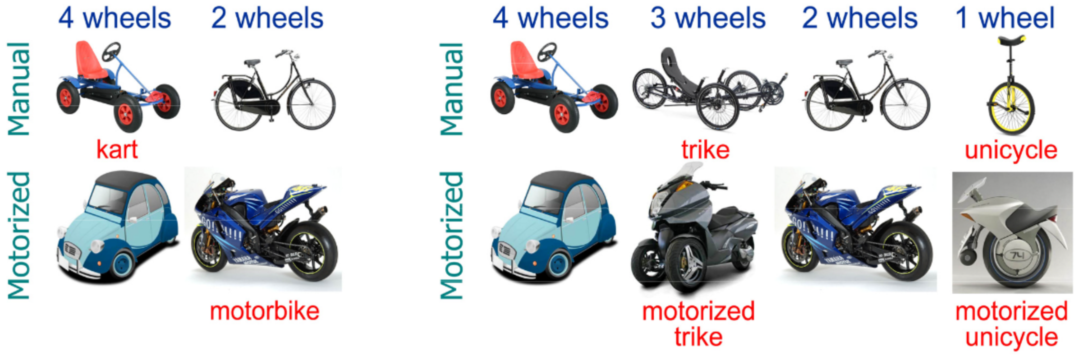


Figure 2.2: Reflecting and extending results in new solutions.

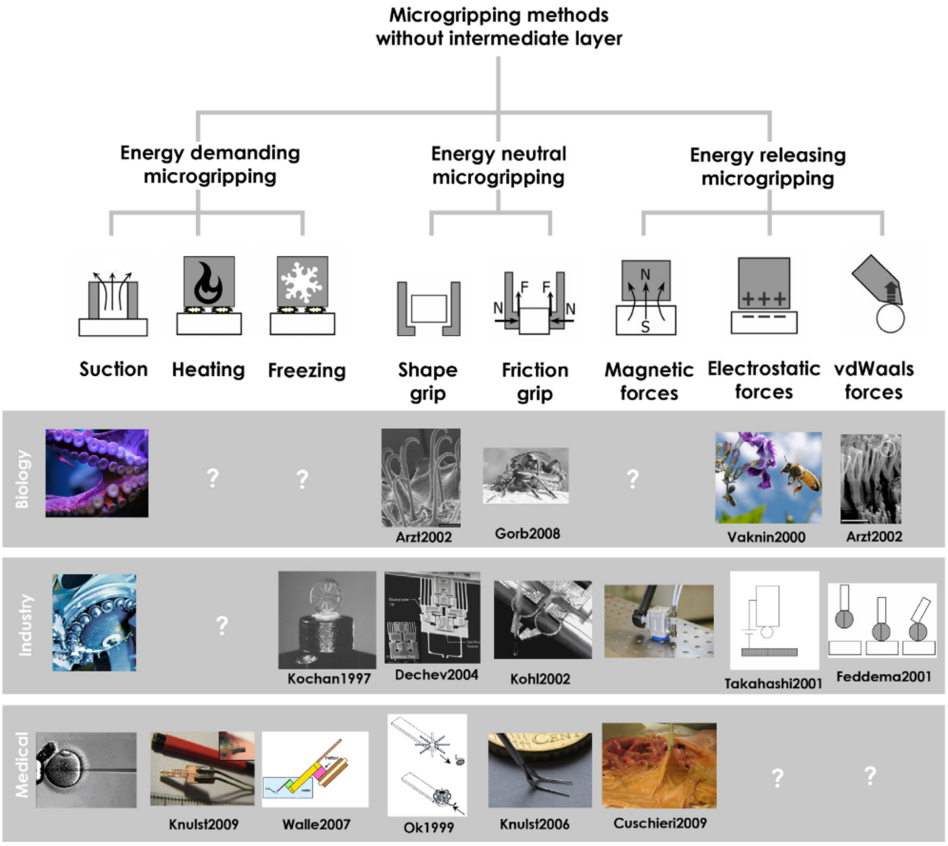


Figure 2.3: An ACRREx tree.

2.1.3 Insight Combination

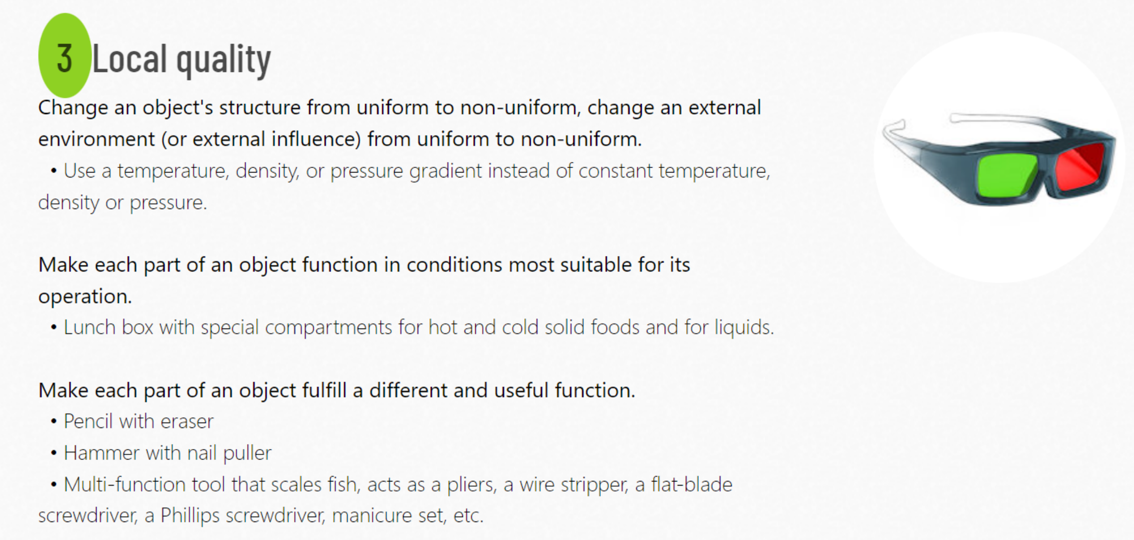
Insight combination [14] starts by identifying insights about the problem and problem analysis. The designer will write down observations within the gathered data and link them to a piece of their knowledge that is related, this is an insight. This link or insight may not be accurate, which is acceptable. 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.

2.1.4 40 Inventive Principles (TRIZ)

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. One of these principles is shown in Figure 2.4. 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.



3 Local quality

Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.

- Use a temperature, density, or pressure gradient instead of constant temperature, density or pressure.

Make each part of an object function in conditions most suitable for its operation.

- Lunch box with special compartments for hot and cold solid foods and for liquids.

Make each part of an object fulfill a different and useful function.

- Pencil with eraser
- Hammer with nail puller
- Multi-function tool that scales fish, acts as a pliers, a wire stripper, a flat-blade screwdriver, a Phillips screwdriver, manicure set, etc.

Figure 2.4: One of the 40 inventive principles from TRIZ. Among others, it can help improve the weight of a moving object while preserving its reliability.

Originally, all parameters are set out against each other in one big table. The parameters are on both axes, one parameter to be optimized, the other to be preserved. Where these meet each other in the table, a number references the applicable design solution directions. The size of this table makes it cumbersome and inefficient to use. On www.triz40.com [1], there is an interactive tool that will be used during the research. The website also holds other relevant information about the 40 principles, including a complete list with elaboration.

2.1.5 TRIZ 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.

2.1.6 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.

2.1.7 Brainstorming

Brainstorming was first formalized by Alex Osborn in 1957[15]. 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.

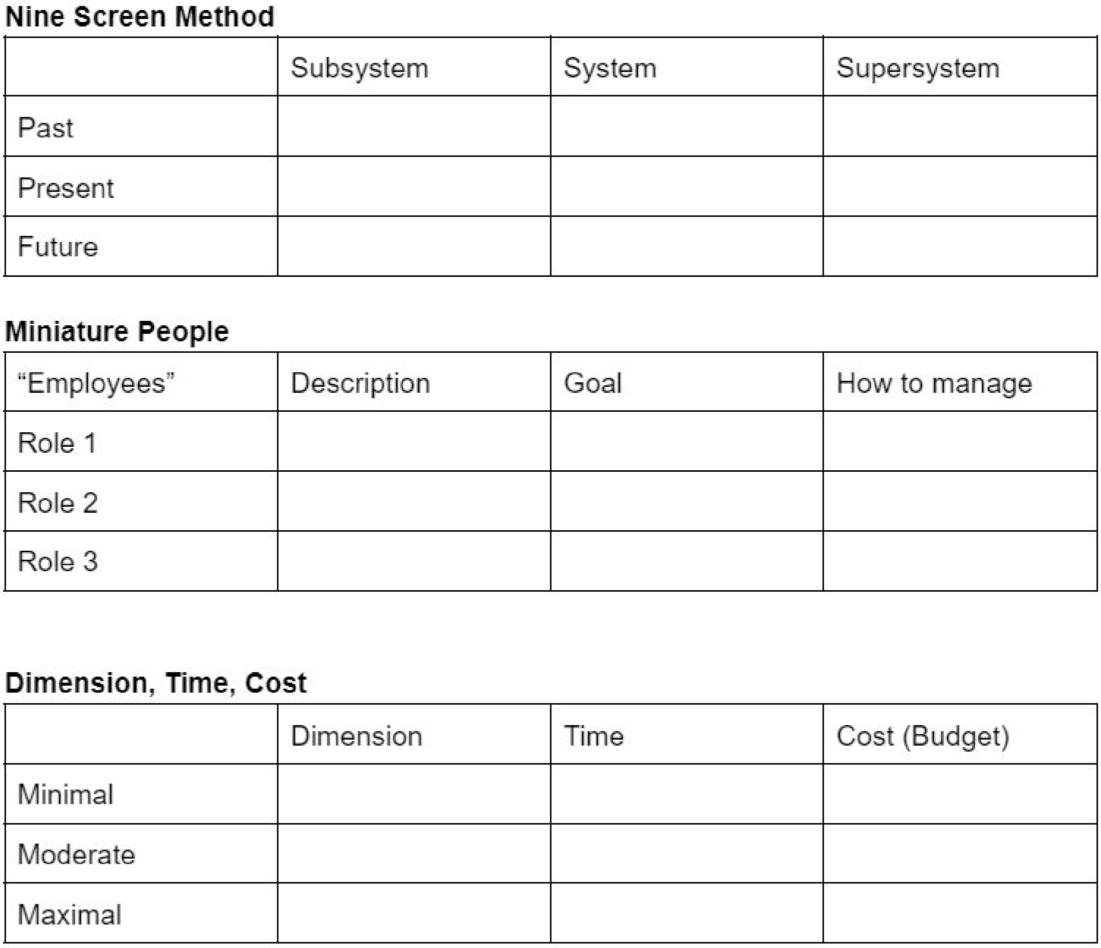
Many of the advantages of brainstorming come from the group element of this method. This can already be seen in rule four. Also, Osborn points out that sparking each other to come up with new ideas will lead to chain reactions of ideas. On top of that, he describes that friendly rivalry in finding good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

2.1.8 Overcoming Psychological Inertia (TRIZ)

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.

Example tables of these three submethods are shown in Figure 2.5, to give a clearer insight into how they are to be executed.



Nine Screen Method

	Subsystem	System	Supersystem
Past			
Present			
Future			

Miniature People

“Employees”	Description	Goal	How to manage
Role 1			
Role 2			
Role 3			

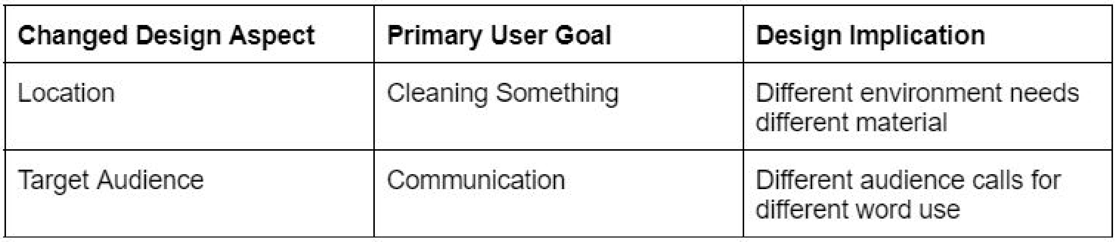
Dimension, Time, Cost

	Dimension	Time	Cost (Budget)
Minimal			
Moderate			
Maximal			

Figure 2.5: All tables that need filling in to complete the O.P.I method.

2.1.9 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.



Changed Design Aspect	**Primary User Goal**	**Design Implication**
Location	Cleaning Something	Different environment needs different material
Target Audience	Communication	Different audience calls for different word use

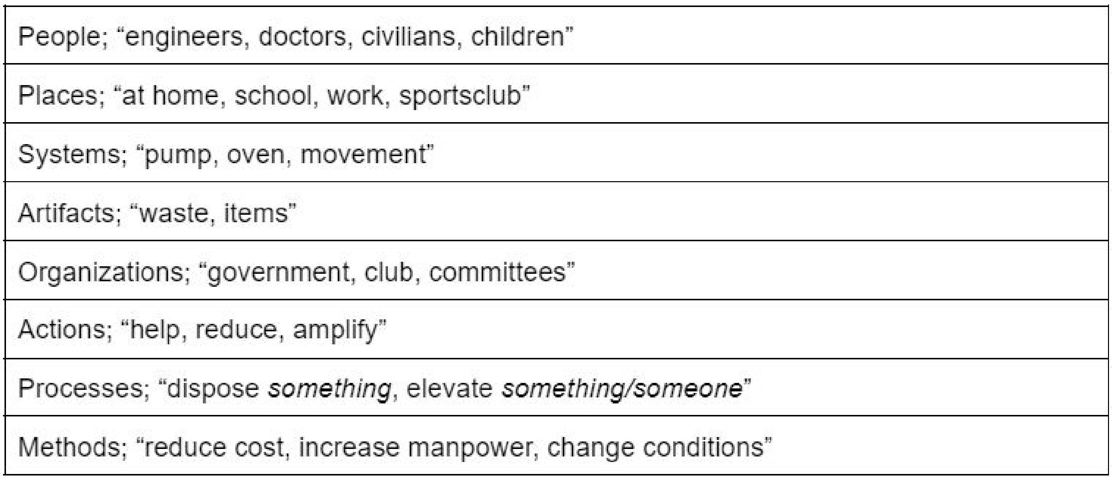
Figure 2.6: A small example of what the reframing table could look like.

The method of reframing [14] 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. An example chart is shown in Figure 2.6.

2.1.10 Concept Mapping

A concept map[14] is created in three steps. The first step consists of identifying the core taxonomy of the problem, see Figure 2.7. Verbs and nouns that describe the context of the problem are put onto paper. 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 taxonomy into a certain hierarchy, which is subjective to the designer. The taxonomy items could also be arranged into 'parent' or 'child' items, indicating subgroups within the taxonomy. Now, the concept map itself can be created with the items as building blocks. On a large sheet of paper the items can be spread out according to the hierarchy defined before, and connecting line elements with small pieces of sentences indicate the interrelationships between the elements, which is demonstrated in Figure 2.8.

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.



People; “engineers, doctors, civilians, children”
Places; “at home, school, work, sportsclub”
Systems; “pump, oven, movement”
Artifacts; “waste, items”
Organizations; “government, club, committees”
Actions; “help, reduce, amplify”
Processes; “dispose *something*, elevate *something/someone*”
Methods; “reduce cost, increase manpower, change conditions”

Figure 2.7: All categories of the core taxonomy with examples.

Figure 2.8: A concept map about brushing teeth [14].

Chapter 3

Method and Execution

As stated before, the research question is; ”Which design synthesis method is optimal to improve frame design or the frame design process?”. All the relevant design synthesis methods are now known, yet which one is optimal for this specific goal remains unknown. A ’meta-method’ has to be created to evaluate the performance of the individual synthesis methods, because there currently is no set method to do this.

In this chapter, the creation of this meta-method will be discussed. Grading and ranking design methods are susceptible to subjectivity and personal interpretation. In order for the results to still be valid, proper preparation is crucial. Filtering out this subjectivity is attempted in various ways as will be elaborated upon throughout.

3.1 Research Plan

At the start of the research, the idea was to select any number of relevant synthesis methods and apply them to the Lunar Zebro design case. That was, after all, the design case this research started with. This would have caused problems for two reasons. Firstly, comparing synthesis methods based on one single application does not produce insightful results. There would simply be too little data to make any valuable conclusions. Secondly, any method that does not apply well to this specific design case would perform poorly, while it may perform adequately for other design cases. Especially because the Lunar Zebro is not an average engineering design case, considering the difficult circumstances outer space imposes on the little rover.

The plan is shifted from applying all synthesis methods to the Lunar Zebro design case to applying them to multiple design cases. Multiple design cases allow for a larger data set and aid with finding the strengths and weaknesses of each method. Because the focus lies on synthesis, only concept generation is done for every combination of design case and synthesis method. The performance of the concept generation will then be evaluated and graded accordingly. The grades and findings on each case-method combination will enter the data set. When all combinations are executed, the data will be assessed as a whole and conclusions can be drawn. Summarized;

- Find relevant synthesis methods within the literature
- Set up adequate design cases

- Perform and evaluate all case-method combinations
- Examine and assess the data set
- Draw conclusions on performance of the synthesis methods

3.2 Research Outset

This research is not a common engineering research and could maybe better be described as a cognitive experiment. That being said, the nature of the research does call for sufficient engineering experience from the person executing the synthesis, in this case solely the author. This categorizes the research within the field of engineering. The sole executor of the experiments does make it susceptible to subjectivity, which is undesirable.

This subjectivity must be filtered out as much as possible, but cannot be eradicated completely. Certain parameters can be measured objectively, such as the number of concepts that are generated or the time it takes to execute a certain method. Still, these are influenced by intrinsic subjectivity. The familiarity with some methods from previous experiences may result in them performing better than methods that are new to the executor.

Also, it is difficult to keep all external parameters consistent. These would be the working environment and its noise levels, but also the mental state of the executor. Performing the methods and thinking about solutions requires a certain focus and mental energy, which can fluctuate for all sorts of reasons. All of these are external parameters that can influence the outcome of the experiments.

Below is a concise list of conditions that were of importance during the research. Not only is it a list of research conditions but perhaps also a disclaimer for the results. Nonetheless, the outcome of the research can be valuable.

The research was done...

- by one person (a mechanical engineering student of master level)
- limited to the concept generation
- under circumstances subject to change; working environment, noise, mental state.
- at random, minimizing preference for a certain solution pattern or profiting from earlier found solutions.

3.3 Design Cases

3.3.1 Design Field

The design cases are chosen based on a number of requirements. First of all, the design cases should all be within the field of mechanical engineering. Undoubtedly the design methods will also be applicable in other fields, but to keep consistency between cases other disciplines will not be considered now. Secondly, all cases must have a clear frame or chassis part that holds everything together. This is to stay relevant to the initial approach of the research, the frame design. Luckily, within mechanical engineering many designs have a chassis or frame-like structure as a subsystem.

Although the focus will be at finding innovative solutions regarding the frame, other aspects of the design cases may not be ignored. Some design synthesis methods may not apply well to the frame problem, but may perform well at other parts of the design. This is also valuable and therefore finding solutions for other parts is included within the research. Consequently, the design cases cannot be limited to only a frame or chassis. Fortunately, chassis or frames are often part of a bigger whole.

3.3.2 Level of Design Freedom and Complexity

Another key factor is the complexity of the chosen design cases. As the Lunar Zebro is a highly complex design case, it was reasoned that there must also be a case that is low in complexity. While searching and creating adequate design cases, another key feature was identified; design freedom. Freedom in design comes when there are few restrictions. Restrictions can be rules, laws or defining circumstances that apply to the design case.

As these properties are thought to have large influence on the outcome of applying the design method, design cases that vary in these properties are chosen. To properly represent a development in both design complexity and freedom it is chosen to assign cases to five different levels of complexity and freedom.

Level One

In the first level, the design case must have a high design freedom and low complexity. This would mean that the case has a simple working principle, which is easily grasped mentally. The frame or chassis must be the prominent part and preferably subframes are not part of the solution space.

Level Two

At the second level the complexity shall increase considerably, introducing subsystems that must be integrated into the design. This will inevitably come with some decrease in design freedom yet not explicitly. The complexity of the subsystems does not necessarily impact the needed complexity of the frame, which is an important distinction.

Level Three

In the next level the complexity will go up further. This can be due to more integration, more demanding environment, more requirements etc. The design freedom will go down further, yet still mostly implicitly. Some explicit items that can affect freedom could be rules or laws or extreme environments. For this design case they will not be prominent but may be present.

Level Four

For the fourth level the complexity does not rise much, however, the design freedom drops significantly. This similarity in complexity but change in freedom is to assess how the design freedom affects the performance of the method. This design case will then be more heavily subjected to rules, laws or extreme environments.

Level Five

For the last level the complexity reaches a climax. The chassis or frame must comply with challenging requirements while being bound in its design freedom. Finding new concepts at this level within the boundaries of this research will be difficult, which is exactly why this is the highest level.

The five chosen design cases, one for each level, are listed below. To a certain degree, the choice of each design case is arbitrary. They must only comply with what each level prescribes.

3.3.3 Chosen Design Cases

Garbage Bin

As a simple and straightforward design case to test the process of applying all relevant synthesis methods, the design case of making a garbage bin has been chosen. It should allow for enough variation, of which a glimpse is shown in Figure 3.1, whilst keeping the design task straightforward. Many of the existing garbage bins only have one mechanism, making it one of the simplest mechanical engineering systems.

Figure 3.1: Garbage bins already come in all shapes and sizes, showing the design freedom that comes with this design case.

The design requirements for the garbage bin are;

- There should be sufficient storage for disposed waste
- The odor of the waste should be kept within the bin or mitigated otherwise
- The bin should be able to be emptied
- Waste should easily be inserted into the bin

The design requirements for this case are easy to grasp, which helps in visualizing ideas. It is expected that many concepts will be generated when applying the synthesis methods. Many of these concepts will likely already exist as the garbage bin has been reinvented many times. Finding fundamentally new concepts could be a challenge.

Portable 3D Printer

FDM printers can be very useful to create prototypes, quick solutions or any other small objects. Most FDM printers are rather bulky, making them machines to be placed at home, akin to desktop computers. However, a lot of printed parts do not utilize the relatively big build volumes of these printers. For this reason, many companies and enthusiasts have made attempts in creating small 3d printers that could be portable, such as the Vertex Nano in Figure 3.2. Every design has their own benefits and drawbacks, concerning noise, speed, quality and usability. To create a portable 3D printer all components must be packaged close together and preferably the design is lightweight. These two properties are heavily dependent on the frame design, making it an excellent design case for this research.

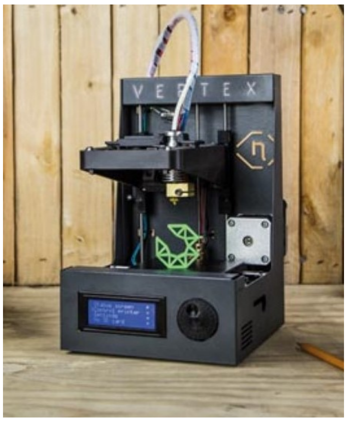


Figure 3.2: The Vertex Nano, a small sized FDM 3D printer.

The goal of this design case is to create a portable FDM 3D printer. To keep it short that goal can be translated into two design requirements;

- The design should be able to produce FDM 3D prints
- The design should be portable

My personal familiarity with FDM 3D printers makes this design case not much more complex than the garbage bin design case, but definitely a step up. On top of that, the already existing variety in FDM printers shows what level of design freedom is available. Naturally, all FDM printers need certain components to function, so the level of freedom is lower compared the previous case.

Autonomous Car

More and more new cars are built with self-driving modes or at least features that take away tasks from the human driver. When the autonomous system becomes reliable enough, the user interface and controls for the driver could be omitted completely. The traditional layout of the steering wheel, gear shifter and pedals will not be necessary anymore. This leaves space and freedom to alter the shape of both the inside and outside of the car. An interpretation of this is reflected in Figure 3.3.

Figure 3.3: Seating arrangements can be altered compared to conventional cars because a traditional driving position is not needed.

Cars, also autonomous ones, are however subjected to laws and safety regulations, inhibiting design freedom. Also, they are dependent on the available infrastructure and the current traffic composition. This means that an autonomous car that takes up two lanes or ignores speed limits is not possible. These restrictions combined with the renewed design freedom that autonomous driving provides make this design case a good compromise. Both design freedom and complexity are present and neither overrules the other.

This design case possesses the following design requirements for use in this research;

- The car should transport at least 4 people and their luggage
- The car should be suitable for use on the currently available infrastructure
- The car should comply with current safety regulations and other relevant laws

Robocup

Robocup SSL is a competition where small robots play football with a golf ball. Robots can move unidirectionally over the field and are equipped with a dribbler and a kicker. The teams that build the robots and the robots themselves, shown in Figure 3.4, must follow the rulebook given by the competition organizers. This means that a large part of the design freedom is taken away. The complexity is not necessarily much higher than with the autonomous car but the familiarity of cars

Figure 3.4: A team of Robocup football robots.

and how they work makes that design case easier. Especially considering concept generation that familiarity will play a role.

As for the design requirements, the most complete piece of information is the rulebook. For the sake of this research design case it comes down to the following requirements to execute the design methods properly;

- The robot should move and rotate on a plane (the playing field, 3 degrees of freedom)
- The robot should be able to dribble
- The robot should be able to kick and pass the ball

Relevant to mention as well is the imposed size limit on the robot. Namely, the robot must fit inside a cylinder that measures 0.18m in diameter and 0.15m in height. In short, with this design case the complexity increase is minimal but the amount of design freedom decreases substantially.

Lunar Zebro

The Lunar Zebro, shown once more in Figure 3.5, is by far the most extreme design case in this research. Interestingly, the level of design freedom is high but so is the complexity. There are, strictly speaking, no rules that the Zebro has to conform to. However, to ensure a successful take-off and landing procedure the interface with the other parts of the vessel may impose some limitations. Beyond those it is up to the designer(s) to create the best possible small rover.

As the Lunar Zebro is very complex, the focus will lie more on exploring the chassis subsystem than may be the case with the other design case. This does not mean that the other subsystems will be ignored when applying any design methods. However, finding new solutions will mostly be directed at the chassis subsystem.

This is also reflected in the design requirements;

- The Zebro (chassis) should protect all susceptible parts from harmful radiation
- The Zebro (chassis) should handle the extreme temperatures adequately

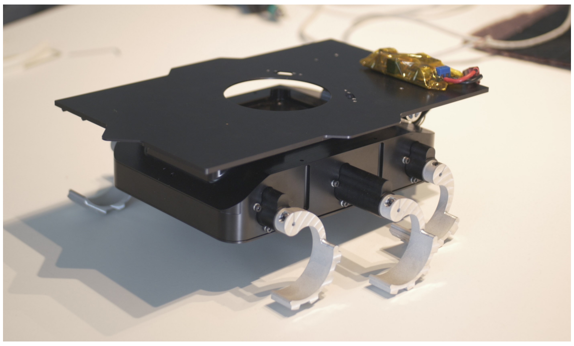


Figure 3.5: The Lunar Zebro, a small moon rover intended to be used in swarms.

- The Zebro (chassis) should protect all susceptible parts from moondust
- The Zebro (chassis) must be able to bear all the loads during take-off, transport, landing and intended use

3.4 Execution

The execution of all case-method combinations is rather straightforward. The five cases and ten methods were put into a random list generator to create a random list of all possible combinations. This is done to prevent making habits during the execution phase, which could alter the outcome. For example, if a certain method is applied for the tenth time in a row, it will likely perform better the tenth time than it did the first time. Naturally, there is still some gradual change in familiarity and experience, but that is minimized by applying the random shuffle.

The execution is either done on paper and then digitized or immediately done digitally. Each case has its own folder containing all ten methods applied to it. This creates a collection of the raw results that has good overview. In an excel file a layout was drawn up (seeA.1) that allowed for filling in whether a case-method combination had been executed, evaluated and graded. Also comments were collected to not lose the verbal data which cannot be made explicit in grades alone.

3.5 Explorative Evaluation

After applying a methods to a case the performance of the method has to be evaluated. Evaluation is susceptible to subjectivity, which preferably is eliminated completely. Unfortunately, that is not possible as an objective analysis method such as FEM or calculations does not exist for this type of problem. Certain parameters can be kept constant throughout the execution phase.

As mentioned before, the design methods are all applied by one person. This removes any speculation on whether one method performed better than another solely because it was executed by another person. Naturally, some bias still persists as some methods may suit the person better than others. Secondly, executing the methods solely on deductive and inductive reasoning is pursued. Abduction and 'innoduction' is to be avoided, as those would circumvent the method and rely on one's own creativity.

Most importantly however, a points scoring system is devised that evaluates different aspects of the synthesis process and gives points per category. This removes the vagueness and opacity that arise when the methods would only verbally be evaluated. The following parameters were carefully chosen to evaluate the methods in a balanced way.

Number of Concepts Generated

A greater number of concepts implies a greater chance of reaching an optimal design. However, if the concepts only differ little or the concepts are not feasible, they hold little value. For these reasons the number of generated concepts should have sufficient weight in grading the synthesis methods but by no means should become the deciding factor.

Time to Execute

A short time to execute a synthesis method can be relevant when the designer is pressed for time. Given the fact that the design process is of iterative nature, a short synthesis method can save time at multiple instances. Short execution time should not decrease the quality of the generated concepts though, and rushing certain methods should also not be rewarded. If the time to execute a single iteration is so short that it can be mentally implied at an instance, then that would be beneficial.

Insight Gained

If a synthesis method does not deliver promising concepts straightaway but the overall insight gained by generating the concepts aids in reaching a good design, then the synthesis method was relevant and beneficial to the design process. In the end, generating a concept is a form of reaching a new insight, so although the final concept is not directly caused by the chosen synthesis method, it can still be the indirect cause of a good design. Objectively measuring this parameter will be difficult.

Feasibility of Generated Concepts

Feasible concepts can be used directly and therefore hold value. If a second (or third, fourth, etc) iteration is needed before reaching a feasible concept then that may pose problems and create frustration within the design process. This characteristic goes hand in hand with the time to execute as well as the insight gained. “Extreme” concepts may help in gaining insight into the design problem but may also cost a lot of time.

Ease of Use

The ease of use can help in streamlining the design process and keep a good overview of what is going on. Ease of use does not necessarily mean the time to execute is short or that the generated concepts are simple, it means that the method itself is easy to grasp and perform. Ease of use can be valuable when performing the method with multiple people or when it has to be done multiple times.

Applicability

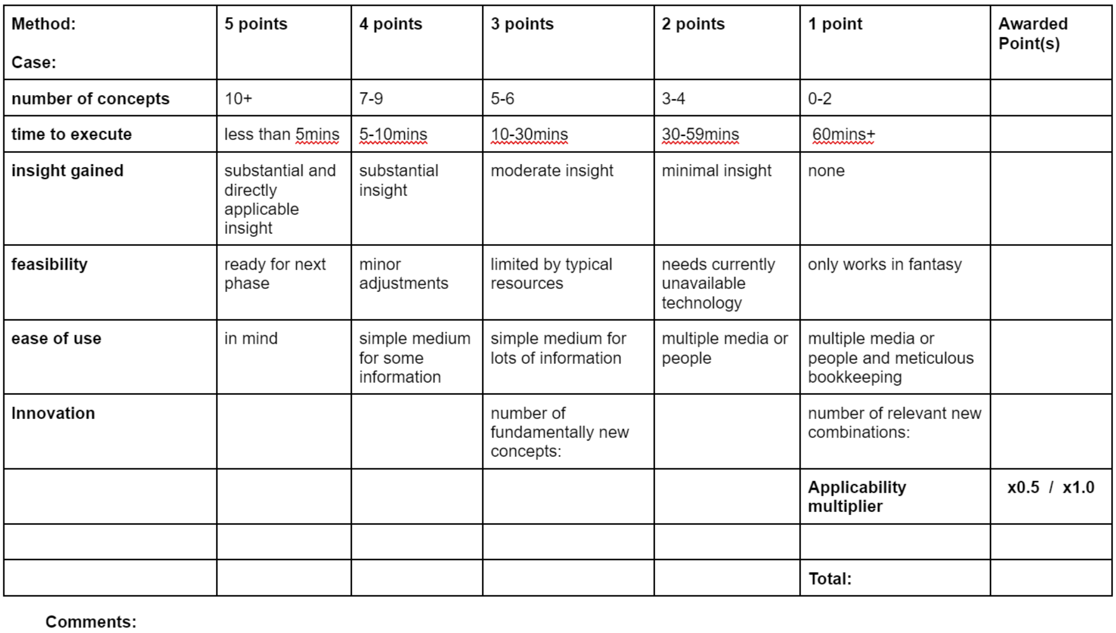
Not all methods match all design cases. Design cases that will inevitably need to be done at macro or micro scale, or have to be static or dynamic may not lend themselves to certain synthesis methods. Applicability may not need to have a weight as a go/no go statement will be sufficient. Namely, if the method cannot be applied to a design case then the method is rendered useless and any further effort towards that combination is unusable. This go/no go statement will make part of the acquired data useless however. If multiple methods are not directly applicable they will score zero points. Without any contrast between methods in the lower region, there is no use for the evaluation. In the end, an applicability multiplier is chosen. If the method is applicable to the design case then it will receive full points. If not, the points are multiplied by 0.5.

Innovation

Possibly the most difficult parameter to assess is the innovation of the generated concepts. A synthesis method only has value if it leads to new concepts. If the synthesis method would only lead to already widely known concepts then one might as well copy a concept from literature or experience and continue with that. Also, combinations of existing concepts may be produced by the synthesis methods. These can be valuable but also caution is needed for awarding points for creating new combinations just for the sake of making new combinations. A new combination has to make sense somehow and truly add to the functionality of the design for it to have value.

3.5.1 Rubric

The parameters and scores between one and five points per level are combined into a single evaluation rubric. This form will be used and filled in for every case-method combination. Furthermore, the method and case combination are shuffled randomly. To stress it once more, the rubric aims to filter out subjectivity as much as possible within the context of this research. The rubric can be seen in Figure 3.6.



Method: **Case:**	**5 points**	**4 points**	**3 points**	**2 points**	**1 point**	**Awarded Point(s)**
number of concepts	10+	7-9	5-6	3-4	0-2	
time to execute	less than 5mins	5-10mins	10-30mins	30-59mins	60mins+	
insight gained	substantial and directly applicable insight	substantial insight	moderate insight	minimal insight	none	
feasibility	ready for next phase	minor adjustments	limited by typical resources	needs currently unavailable technology	only works in fantasy	
ease of use	in mind	simple medium for some information	simple medium for lots of information	multiple media or people	multiple media or people and meticulous bookkeeping	
Innovation			number of fundamentally new concepts:		number of relevant new combinations:	
					Applicability multiplier	**x0.5 / x1.0**
					Total:	

Comments:

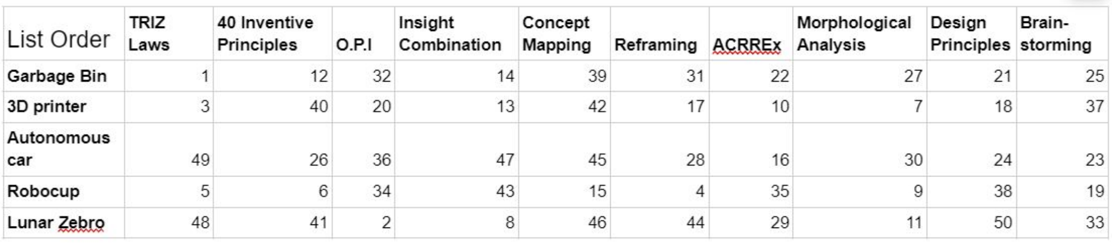
Figure 3.6: The evaluation rubric that was used to assess each case-method combination.

3.6 Practical Execution

In order to give a clear insight into how the experiments are performed, a description will be given of how one executes a case-method combination. Firstly, it has to be checked which case-method combination is next, as the combinations are not in any particular order. As mentioned earlier, this was done to prevent familiarity with cases or methods that can influence the results of a successive case-method combination. In Figure 3.7 it can be seen that there is indeed no particular order for the case-method combinations.

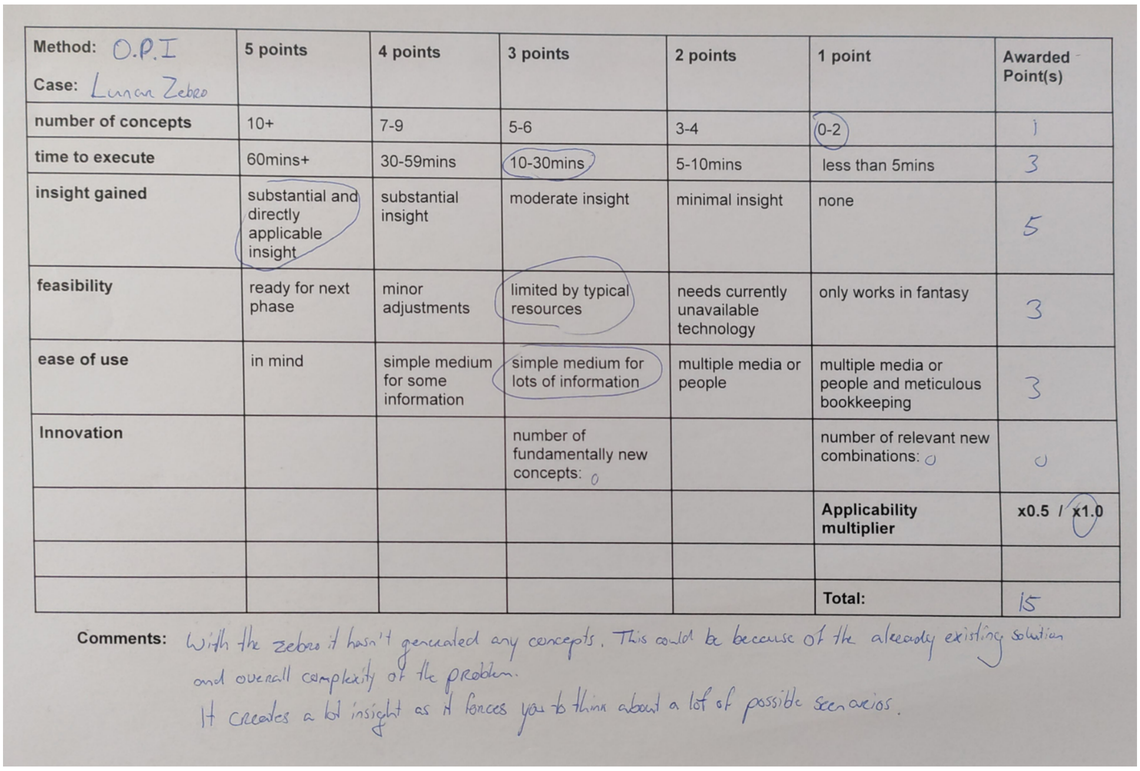
For any combination, a file is made in which can be worked directly or a digitized version of the execution can be entered. To start the execution, the case description and requirements are consulted to ensure the case is handled as intended. Similarly, this is also done for the respective method.

The method is then applied to the case, during which all necessary items are written down. Naturally, this differs per method. The result is a set of concepts or insights for the corresponding design case. Directly after the execution the rubric comes forward, is filled in and comments are written down. The rubric is done immediately after execution to prevent interpretation of the execution as much as possible. An example of a case-method evaluation is given in Figure 3.8. The respective execution can be found in appendix A.4.



List Order	TRIZ Laws	40 Inventive Principles	O.P.I	Insight Combination	Concept Mapping	Reframing	ACRREx	Morphological Analysis	Design Principles	Brain-storming
Garbage Bin	1	12	32	14	39	31	22	27	21	25
3D printer	3	40	20	13	42	17	10	7	18	37
Autonomous car	49	26	36	47	45	28	16	30	24	23
Robocup	5	6	34	43	15	4	35	9	38	19
Lunar Zebro	48	41	2	8	46	44	29	11	50	33

Figure 3.7: The order of the case-method combinations.



Method: O.P.I Case: Lunar Zebro	5 points	4 points	3 points	2 points	1 point	Awarded Point(s)
number of concepts	10+	7-9	5-6	3-4	[✓ 0-2]	1
time to execute	60mins+	30-59mins	[✓ 10-30mins]	5-10mins	less than 5mins	3
insight gained	[✓ substantial and directly applicable insight]	substantial insight	moderate insight	minimal insight	none	5
feasibility	ready for next phase	minor adjustments	[✓ limited by typical resources]	needs currently unavailable technology	only works in fantasy	3
ease of use	in mind	simple medium for some information	[✓ simple medium for lots of information]	multiple media or people	multiple media or people and meticulous bookkeeping	3
Innovation			number of fundamentally new concepts: 0		number of relevant new combinations: 0	0
					Applicability multiplier	x0.5 / [✓ x1.0]
					Total:	15

Comments: With the zebro it hasn't generated any concepts. This could be because of the already existing solution and overall complexity of the problem.
It creates a lot insight as it forces you to think about a lot of possible scenarios.

Figure 3.8: An example of a filled-in rubric.

Chapter 4

Results

Because of the nature of the research, the measurements done contain a certain degree of subjectivity. The evaluation form that the scores are based on was made to create a more objective and transparent ranking of the design methods. The scores do not represent the entire data set however. Verbal comments and findings are still of importance to properly evaluate the experiment. Although they may be of subjective nature, they are still data points, as they would be in a survey. An overview of the raw data can be found in A.1. Also all of the filled-in evaluation forms are available in an external file.

4.1 Scores

4.1.1 Average Points per Design Case

Not only do the methods receive scores, but effectively also the design cases do. As the cases were intentionally chosen based on their complexity and design freedom, it is valuable to show their average score (Figure 4.1). This information may help in deciding which type of case is suited when.

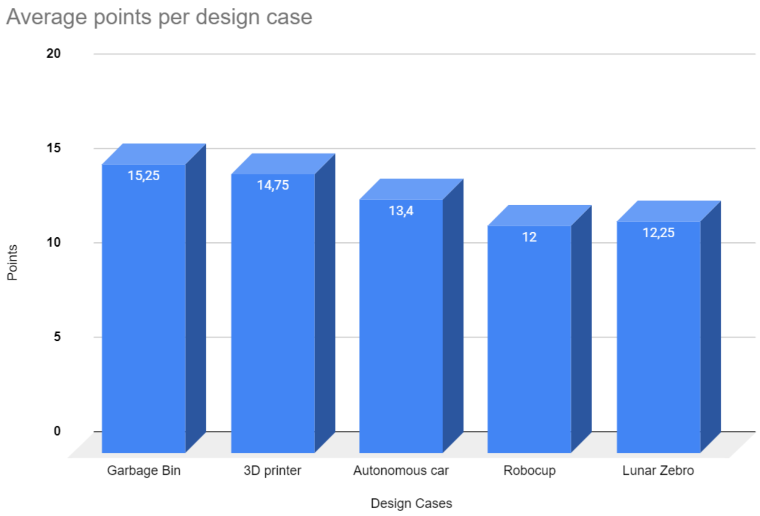


Figure 4.1: The average points each case scored after every method was applied to them.

The cases are shown from left to right with increasing design complexity primarily, and decreasing design freedom secondarily. A downward trend can be seen in average points scored. Apparently, low complexity or high freedom allows for better concept generation and thus receives better scores.

4.1.2 Average Points per Design Method

The average points scored by the methods, shown in Figure 4.2,is the most direct way of ranking the methods. Notably, there is enough variation in scores to draw justified conclusions on the performance of different methods. This means that the evaluation form has worked, and it is not needed to rely on verbal comments alone to distinguish methods.

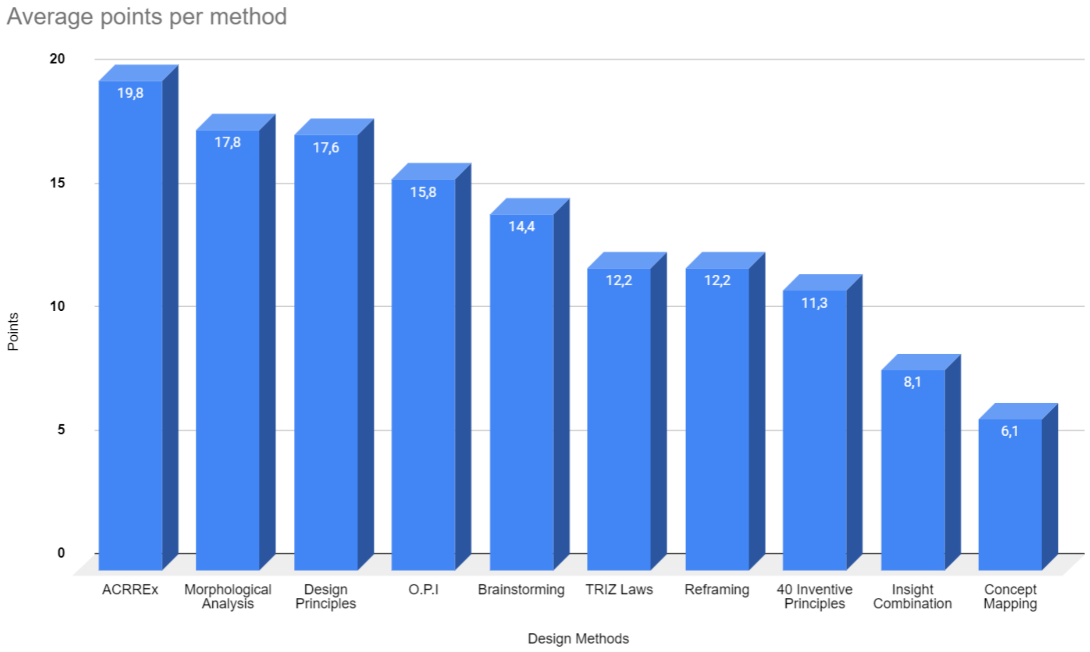


Figure 4.2: The average points each method scored after being applied to every case.

The best performing method is ACRREx, scoring more than three times the points of the worst performer; concept mapping. A major factor in this difference is the applied score multiplier. In the raw data A.1, it can be seen that concept mapping has the 0.5 multiplier applied on all instances. Furthermore it can be seen that morphological analysis and design principles are close seconds to ACRREx. Also, insight combination seems to score poorly. Namely, insight combination had the 0.5 multiplier applied on four of the five instances.

4.1.3 Complete Scoring Results

A complete overview of the scores, given in Figure 4.3, helps to single out remarkable results. An average does not tell the whole story after all, as one case-method combination could bump the average while the method mostly has not performed well. This can happen the other way around as well, when one case scores low and drags the average down.

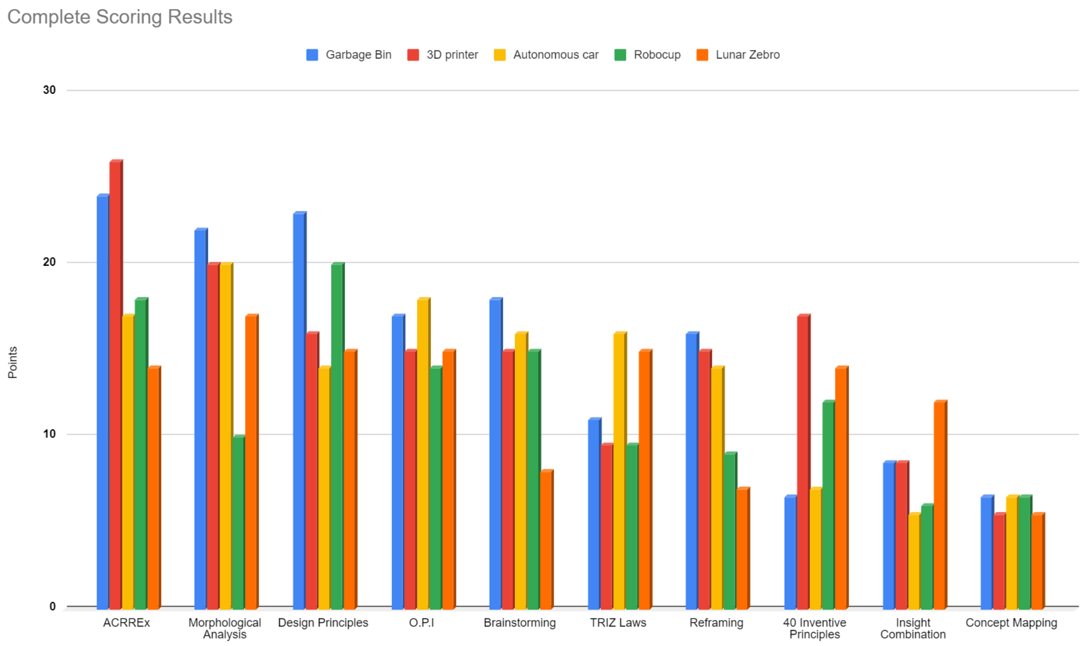


Figure 4.3: The complete results in one graph, this can help in spotting any anomalies or outliers.

The first thing that pops up is the low score of the Robocup at morphological analysis. This is due to applying the multiplier, as the method could not adequately provide a solution for the frame of robot. As the chassis subsystem is of high importance within the context of this research, the multiplier was applied. Secondly, brainstorming seemed to perform consistently but suddenly scores low when applied to the Lunar Zebro case. Reframing on the other hand shows a drop off in points similar to the average points per case as seen in 4.1. Another interesting observation is that the 40 inventive principles are a hit or miss, varying substantially between cases.

4.1.4 Multiplier

The multiplier was applied to provide stronger contrast between scores. The value of the multiplier of 0.5 and the criteria for its usage are rather arbitrary however. In other words, the research could have been done without, which may have had a different outcome. For that reason it is relevant to also consider the unfiltered results, given in Figure 4.4 and Figure 4.5. Without the usage of the multiplier the results show how well the methods worked regardless of they fulfilled the intended purpose. For example, if a complete system concept was desired but the method had an excellent concept for a subsystem solution, it receives full points for that although the method lacks the output of a system solution.

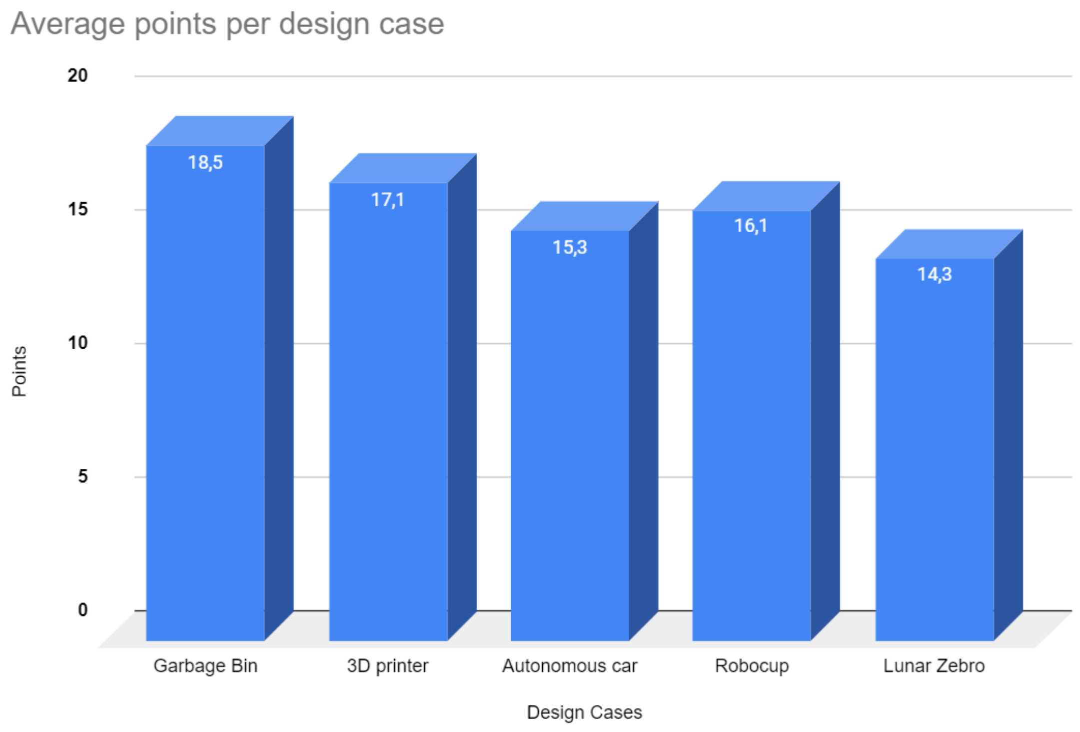


Figure 4.4: The average points per case if the multiplier of 0.5 was not applied at any combination.

The downward trend is still visible with increasing complexity and decreasing freedom. Whether the Robocup design case is truly more complex than the autonomous car may be arguable.

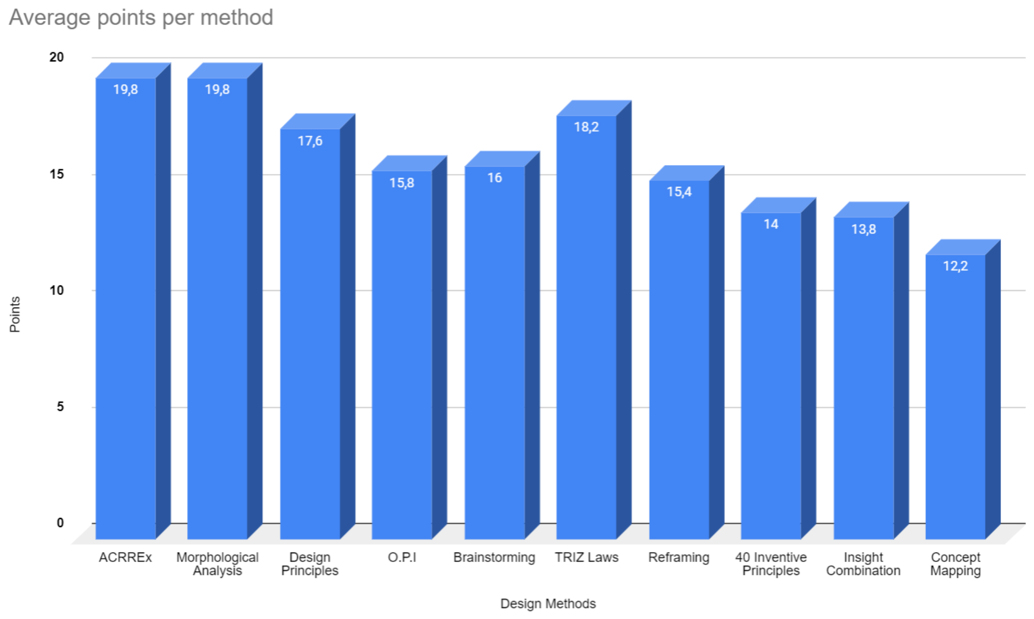


Figure 4.5: The average points per method if the multiplier of 0.5 was not applied at any combination.

Also among the design methods the ranking is mostly preserved compared to the results with multiplier. The only real significant change comes from the TRIZ laws. The multiplier was applied twice, once because the method was not suitable for frames whatsoever and another time because the method had to change in order to work. On the latter there is further elaboration later on. Remarkably, the TRIZ laws method does provide relevant solutions but not always the ones that were sought after.

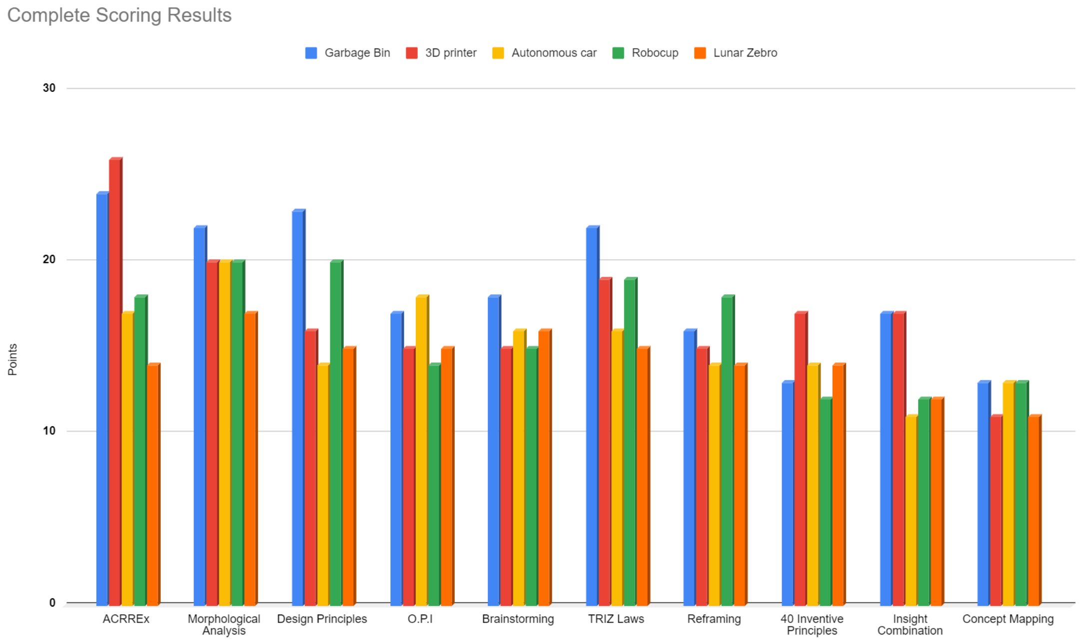


Figure 4.6: The complete results if the multiplier of 0.5 was not applied at any combination.

When reviewing the complete results without usage of the multiplier it is noticeable that each method scores more consistently with less anomalies.

4.2 Design Case Findings

This section covers the findings of every design case, the verbal evaluation. Did the design lend itself well for concept generation and why? Evaluating this will be valuable, as it will help identify what future cases may benefit from and which methods may apply to those adequately.

4.2.1 Garbage Bin

The garbage bin design case was the least complex one out of the five. The four requirements were simple and all other design aspects were free. This combination of low complexity and high design freedom allowed for many concepts across all methods. This resulted in the highest average score of all design cases. Only the ‘40 principles’ had a significantly low score for the garbage bin as that method focuses more on solving complex subproblems than generating concepts.

All in all the garbage bin was an adequate addition to the pool of design cases and it is definitely recommended to keep a similar type of case in similar studies. That meaning a case that is low in complexity and has lots of room for adaptations.

4.2.2 3D printer

The 3D printer case still has a considerable amount of design freedom compared to most other design cases. There is no rulebook and no special environment it has to comply with, it simply has to be able to make a 3D print. Also, the field of 3D printing has matured quickly over the past years, meaning that there are already a lot of concepts out there. The knowledge about 3D printers is also common among engineers, including the author. This makes the 3D printer design case perhaps seem more complex than it is. This would explain the relative high average of points across all applied design methods.

The need for more subsystems than with the garbage bin also resulted in generating more concepts, especially with methods such as morphological analysis and ACRREx, where the method relies on combining subsystem solutions.

4.2.3 Autonomous Car

The autonomous car has added design freedom over normal cars as the autonomous driving allows for unconventional seating arrangements. However, cars must still comply with the law and safety regulations imposed by the respective governmental body. Design wise it is a midground between high freedom and high restrictions. Also, the existing infrastructure which is based on normal cars has influence on possible designs. A new concept for autonomous vehicles may be accompanied by a new concept for its' supersystem, the infrastructure.

4.2.4 Robocup

The football robots are bound to the rules set by the competition organizers and with that a large amount of design freedom is taken away. On top of that, within a competition such as the robocup it is common for teams to converge to an optimal design as a collective. As the competition matures teams will copy each other and after some time the challenge lies with execution and optimisation rather than with innovation.

The application of most methods would have been more suitable if it was at the start of a new competition or if it concerned generating new ideas for the subsystems.

4.2.5 Lunar Zebro

The Lunar Zebro is a highly complex design case and has to deal with exceptional phenomena and environments. Space and its effects on technology is an entire research field in itself and is not part of most engineers' knowledge. This led to the fact that reasoning and creativity alone do not automatically result in new and innovative concepts.

As opposed to the Roboleague design case, the restrictions in design freedom do not come from a rulebook but from the special and harsh environment it has to operate in. From this can be deducted that design cases that concern very specialized applications also need a specialized engineer to execute them.

4.3 Design Method Findings

In this section every design method will be evaluated verbally, discussing what went well and what did not. Before, it is relevant to state some findings that apply to all design methods. Most importantly, all design method were now carried out by one single person. This inherently limits the available creativity and designer input. In other words, every single design method would have benefited from being carried out by a group of people. At a certain point, a group may become too big and the added value of performing a method with more people will be gone. This point may differ per design method and that could be an entire research topic in itself. Anyhow, performing the methods with more than one person would have likely increased scores across the board.

Secondly, as there are a total of 50 combinations and time is limited, no method was exhaustively executed. The amount of input is not linear with the amount of concepts or insight generated. So after X amount of time, which may be different per case-method combination, there are diminishing returns. These will be both in concept and insight generation, as well as data needed to contribute to the research.

4.3.1 ACRREx

The ACRREx method achieved the highest average points of all synthesis methods. This is because the method does not only instruct the engineer to categorize subsolutions but also subproblems. Actively thinking about both the possible problems and solutions results in a larger set of subproblems and a larger set of subsolutions than with other methods. If done correctly, nearly all subsolutions of different subproblems can be combined into concepts.

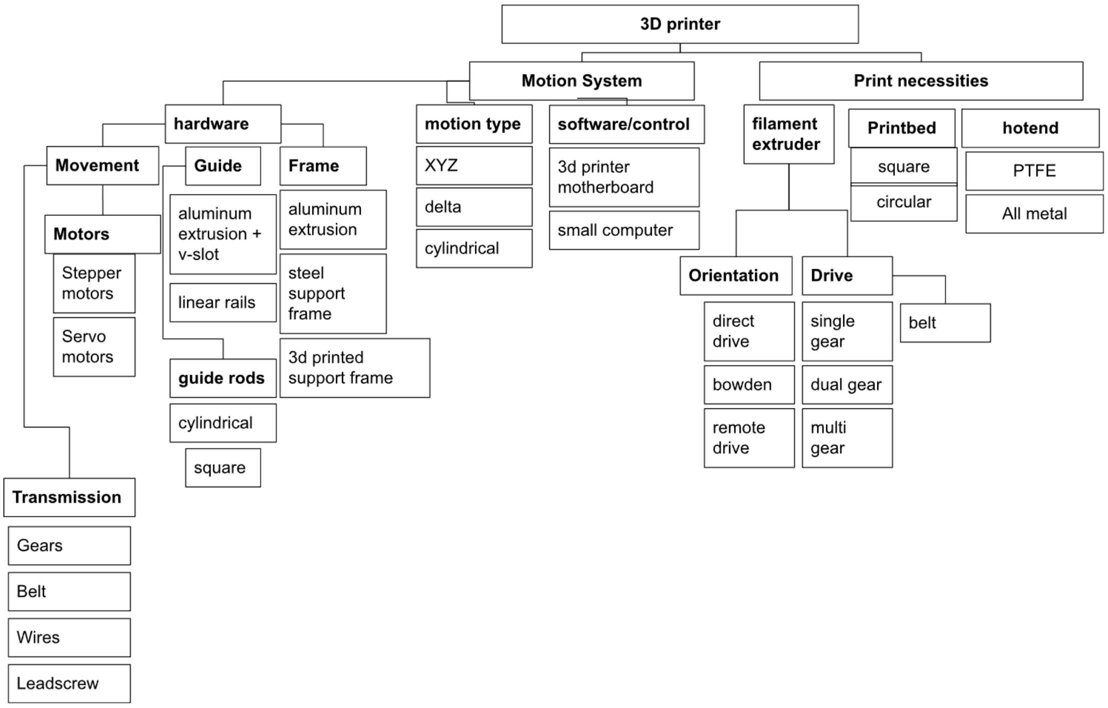


Figure 4.7: The results of applying ACRREx to the 3D printer design case.

The execution of the ACRREx method has been simplified for the use in this research due to time constraints. Normally, ACRREx calls for a larger problem analysis phase where the problem is Abstracted and Categorized. The actual synthesis part arrives later when the Reflecting, Reformulating and above all the Extending happens. In this research the focus lies with the core strengths of ACRREx, which is the categorizing of both problems and solutions. The fact that even with these simplifications of the method, due to time constraints, it still arrived at the top of the table is very promising.

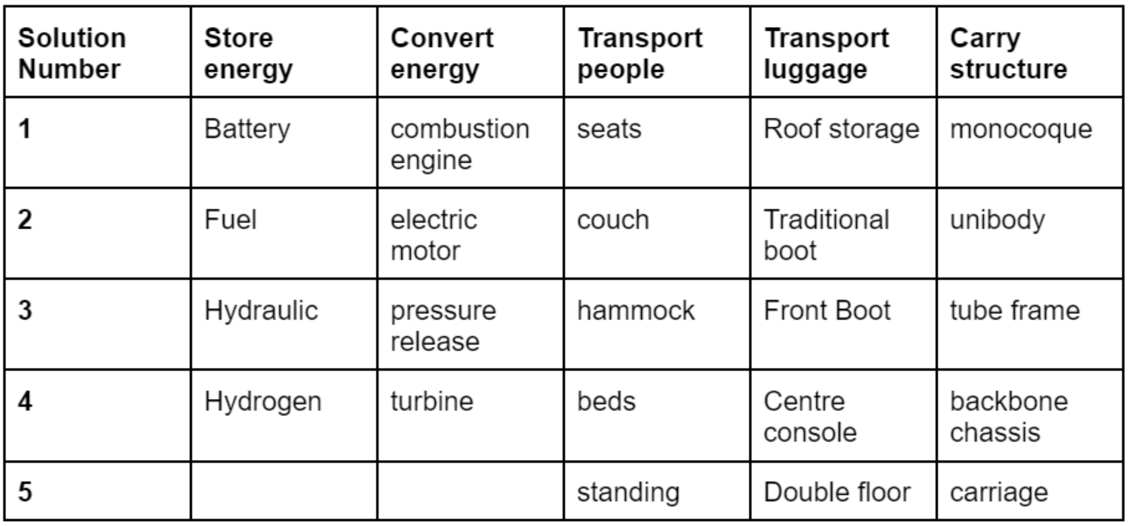
Although this method achieved the highest average points, it is not without its flaws. The method has many facets and requires a lot of initial input to extract new ideas. As originally explained by Breedveld et al, there are a lot of steps in the process and also many ways to achieve the extensions in the solution space. On top of that, when the design case concerns a system with many subsystems the ACRREx tree can become unwieldy and overview is lost. An example of the result of applying ACRREx is shown in Figure 4.7.

4.3.2 Morphological Analysis

At the bachelor of mechanical engineering at TU Delft a large role is played by the morphological analysis method. The results of the method comparison make clear why this method is so suited for helping new engineers with creating new ideas. The method repeatedly scores a lot of points because of its use of combining sub-solutions into concepts, which is more clearly represented in Figure 4.8. Because of the recombination it is likely that a new combination is found and therefore a new concept is created.

Also, the method needs only a handful of subproblems to start working. For most systems it is not difficult to divide it into subproblems that together span the entire larger problem. This is not always a given though and inadequate division may result in incomplete concepts being generated. Usually, bachelor students are not handed engineering problems that have as many facets and that is also why morphological analysis works so well for them.

Another advantage of morphological analysis is the clear representation it provides. When the subproblems are well articulated they together add up to the main problem and idem for the subsolutions. If done correctly, they add up to a total solution for the main problem. Besides, the method can be executed in one single table and works just as well digitally as on traditional media.



Solution Number	**Store energy**	**Convert energy**	**Transport people**	**Transport luggage**	**Carry structure**
1	Battery	combustion engine	seats	Roof storage	monocoque
2	Fuel	electric motor	couch	Traditional boot	unibody
3	Hydraulic	pressure release	hammock	Front Boot	tube frame
4	Hydrogen	turbine	beds	Centre console	backbone chassis
5			standing	Double floor	carriage

Figure 4.8: The results of applying morphological analysis to the autonomous car design case.

The caveats in this method, however, are the filling in of the subproblems and the generation of subsolutions. As said before, if the subproblems together do not span the entire main problem then there will be gaps in created solutions. In other words, practicing correct problem analysis and formulation are musts. On top of that, the method heavily leans on recombination to find new solutions but finding new subsolutions is not necessarily encouraged. The subsolution space is usually limited by the collective knowledge of the designer(s) and therefore the chance of finding innovative solutions is limited.

4.3.3 Design Principles

The design principles method is the odd one out among the synthesis methods. As it is merely a check list of five points not much was expected from it. However, as the design cases are all considering mechanical engineering problems and the design principles are made exactly for this type of problems, it performed well. This does mean that when the design case does not consider typical mechanical problems, the results may be disappointing.

The method also does not inherently generate concepts but gives very useful pointers to the designer. The reasoning behind generating concepts is therefore more abductive in nature rather than deductive. With abductive reasoning the person who enacts it has large influence over the outcome of the design method. The design principles could then perform very differently compared to the other method based on who performs it. Nonetheless going over the design principles as a mechanical engineer can be very fruitful for any design case within the field.

4.3.4 Overcoming Psychological Inertia

This method scored a considerable amount of points but rarely generated any tangible concepts. The point scoring parameter here was the generated insight after executing the method. This method is not really one method but rather a collection of three smaller methods that all try to achieve the same goal in slightly different ways.

The nine screen method generates insight into the evolution of the system that is to be dealt with. As the designer has to put into words what the system looked like in the past and what it looks like now, they can often continue the found trend into the future. When an image is sketched of what the future might look like, the engineer may see how to get there and what their priorities are. By doing this on subsystem, system and supersystem all parts may be placed into context and even more insight is created into how one must prioritize or handle certain aspects of the design problem.

The miniature people method provides insight in a different way. The main learning point from this exercise is how different subsystems interface with each other. Seeing a function as a role to be fulfilled by an employee and then asking how that employee is to be managed helps with ensuring the different subsystems work together harmoniously.

The time, dimension and cost method was found to yield the most directly applicable insight. By distorting the available time, dimension and cost from minimal to maximal the engineer clearly sees what can be done to improve a design or what is relevant.

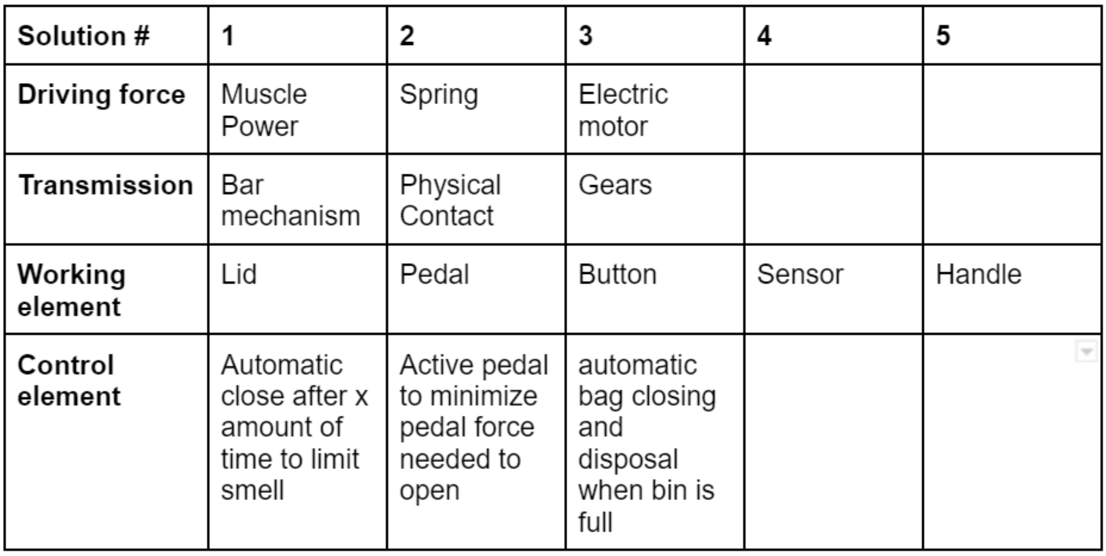
As this method does not generate any concepts directly but does generate relevant insight, it may be best to perform it as a problem or concept analysis. This would mean that it will accompany a different method that does generate concepts but lacks in developing insight.

4.3.5 Brainstorming

Brainstorming is a very average scoring design method which is not unexpected. The method will always result in some concepts as the designer(s) tries to think about as many aspects of the problem and writes down possible solutions. It is, however, severely limited to the designers' knowledge and experience in the field of the design problem. Brainstorming does not provide any tools to extrapolate new ideas from existing ones and relies on the improvisational abilities of the designer(s).

4.3.6 TRIZ Laws

The TRIZ laws are laws that, according to TRIZ theory, every design should comply with. This poses a problem as holding a design against a set of laws means a design should already exist. To convert these laws into a synthesis method it was chosen to alter the first four laws into four requirements. So instead of checking if a certain design has a driving force, transmission, working element and a control element, they become prerequisites and are categories where subsolutions must be filled in. This renewed version of the TRIZ laws is shown in Figure 4.9. This version is akin to how the morphological analysis method works. The difference lies in the fact that there are given subproblems instead of subproblems that the designer must give themself. The remaining laws were found to be only applicable in a stage beyond the synthesis and were therefore not transformed into this ‘synthesis’-form of the TRIZ laws.



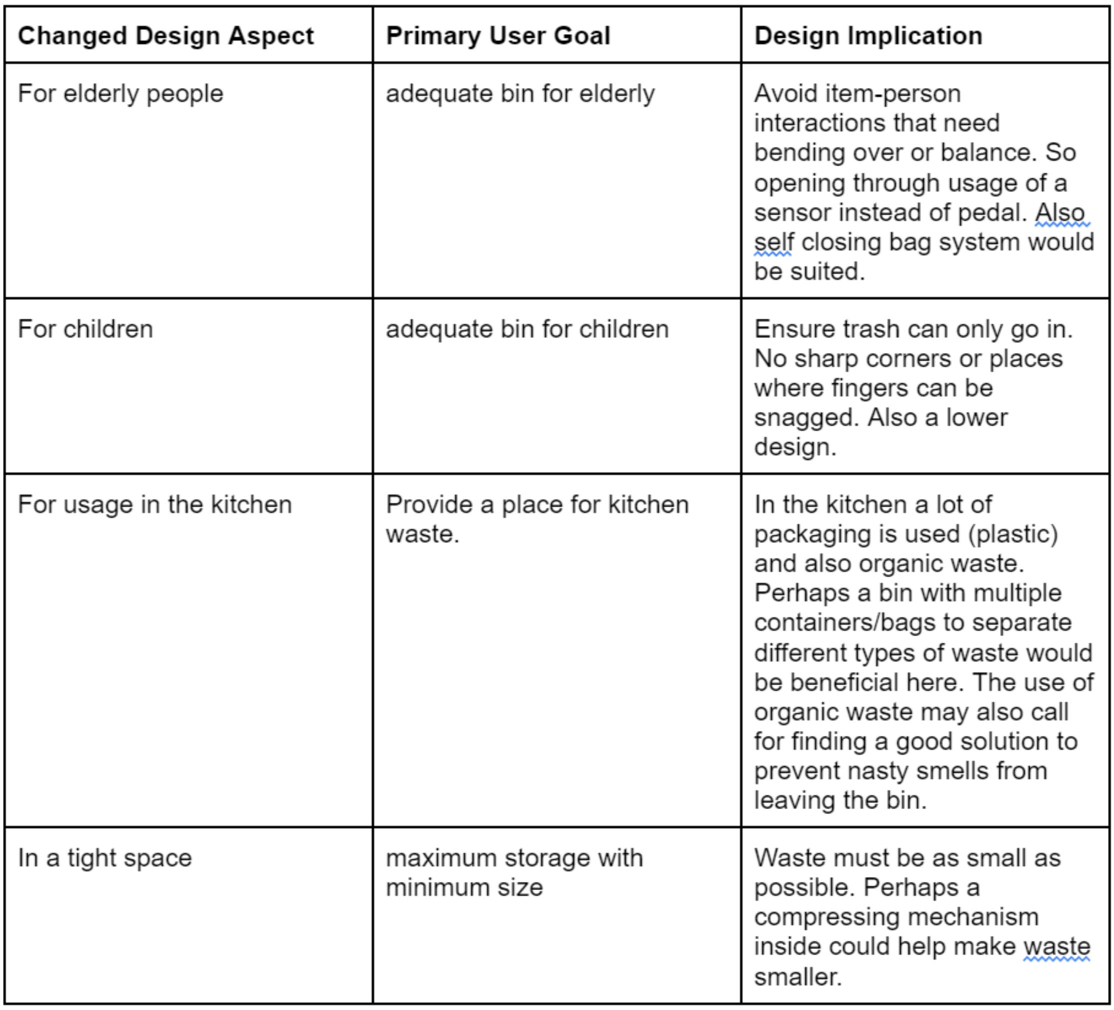
Solution #	**1**	**2**	**3**	**4**	**5**
Driving force	Muscle Power	Spring	Electric motor		
Transmission	Bar mechanism	Physical Contact	Gears		
Working element	Lid	Pedal	Button	Sensor	Handle
Control element	Automatic close after x amount of time to limit smell	Active pedal to minimize pedal force needed to open	automatic bag closing and disposal when bin is full		

Figure 4.9: The results of applying the renewed TRIZ Laws method to the garbage bin design case.

The outcome of this transformation became a decent synthesis method that sometimes resulted in fundamental new concepts. However, in some cases the four requirements did not suit the design case and inadequate solutions were found. Also, the four requirements could fall short and some aspects of the design problem were not covered by them.

4.3.7 Reframing

Reframing forced the designer to place the system at hand in a different context and think of what implications that may bring. This works well when there is a lot of design freedom and the product can be placed in different contexts and still function. For example, the garbage bin can be placed in many different contexts and still function as a garbage bin, as seen in Figure 4.10. This still held up for the 3D printer but to a lesser extent, and was less applicable still to the autonomous car. For the Roboleague and Lunar Zebro design cases it was completely inapplicable however. Both of these cases have very little room for change, either because of the imposed rules or the specific environment. These mean that any sort of reframing quickly leads to an infeasible design and therefore holds no value to the concept generation.



Changed Design Aspect	Primary User Goal	Design Implication
For elderly people	adequate bin for elderly	Avoid item-person interactions that need bending over or balance. So opening through usage of a sensor instead of pedal. Also self closing bag system would be suited.
For children	adequate bin for children	Ensure trash can only go in. No sharp corners or places where fingers can be snagged. Also a lower design.
For usage in the kitchen	Provide a place for kitchen waste.	In the kitchen a lot of packaging is used (plastic) and also organic waste. Perhaps a bin with multiple containers/bags to separate different types of waste would be beneficial here. The use of organic waste may also call for finding a good solution to prevent nasty smells from leaving the bin.
In a tight space	maximum storage with minimum size	Waste must be as small as possible. Perhaps a compressing mechanism inside could help make waste smaller.

Figure 4.10: The results of applying reframing to the garbage bin design case.

This method works well if someone wants to create new products from products that already exist. This could be any product that is now placed in context X and may also work in context Y with some adaptations. But when a purpose has to be fulfilled, something fundamentally new has to be created, the reframing method is inadequate. On top of that, the needed creativity to create new designs now shifts from directly making new solutions to creating new frames. In the end, the method still heavily relies on the intrinsic creativity of the designer. It may be possible to create an amount of predetermined new frames to help designers initiate the concept generation, but they may not be applicable in many cases.

4.3.8 40 Inventive Principles

The 40 inventive principles of TRIZ form more of a checklist than a real design method. Naturally, not every principle can be applied to every design case and even if they could, it is not directly clear how that application would go. With this design method it is very dependent on the designer if they can come up with an applicable solution after holding the design case and one of the principles together. Sometimes it can spark a relevant solution but more often than not nothing significant comes out.

Besides, the solutions that do come out of the design method are often only on subsystem level. The 40 inventive principles solve small problems within a design by showing a way it can also be done. Perhaps it is more suited to go over the 40 inventive principles when problems with finalizing a concept or prototype are encountered rather than as an upfront synthesis method.

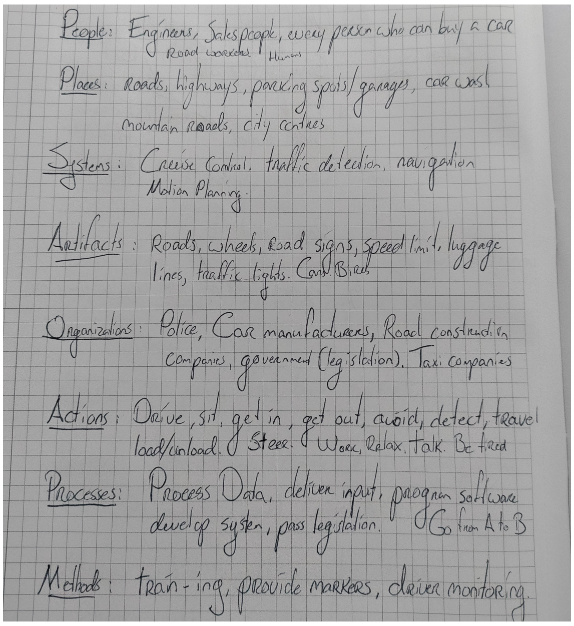
4.3.9 Insight Combination

In theory insight combination could work very well but in practice it does not. The method prescribes using note cards to write down insights about the design problem and add to those solution patterns that already exist. First of all, creating a heap of loose notecards with varying insights about the design problem does not provide a structured overview for the engineer(s). Secondly, the solution patterns found are often not transferable between subsystems. This means very little concepts are created.

Also, as the designer writes down random insights, there is no structured way to come to new insights either. This inhibits the method from scoring points at creating new insights as well. Finally, the loose notecards will likely also cause problems when working in a group, as it is difficult to create a clear overview for everyone working on the design case.

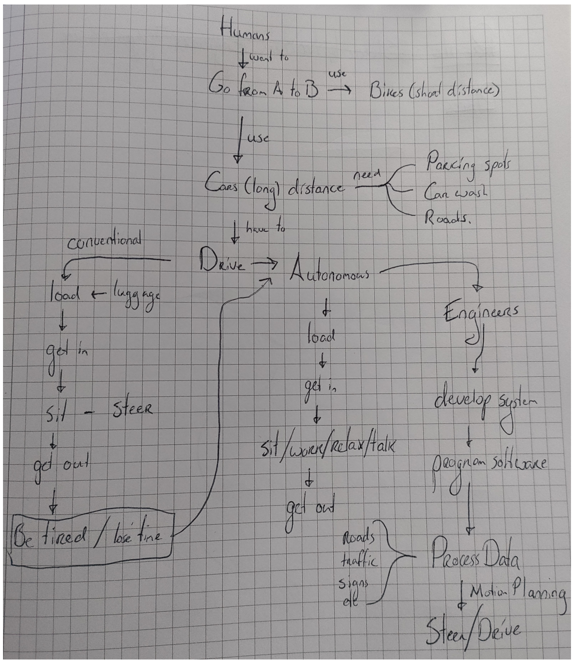
4.3.10 Concept Mapping

Surprisingly, concept mapping works very well, only not for the intended purpose. This method creates a lot of insight at supersystem level, the larger context the design is to be placed in. Especially when the field is not the designers' expertise, the concept map helps in understanding the bigger picture. The reason that concept mapping scores so low is because none of the insight is directly applicable to the system level. This does not mean that the gathered knowledge is not valuable though.



People: Engineers, Salespeople, every person who can buy a car
Road workers, Humans
Places: Roads, highways, parking spots/garages, car wash
mountain roads, city centres
Systems: Cruise Control, traffic detection, navigation
Motion Planning.
Artifacts: Roads, wheels, road signs, speed limit, luggage
lines, traffic lights. Cars. Bikes
Organizations: Police, Car manufacturers, Road construction
Companies, government (legislation). Taxi companies
Actions: Drive, sit, get in, get out, avoid, detect, travel
load/unload. Steer. Work, Relax, talk. Be tired
Processes: Process Data, deliver input, program software
develop system, pass legislation. Go from A to B
Methods: train-ing, provide markers, driver monitoring.

((a)) Taxonomy creation



((b)) Concept map

Figure 4.11: Example of how the concept mapping method was applied to the autonomous car design case.

Concept mapping could be valuable to organizers or managers, as it sketches a rather complete picture of the supersystem. Especially being forced to list all people that interact with the design and all possible locations the design may find itself can be useful. An example of one of the concept map applications is seen in Figure 4.11.

Chapter 5

Discussion

As there is no precedent in the literature that compares synthesis methods in this way, the method behind the research required some ”synthesis” as well. By no means is this proven to be the optimal way to make a comparison between the synthesis methods. Although it may not be optimal, the results are clear and there is definitely significant variation between the performance of the design methods.

5.1 Choice of methods and cases

The picking of the synthesis methods was done by performing a literature review. At a certain point, it became difficult to find new relevant methods while there were already ten collected. Due to time constraints, it was chosen to stop looking any further at this point. In a similar way, it was chosen to execute five design cases as mentioned before. Overall, both the design cases and methods show sufficient variation without lying too far apart from each other, which makes drawing conclusions valuable. The amount of cases and methods was also adequate without hindering progress of the research by being exhaustive. Naturally, more methods and more cases would improve the data set, at cost of the time it would take to perform the research.

5.2 Evaluation method

There is certainly room for improvement concerning the evaluation process. The evaluation form, although sufficiently adequate, may need revising. Five points per category may not be enough range to fully contrast between methods that lie closely to each other. Using a 10-point system could benefit differentiating between the design methods further.

Also the criteria in the evaluation form should be quantified better, wherever possible. This was especially noticeable in the feasibility parameter, where many method-case combinations scored three or four. It is likely that these consistent scores were due to the limitation to the concept phase. Assessing the feasibility without performing extensive concept analysis is difficult and may be an unreliable factor. As many case-method combinations scored similarly, it is does not affect the end result significantly. In line with the possibility of having a 10-point system, having more variation within categories could benefit the overall scoring system.

Lastly, the applicability multiplier that was used could be revised. The current multiplier of either 1 or 0.5 is rather black and white, penalizing heavily while a method could still have produced useful results. Namely, in some cases the lower multiplier was used when the method applied well on the subsystem level while the design case concerned the system level and vice versa. The generated concepts for the other system level then scored well initially, yet after the multiplication their scores were subpar. Perhaps a step wise multiplier would be more suited over a 'binary' one or half multiplier. For example, when hindrance occurs in a certain shape or form, the score is multiplied by 0.9. If another barrier is reached, the score is multiplied by 0.9 again, stacking the penalties. In this way the multiplication factor becomes more nuanced, avoiding overly heavy point deductions. A proper framework for such a system should be laid down before performing any experiments, as was done in this research.

Chapter 6

Conclusions

6.1 System levels

An important finding within the research is the division between system levels. Some methods worked well on one system level and then were nearly inapplicable at another system level. This has implications on when and if a method should be used, which is ultimately what this research is trying to answer.

6.1.1 Subsystem

The synthesis methods that performed well at the subsystem level were the 40 inventive principles and design principles, which are both part of the principles category. Remarkably, these two methods are also the only 'checklist methods'. This is exactly why they work on the subsystem level, they provide tricks and solutions that cover one aspect of a design solution. Clearly, picking a subsolution picked from either checklist will only be applicable at the subsystem level.

This also means that the subsystem must already be present within its respective system. In other words, a system concept consisting of multiple subsolutions must already be made before the checklist can be applied adequately. Therefore, the application of the 40 inventive principles and design principles is recommended to be done after a concept is already chosen or at least after concept generation.

6.1.2 System

The methods that perform well on system level were mostly of the systematic type. These are the morphological analysis, ACRREx and also the TRIZ laws. The latter was originally not a systematic method, as mentioned within the categorisation section. However, the method was altered to work better for synthesis, transforming it from a checklist to a method that more closely resembles morphological analysis. These methods work well at system level because they combine subsolutions into a solution for the entire system. Acquiring subsolutions mostly relies on experience and knowledge with the TRIZ laws and morphological analysis, achieving little innovation. The TRIZ laws do however force criteria that sometimes are originally not part of the subproblems, leading to fundamentally new concepts. There is a flipside to this, as it sometimes also renders the TRIZ laws method useless.

The ACRREx method sparks more creativity, as it leaves blank spaces open that can be filled in. This is where true new subsolutions can be found and later integrated into new concepts. Also the clear overview of the subproblems is helpful. The fact that it outperforms all other methods even when it is not used to its full potential, is very promising.

Morphological analysis delivers less innovative solutions, but does provide solutions quicker and with a better overview. Also, morphological analysis requires only one table to function, whereas cross-examining many parameters with ACRREx requires many tables and then also a tree structure to make a comprehensible overview of the solution space.

At last, there is the brainstorming method, fittingly a very mediocre scoring method. The method comes down to thinking freely without restricting oneself, which truly is only one step above enacting a ”non-method”, thinking and being critical. Brainstorming and ’thinking’ rely on a designers experience within the field of the design case and the designer’s intrinsic creativity. It is by no means a bad method, solutions will be found. However, it will not consistently help one find better solutions and there is always the pitfall of getting stuck.

Unsurprisingly, these method are to be applied at concept generation, exactly where they were applied within the research. ACRREx will generate the best results overall, which comes at a relatively high input cost compared to the others.

6.1.3 Supersystem

The methods that perform well at supersystem level are the ones that usually generate few concepts but score well at generating insight. Among these are concept mapping, reframing and overcoming psychological inertia. From these three concept mapping focused the most on the supersystem and therefore performed worst when applied to the design cases in this research. This does not mean however that it cannot be useful. The concept map can create substantial insight into how a design is placed within its context, which can be very useful knowledge to have during the design process. For that reason, it is recommended to perform a concept map at the very beginning of a design project.

Reframing and O.P.I both ask the designer to put their design problem into different perspectives to come to new solutions. Still, O.P.I works significantly better than reframing. This is mainly because O.P.I has predetermined perspective changes, whereas reframing requires creative input from the designer to create new perspectives. Also, O.P.I does not only ask the designer to look at the design in a new frame, but with a completely different set of eyes. The designer becomes a manager of a workforce, a cost engineer, a planner and a time traveler. This may be a bit overstated but it does show that O.P.I changes the perspective more extensively.

Anyhow, the value of these methods lies in prioritizing factors that influence the design. How the context, the supersystem, directly influences design choices. This would cover the time, dimension and cost as handled within O.P.I, yet also the end users which come forward mostly in reframing. In concept mapping factors such as stakeholders are also given importance, something which may be overseen during the other design methods. As opposed to concept mapping, reframing and O.P.I are perhaps suited best for after the concept generation. They would likely be most helpful with developing the most promising concepts to a higher level of integration within their supersystem.

6.1.4 Outliers

Among the synthesis methods, there is one outlier; insight combination. This method generated very few concepts, only outscoring concept mapping. Whereas concept mapping had its strength laying elsewhere, namely the supersystem, insight combination did not have that. Applying solution patterns to different aspects of a design did not work well and therefore insight combination does not have a place within the design process.

Though the application may not be useful, finding solution patterns is valuable. The way they are reached, by writing down insights is also rather intuitive. These two properties make it suitable to use when performing a literature review, or simply exploring the state of the art of a certain subject.

6.2 Design Freedom and Complexity

As is reflected by the average scores and discussed in the design case findings, low complexity and high design freedom allow for good concept generation. As the complexity increases and/or the design freedom decreases, the scores lower as concept generation becomes harder. These two properties should be assessed before the synthesis process start. The choice of synthesis method could be altered to suit the corresponding freedom and complexity levels. For example, when there is substantial design freedom methods such as reframing perform better than what its average score might suggest. Alternatively, when the complexity is high one may find the biggest design improvements in changing subsystems. For that purpose a method such as the 40 inventive principles may provide out come.

6.3 Frame Design

Although the research did not completely focus on frame design in the end, there are still relevant conclusions to draw on it. The frame or chassis being a subsystem of a greater whole, the 40 inventive principles apply well and will help the designer find structural improvements. The design principles method does not apply as well as the 40 principles, mainly because they are suited for mechanisms. There is one noticeable design principle however, the 'matching' principle. It states that all parts of the system should be developed at a similar level. This applies well to chassis and frames as a weak link could negate a large part of their stiffness. Unfortunately, this is more of a tip than a true design method to aid in structural design. Apart from the subsystem, also the methods that concern the supersystem may benefit chassis design. The chassis and frame are parts that have to deal with all external and internal loads. These loads come from the supersystem. Therefore, understanding the supersystem better could in the end prepare the chassis better for its use in the outside world. Especially concept mapping could indirectly have very positive effects on chassis and frame design, although that may not be reflected in the results. This is because the results rely on concept generation and concept mapping would reap its benefits when applied within the entire design process, not just the synthesis.

Chapter 7

Future Work

As the conclusions show when and where in the design process the methods could be used, actually using them as recommended would be the next step. Not only to help engineers create the best possible solutions to their design problems, but also to validate the findings of this research.

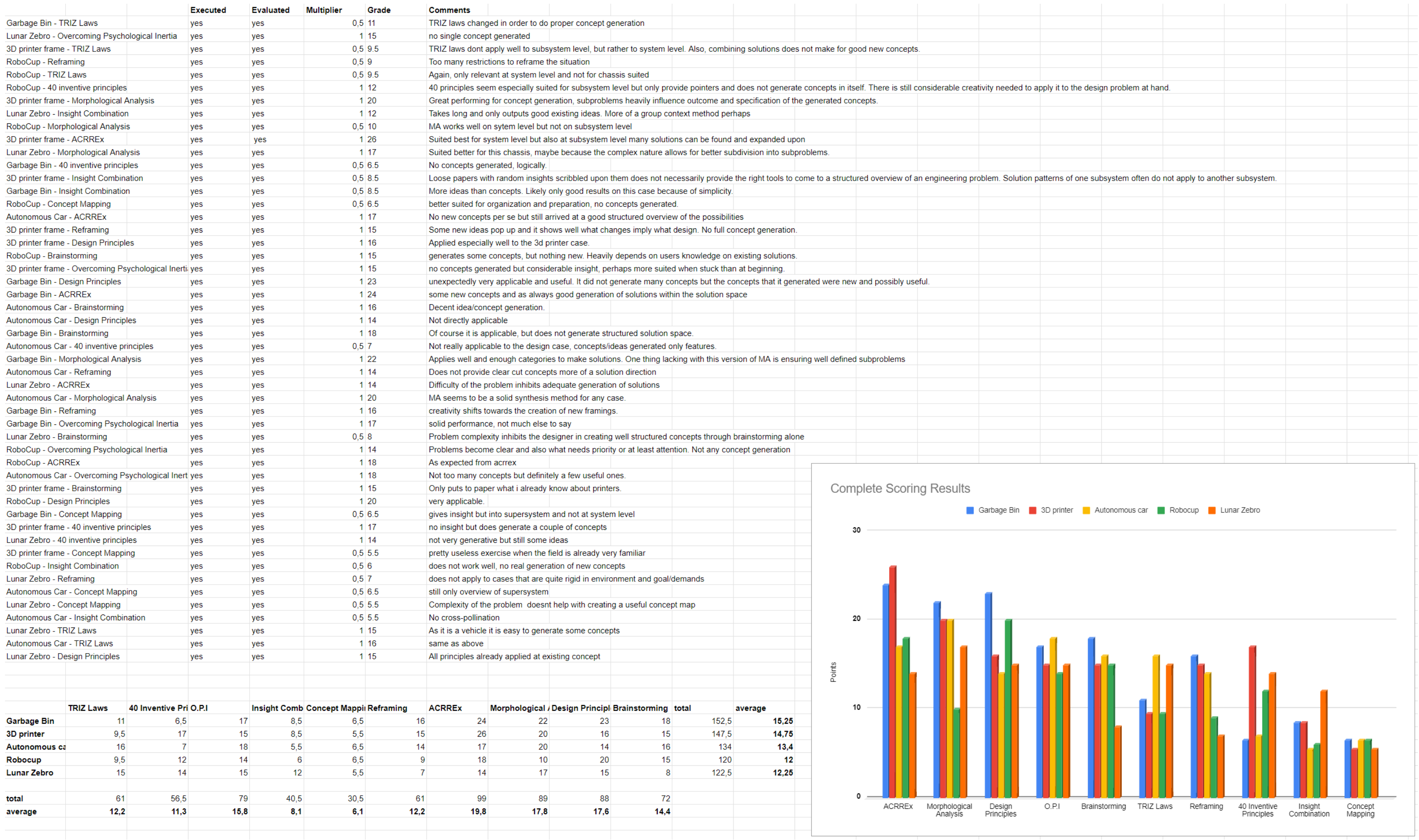
A better version of this research would contain a multitude of people performing the same case-method combination independently and evaluating their results. If done with enough people and on enough cases and methods, a true consensus could be created on the performance of the various design methods. Also, the difference between performing methods with a groups of various sizes would be an interesting field of exploration.

For example, brainstorming is a method that would benefit a lot from being performed by multiple people. It would be easier to hook on to each other's ideas and expand them. However, there must be a certain point where adding more people does not necessarily generate more or better ideas. Similarly, the other design methods will also have an ideal amount of people. Going past the ideal amount would mean that the time and energy of the extra people would be better used working on different aspects of the overall design problem.

Nevertheless, also without further research the outcome of this research can reap its benefits. Many engineers are familiar with technical pocket guides, or formula booklets aiding them by allowing them to quickly find the information they need. Comparably, a guide booklet could be made containing short yet effective descriptions of design methods. Accessible information on how and when to use them could be very useful when feeling stuck. Not only synthesis methods but also analysis tools could have their own sections to make the booklet as complete as possible.

Appendix A

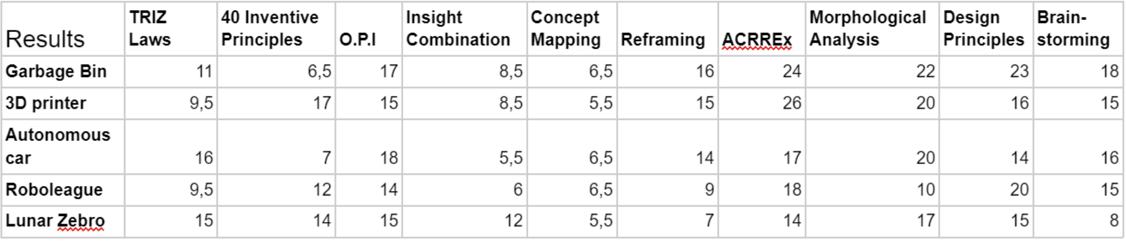
Appendix



	Executed	Evaluated	Multiplier	Grade	Comments
Garbage Bin - TRIZ Laws	yes	yes	0,5	11	TRIZ laws changed in order to do proper concept generation
Lunar Zebro - Overcoming Psychological Inertia	yes	yes	1	15	no single concept generated
3D printer frame - TRIZ Laws	yes	yes	0,5	9.5	TRIZ laws dont apply well to subsystem level, but rather to system level. Also, combining solutions does not make for good new concepts.
RoboCup - Reframing	yes	yes	0,5	9	Too many restrictions to reframe the situation
RoboCup - TRIZ Laws	yes	yes	0,5	9.5	Again, only relevant at system level and not for chassis suited
RoboCup - 40 inventive principles	yes	yes	1	12	40 principles seem especially suited for subsystem level but only provide pointers and does not generate concepts in itself. There is still considerable creativity needed to apply it to the design problem at hand.
3D printer frame - Morphological Analysis	yes	yes	1	20	Great performing for concept generation, subproblems heavily influence outcome and specification of the generated concepts.
Lunar Zebro - Insight Combination	yes	yes	1	12	Takes long and only outputs good existing ideas. More of a group context method perhaps
RoboCup - Morphological Analysis	yes	yes	0,5	10	MA works well on sytem level but not on subsystem level
3D printer frame - ACRREx	yes	yes	1	26	Suited best for system level but also at subsystem level many solutions can be found and expanded upon
Lunar Zebro - Morphological Analysis	yes	yes	1	17	Suited better for this chassis, maybe because the complex nature allows for better subdivision into subproblems.
Garbage Bin - 40 inventive principles	yes	yes	0,5	6.5	No concepts generated, logically.
3D printer frame - Insight Combination	yes	yes	0,5	8.5	Loose papers with random insights scribbled upon them does not necessarily provide the right tools to come to a structured overview of an engineering problem. Solution patterns of one subsystem often do not apply to another subsystem.
Garbage Bin - Insight Combination	yes	yes	0,5	8.5	More ideas than concepts. Likely only good results on this case because of simplicity.
RoboCup - Concept Mapping	yes	yes	0,5	6.5	better suited for organization and preparation, no concepts generated.
Autonomous Car - ACRREx	yes	yes	1	17	No new concepts per se but still arrived at a good structured overview of the possibilities
3D printer frame - Reframing	yes	yes	1	15	Some new ideas pop up and it shows well what changes imply what design. No full concept generation.
3D printer frame - Design Principles	yes	yes	1	16	Applied especially well to the 3d printer case.
RoboCup - Brainstorming	yes	yes	1	15	generates some concepts, but nothing new. Heavily depends on users knowledge on existing solutions.
3D printer frame - Overcoming Psychological Inerti	yes	yes	1	15	no concepts generated but considerable insight, perhaps more suited when stuck than at beginning.
Garbage Bin - Design Principles	yes	yes	1	23	unexpectedly very applicable and useful. It did not generate many concepts but the concepts that it generated were new and possibly useful.
Garbage Bin - ACRREx	yes	yes	1	24	some new concepts and as always good generation of solutions within the solution space
Autonomous Car - Brainstorming	yes	yes	1	16	Decent idea/concept generation.
Autonomous Car - Design Principles	yes	yes	1	14	Not directly applicable
Garbage Bin - Brainstorming	yes	yes	1	18	Of course it is applicable, but does not generate structured solution space.
Autonomous Car - 40 inventive principles	yes	yes	0,5	7	Not really applicable to the design case, concepts/ideas generated only features.
Garbage Bin - Morphological Analysis	yes	yes	1	22	Applies well and enough categories to make solutions. One thing lacking with this version of MA is ensuring well defined subproblems
Autonomous Car - Reframing	yes	yes	1	14	Does not provide clear cut concepts more of a solution direction
Lunar Zebro - ACRREx	yes	yes	1	14	Difficulty of the problem inhibits adequate generation of solutions
Autonomous Car - Morphological Analysis	yes	yes	1	20	MA seems to be a solid synthesis method for any case.
Garbage Bin - Reframing	yes	yes	1	16	creativity shifts towards the creation of new framings.
Garbage Bin - Overcoming Psychological Inertia	yes	yes	1	17	solid performance, not much else to say
Lunar Zebro - Brainstorming	yes	yes	0,5	8	Problem complexity inhibits the designer in creating well structured concepts through brainstorming alone
RoboCup - Overcoming Psychological Inertia	yes	yes	1	14	Problems become clear and also what needs priority or at least attention. Not any concept generation
RoboCup - ACRREx	yes	yes	1	18	As expected from acrrex
Autonomous Car - Overcoming Psychological Inert	yes	yes	1	18	Not too many concepts but definitely a few useful ones.
3D printer frame - Brainstorming	yes	yes	1	15	Only puts to paper what i already know about printers.
RoboCup - Design Principles	yes	yes	1	20	very applicable.
Garbage Bin - Concept Mapping	yes	yes	0,5	6.5	gives insight but into supersystem and not at system level
3D printer frame - 40 inventive principles	yes	yes	1	17	no insight but does generate a couple of concepts
Lunar Zebro - 40 inventive principles	yes	yes	1	14	not very generative but still some ideas
3D printer frame - Concept Mapping	yes	yes	0,5	5.5	pretty useless exercise when the field is already very familiar
RoboCup - Insight Combination	yes	yes	0,5	6	does not work well, no real generation of new concepts
Lunar Zebro - Reframing	yes	yes	0,5	7	does not apply to cases that are quite rigid in environment and goal/demands
Autonomous Car - Concept Mapping	yes	yes	0,5	6.5	still only overview of supersystem
Lunar Zebro - Concept Mapping	yes	yes	0,5	5.5	Complexity of the problem doesnt help with creating a useful concept map
Autonomous Car - Insight Combination	yes	yes	0,5	5.5	No cross-pollination
Lunar Zebro - TRIZ Laws	yes	yes	1	15	As it is a vehicle it is easy to generate some concepts
Autonomous Car - TRIZ Laws	yes	yes	1	16	same as above
Lunar Zebro - Design Principles	yes	yes	1	15	All principles already applied at existing concept

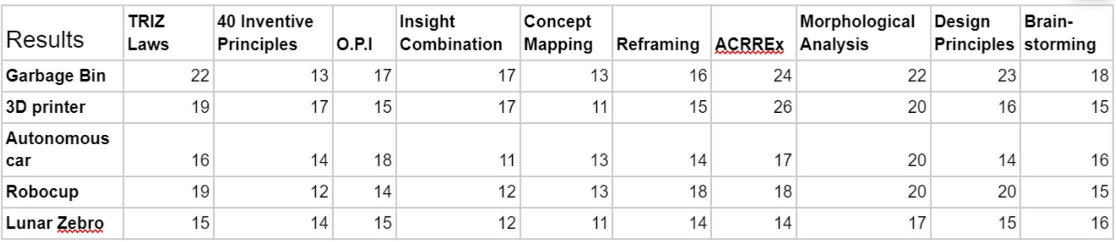
	TRIZ Laws	40 Inventive Pri	O.P.I	Insight Comb	Concept Mappi	Reframing	ACRREx	Morphological /	Design Principl	Brainstorming	total	average
Garbage Bin	11	6,5	17	8,5	6,5	16	24	22	23	18	152,5	**15,25**
3D printer	9,5	17	15	8,5	5,5	15	26	20	16	15	147,5	**14,75**
Autonomous ca	16	7	18	5,5	6,5	14	17	20	14	16	134	**13,4**
Robocup	9,5	12	14	6	6,5	9	18	10	20	15	120	**12**
Lunar Zebro	15	14	15	12	5,5	7	14	17	15	8	122,5	**12,25**
total	61	56,5	79	40,5	30,5	61	99	89	88	72		
average	**12,2**	**11,3**	**15,8**	**8,1**	**6,1**	**12,2**	**19,8**	**17,8**	**17,6**	**14,4**		

Figure A.1: An overview of the raw data.



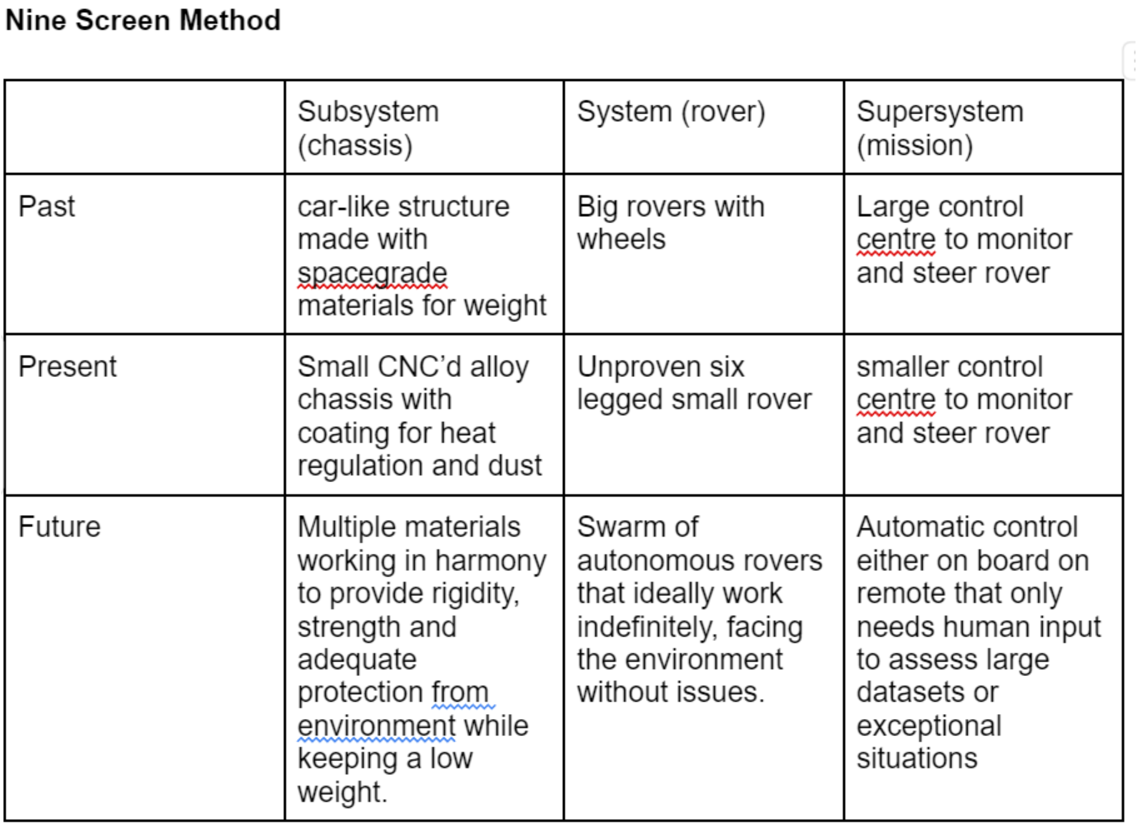
Results	TRIZ Laws	40 Inventive Principles	O.P.I	Insight Combination	Concept Mapping	Reframing	ACRREx	Morphological Analysis	Design Principles	Brain-storming
Garbage Bin	11	6,5	17	8,5	6,5	16	24	22	23	18
3D printer	9,5	17	15	8,5	5,5	15	26	20	16	15
Autonomous car	16	7	18	5,5	6,5	14	17	20	14	16
Roboleague	9,5	12	14	6	6,5	9	18	10	20	15
Lunar Zebro	15	14	15	12	5,5	7	14	17	15	8

Figure A.2: A table with all of the scores.



Results	TRIZ Laws	40 Inventive Principles	O.P.I	Insight Combination	Concept Mapping	Reframing	ACRREx	Morphological Analysis	Design Principles	Brain-storming
Garbage Bin	22	13	17	17	13	16	24	22	23	18
3D printer	19	17	15	17	11	15	26	20	16	15
Autonomous car	16	14	18	11	13	14	17	20	14	16
Robocup	19	12	14	12	13	18	18	20	20	15
Lunar Zebro	15	14	15	12	11	14	14	17	15	16

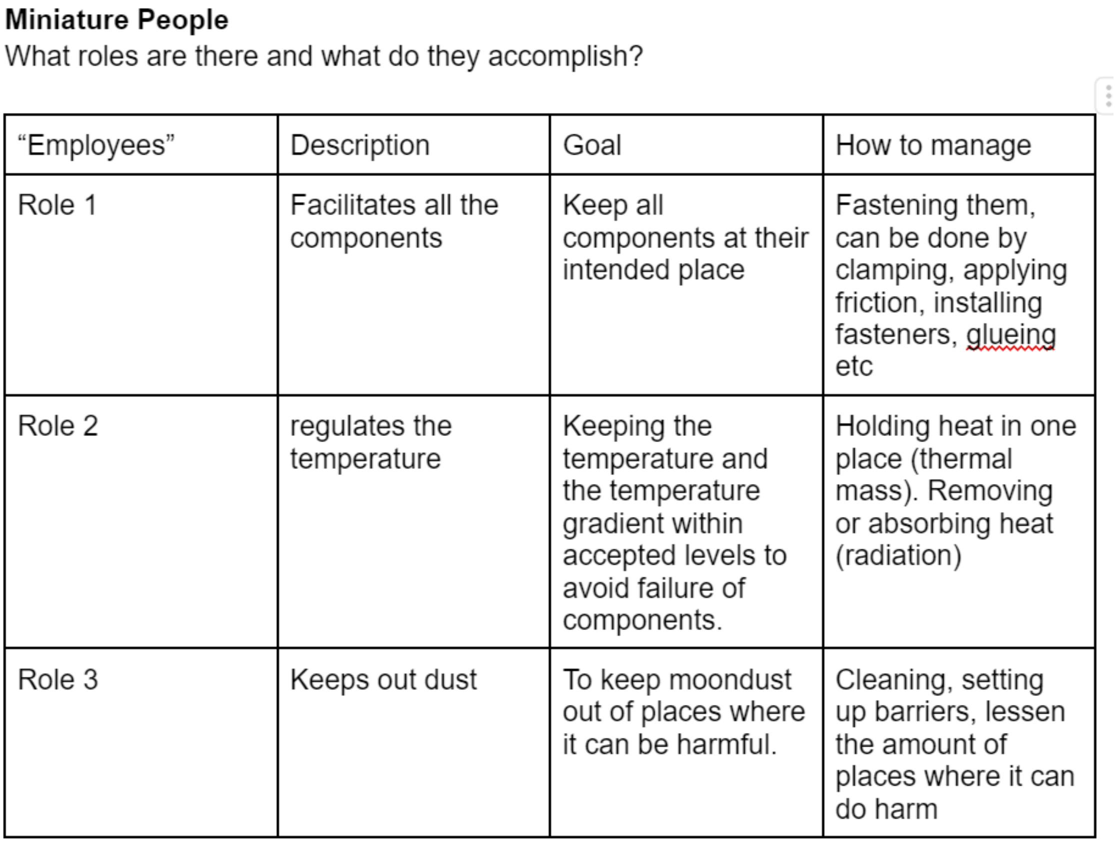
Figure A.3: A table with all of the scores without use of the multiplier.



Nine Screen Method

	Subsystem (chassis)	System (rover)	Supersystem (mission)
Past	car-like structure made with spacegrade materials for weight	Big rovers with wheels	Large control centre to monitor and steer rover
Present	Small CNC'd alloy chassis with coating for heat regulation and dust	Unproven six legged small rover	smaller control centre to monitor and steer rover
Future	Multiple materials working in harmony to provide rigidity, strength and adequate protection from environment while keeping a low weight.	Swarm of autonomous rovers that ideally work indefinitely, facing the environment without issues.	Automatic control either on board on remote that only needs human input to assess large datasets or exceptional situations

Figure A.4: First part of OPI applied to the Lunar Zebro.

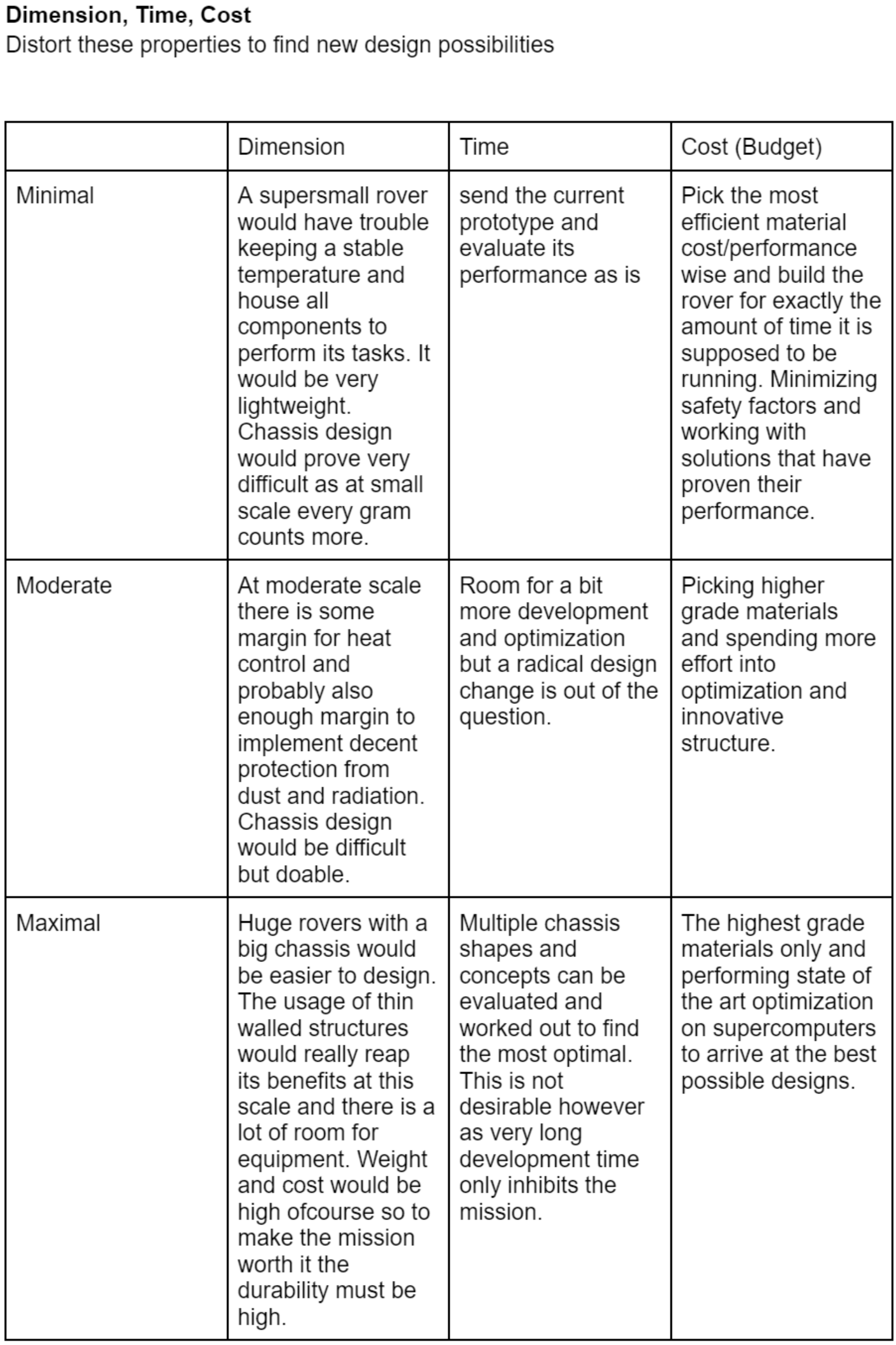


Miniature People

What roles are there and what do they accomplish?

"Employees"	Description	Goal	How to manage
Role 1	Facilitates all the components	Keep all components at their intended place	Fastening them, can be done by clamping, applying friction, installing fasteners, glueing etc
Role 2	regulates the temperature	Keeping the temperature and the temperature gradient within accepted levels to avoid failure of components.	Holding heat in one place (thermal mass). Removing or absorbing heat (radiation)
Role 3	Keeps out dust	To keep moondust out of places where it can be harmful.	Cleaning, setting up barriers, lessen the amount of places where it can do harm

Figure A.5: Second part of OPI applied to the Lunar Zebro.



Dimension, Time, Cost
Distort these properties to find new design possibilities

	Dimension	Time	Cost (Budget)
Minimal	A supersmall rover would have trouble keeping a stable temperature and house all components to perform its tasks. It would be very lightweight. Chassis design would prove very difficult as at small scale every gram counts more.	send the current prototype and evaluate its performance as is	Pick the most efficient material cost/performance wise and build the rover for exactly the amount of time it is supposed to be running. Minimizing safety factors and working with solutions that have proven their performance.
Moderate	At moderate scale there is some margin for heat control and probably also enough margin to implement decent protection from dust and radiation. Chassis design would be difficult but doable.	Room for a bit more development and optimization but a radical design change is out of the question.	Picking higher grade materials and spending more effort into optimization and innovative structure.
Maximal	Huge rovers with a big chassis would be easier to design. The usage of thin walled structures would really reap its benefits at this scale and there is a lot of room for equipment. Weight and cost would be high ofcourse so to make the mission worth it the durability must be high.	Multiple chassis shapes and concepts can be evaluated and worked out to find the most optimal. This is not desirable however as very long development time only inhibits the mission.	The highest grade materials only and performing state of the art optimization on supercomputers to arrive at the best possible designs.

Figure A.6: Third and last part of OPI applied to the Lunar Zebro.

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