UNIVERSITY OF TWENTE
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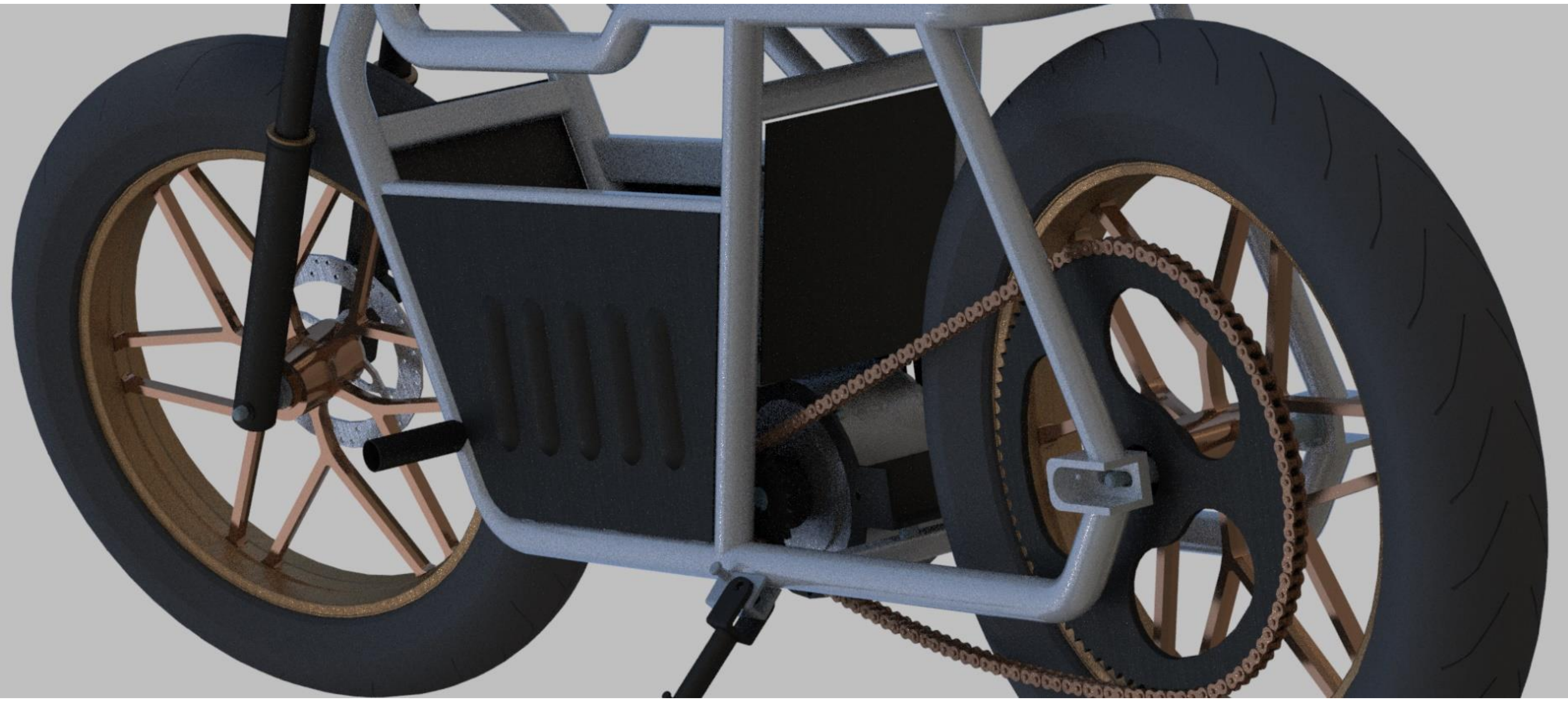
The design of an economic electric motorbike for urban commuting in the Netherlands



Describing a design method that implements axiomatic design and is tailored to overcome the challenges of electric motorbike design.

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Industrial design and Engineering

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Preface

This thesis is part of finalizing the Industrial Design and Engineering master program with specialty track, Management of Product Development (MoPD), at the University of Twente under supervision of Dr.Ir. D. Lutters. This research project was initiated due to the interest of the author, Joel Kopinsky, in the design of electric motorcycles and the believe that electric motorcycles are a clean form of urban transport with a great future potential.

Motorcycle design projects, although multidisciplinary in character, are in practice often led by industrial designers with specialized skills in motorcycle design. This study describes a method for designing motorcycles and integrating the multidisciplinary design efforts into a streamlined process.

The aim of this project is to design an electric motorbike that is affordable and suitable for commuting in the Netherlands. This project explores the challenges to overcome to design an electric motorbike that is economic and has the operational range such that it is suitable for commuting in the Netherlands.

Abstract

There are several factors that negatively affect the adoption of EV (Electric vehicle) technology. In general, the major factors are charging station availability, purchasing cost and range anxiety. For low-powered electric motorcycles specifically, the most noteworthy are range anxiety and purchase cost since charging of electric e-motorcycles is mostly done with standard power outlets. It is therefore assumed that if the operating range of electric motorcycles were increased and the purchasing cost reduced, adoption rate of electric motorcycles would increase rapidly. The problem with this statement and fundamental to EV technology is that the operating range is dependent on battery size and battery size determines a large portion of the purchasing cost of the vehicle. In short, solving the range issue without increasing the purchasing cost is difficult.

This thesis documents a design process tailored to e-motorcycle design and aimed at designing for low cost, high efficiency, simplicity and manufacturability. This process is focused on requirements management to facilitate easy decision making in the conceptual design phase of the project. Furthermore, modeling and analysis tools are used to verify design decisions against motorcycle performance criteria and constraints, thereby determining whether requirements are successfully met.

The strategy behind the development of the process was to start with understanding the system to be designed; then to identify the challenges of the system on the design process and selecting tools to overcome these challenges.

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1 Introduction

'The introduction chapter elaborates on the project context, the target group, design objective and defines the problem addressed through this project. Furthermore, the project's objectives, scope and relevance are discussed.

1.1 Background

The Netherlands, with 1.3 cycles per capita, can be considered the number one cycling country in the World [1]. This shows that the Dutch people understand and embrace the benefits of bicycles. Although the many benefits of bicycles, there are disadvantages. One of these disadvantages is that traveling of larger distances becomes inefficient and uncomfortable. According to the Central Bureau of Statistics in the Netherlands, the average home-to-work distance in 2016 was 22.7 kilometers [2]. Cycling approximately 45 kilometers per day seems quite hard for the average cyclist. According to the ANWB, a distance to travel of 7.5 km is considered comfortable on a normal bicycle [3].The next step up from a human powered bicycle is the electric-assist bicycle. The benefit of this bicycle is especially the increased range of comfortable operation. According to the ANWB, the electric bicycle allows for a comfortable range of operation of 15 kilometers [3]. If this is compared to the average home-to-work distance in the Netherlands, it is evident that an electric bicycle is not the most attractive alternative to travel to work for the average cyclist. Furthermore, a significant disadvantage of an electric bicycle is the price tag (starting around 1500-1800 Euro). Electric bicycles can cost as much as a combustion engine scooter or moped which has practically an unlimited operation radius. One step up from the electric bicycle is the electric scooter or moped. According to ANWB, six electric scooter brands on the market were tested and evaluated, of which the results were featured in the popular ANWB member magazine "De Kampioen". The evaluation concluded that the prizes are still too high compared to combustion engine alternatives, and that the range of operation is still too low with a feasible home-to-work distance of 15 kilometers (this comes down to 30 kilometers on a full charge) [3].

The city of Amsterdam has introduced an environmental zone which prevents the use of scooters and mopeds produced up to the year 2010 [4]. These legislations are likely to be adopted by other densely populated cities in the Netherlands. This gives incentives for motorcyclists to invest in an electric motorbike.

Target group:

Provided with the aforementioned information, it was decided to focus on the Dutch commuter who needs/wants an electric alternative to combustion engine scooters/mopeds, that is economical and has enough operational range to travel from home to work and back.

Design objective:

Given the shortcomings of current electric scooters or mopeds in terms of price and operating range, the following design objective was formulated:

The design objective of this project is to design an electric motorbike which is affordable and has enough operating range for the average Dutch home-to-work commuter. Hereby the price should be as low as possible and the operating range of the vehicle enough to travel the average work-to-home distance at least twice.

1.2 Problem definition

The design objective of designing an electric motorbike where operating range is to be as large as possible and cost is to be as low as possible contains a contradiction between constraints whereby optimization is required. This statement is based on the following:

- There is a positive correlation between the increase of battery capacity and the operational range
- There is a positive correlation between the increase of battery capacity and the cost of the vehicle

This indicates that an increase in operational range of the EV will most likely lead to an increase in the cost. Furthermore, several aspects besides battery capacity influence the cost and the operating range of the vehicle. Also, an electric motorcycle is a system of mechanical performance which includes several system and sub-system functions to be fulfilled. It is therefore that scrupulous attention is required from the designer to understand the effect of design decisions on the cost and operating range and on the high-level system functions corresponding to the intended use and the sub-system functions required to fulfill these high-level functions.

Problem definition:

"An electric motorcycle is to be designed and optimized under two contradicting constraints, namely cost and operating range. Hereby an optimized design is to be created whereby the effect of design decisions on system functions on multiple levels of system hierarchy is unknown."

To effectively address the problem and achieve the project's objective, the following research questions are formulated:

1. What are the parts that a motorcycle is build out of and what are their functions and the relation between these functions? How does electric powertrain technology change the traditional motorcycle?
2. How does operating range affect the cost of the motorcycle, is this the most dominant factor? Which other factors are dominant in determining the cost of the motorcycle?
3. What design tools/principles are required to design motorcycles?
4. How can a motorbike design be verified and when is it a successful design?

1.3 Project objectives, research relevance and scope

Project objectives and relevance:

The objective of this project is to determine a method suitable for electric motorcycle design while designing an e- motorbike for commuting. Although electric motorcycles are not new and the industry is relatively mature and given the fact that a lot of companies develop motorcycles, there is relatively few literatures on motorcycle design online, whereby the top-level design, is considered. This is simply because research of commercial companies is not published. Most research is aimed at very specific aspects within motorcycle related technology/functionality and does not consider the bigger development picture.

Electric motorbike design is upcoming in the motorcycle industry and startup companies are especially addressing the low-power motorcycle segments. Because the powertrain parts of an electric vehicle are much simpler and are widely commercially available, startup companies with some inhouse engineering knowledge can develop these vehicles. However, there is more to motorcycle design than putting some parts together. Therefore, documenting the design process for the design of an affordable electric motorbike with a focus on operational range can help developers by identifying the important aspects of electric motorbike design and the challenges that are inherent to the technology. Hereby the development of low-powered electric vehicles can be supported, and a contribution is done to the transitioning to clean electric vehicles.

Project Scope:

This project focuses on determining and implementing a method that is repeatable and can be used for electric motorbike design projects in the future. Motorcycle manufacturers primarily design the chassis and body parts of the motorbike, whereby all other parts are usually OEM parts. Based on the intended purpose of the motorbike, a specific configuration of motorcycle and its parts are designed. A motorcycle development project therefore consists of a lot of selecting existing parts and putting them together to achieve a specific motorcycle configuration intended for a specific use. This configuration of parts is held together by the chassis of the motorbike, which determines practically every dynamic characteristic of the motorbike. It is for this reason that the scope of this project is limited to the chassis (frame) design whereby the other parts are selected from OEM suppliers. Besides the chassis, the electric powertrain is designed to suit the intended purpose of the motorbike.

1.4 Project workflow

This paragraph describes the workflow throughout the project and aims at documenting the approach throughout the different phases of the project. This does not document the design method used for the design of the motorcycle.

Every design project starts with a target user, which in this project is the commuter motorcyclist who drives low powered motorbikes in the city. Designing motorcycles for a specific user/use requires a lot of knowledge about the functions and behavior of the product. For this reason and to answer the first research question, the project is started by conducting literature research on motorcycle operation, functionality, parts, etc.

- Literature research was conducted on motorcycle structures, part functionality, electric powertrain technology, motorcycle dynamics and characteristics etc.

Motorcycles are complicated products which requires multi-disciplinary teams for successful development. Given the complexity of the product it seems obvious that an industrial designer who often leads motorcycle development projects, must own a significant amount of product specific knowledge, i.e. knowledge of motorcycles. To gain knowledge of the motorcycle domain, it was decided to kickoff this project with a literature study on motorcycles, the principles of their operations, the functions required during their use and the physical components that fulfill these functions. Furthermore, research was conducted on the design challenges that designers face in realizing motorcycle designs. Finally, efforts were conducted to acquire a certain level of empathy for the motorcyclists, in this case specifically the commuter motorcyclist, with the aim of enhancing the ability to come up with creative solutions that address actual needs of the commuter motorcyclist.

- Formulation of design problem and research questions
- Determination of the design approach and the design method to be used.

With a lack of experience in motorcycle design, it is crucial for the author to identify the design tasks which need to be completed to ensure a successful motorcycle design. Furthermore, research was conducted on the available tools which can facilitate effective execution of the tasks by the designer. With this information and through reasoning, a suitable method, tailored to motorcycle design, was formulated. In deciding on how to approach the design of the motorcycle, special focus was on documenting information of the design and the rationale behind it.

- Designing the motorbike using the design methods identified.

During this phase, the design method is executed whereby product design information is generated and documented.

- Project evaluation, discussion and conclusion

During this phase of the project, the design effort is evaluated, verified and discussed. Hereby the used method will be evaluated, and the design verified against its requirements. The advantages and shortcomings of the method will be highlighted. Based on the evaluation, recommendations for further improvement of the method will be done.

Part 1: Literature review, design approach and the design method

2 Motorcycle topology and chassis design considerations

Motorcycles are systems of compromise in which many tradeoffs are made to realize a machine that serves a specific purpose. It is the opinion of the author that before attempting to improve and design relatively complex systems such as motorcycles, designers should fully understand the properties and dynamics of these systems to fully understand the challenges of designing these systems and the impact of design decisions on overall performance. This chapter is aimed at documenting research findings regarding motorcycle functions, parts, motorcycle nomenclature and motorcycle dynamics.

2.1 Motorcycle uses and main functions

Motorcycles are two-wheeled motor vehicles that can serve several purposes in terms of their type of application. As illustrated by Figure 1, motorcycles serve different purposes i.e., they are used for racing, long distance touring, commuting, off-road riding, etc. Depending on the type of use, motorcycles have different styles, constructions and geometry, and they are engineered for specific handling characteristics and performance. Understanding the parameters which influence motorcycle handling and performance are crucial to design engineers to effectively design for the intended type of use and to satisfy user requirements. Before discussing the aspects of handling and performance, the main functions of a motorcycle, along with the parts that fulfill these functions, are identified.

Figure 1: Different motorcycle applications

The main functions of motorcycle operation are acceleration, steering and braking. These functions are shared by all motorcycles independent of the type of use and are fulfilled by part-assemblies. The main functions can be broken down into sub-functions, whereby the individual parts that fulfill these functions are of lower hierarchy and fulfill one specific lower-level function. There are also auxiliary functions, which support the main functions of the motorcycle. Figure 2. Illustrates the three main functions of a motorcycle and the components responsible for executing these functions.

<<Main_function>> **Acceleration**	<<Main_function>> **Steering**	<<Main_function>> **Braking**
parts	***parts***	***parts***
Powertrain : The total of parts responsible for generating and delivering power to the road surface. *Tires: The front tire enabling rolling* *Frame: Support all parts and loads*	**Steering assembly**: The total of parts responsible for steering **TIres**: Transfering steering forces to the road *Frame: Support all parts and loads*	**Braking system**: The total of parts responsible for braking **TIres**: Transfering braking force *Frame: Support all parts and loads*

Figure 2: Motorcycle main functions with corresponding parts

Motorcycle motion

Motorcycle motion can be categorized by linear and angular motion. Linear motion can be in the forward, vertical and sideways direction. Motion in the forward direction is a result of acceleration, motion in the vertical direction is a result of road undulation and hills, and movement in the sideways direction can be a result of sidewinds.

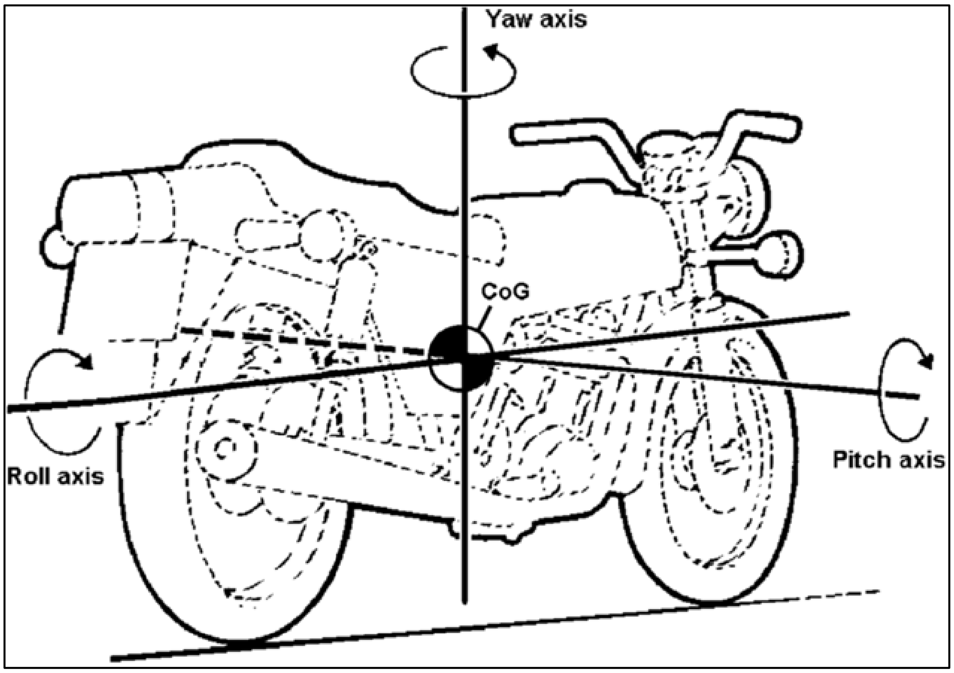

Figure 3: Motorcycle motion: Roll, Yaw, Pitch

Figure 3 illustrates the three axes among which angular motion takes place [5]. The three options of angular motion are defined as roll, yaw and pitch. Roll is rotation among the roll axis and is required during steering of the motorcycle. Pitch is rotation among the pitch axis and is a motion resulting from weight transfer from the rear to the front and vice versa, as a result of braking and acceleration respectively. Yaw is a rotation among the yaw axis and is experienced as sideways sliding of the rear tire, for example due to sidewinds or drifting [5]. The most important aspects in motorcycle dynamic behavior are stability, balance, steerability and road holding, which all together are referred to as motorcycle handling [5].

2.2 Motorcycle handling

Motorcycle handling is defined as the way the motorcycle reacts to the rider's input. This especially considers aspects like steering and riding stability [5]. In rider's language and less specific, this is often described as, how the motorcycle "feels". Motorcycle handling is mostly determined by motorcycle geometry. Motorcycle geometry is defined as the set of key dimensions that define a motorcycle's configuration. In the remainder of this paragraph, the key dimensions that make up a motorcycle's geometry are defined and explained. Figure 4. illustrates the important dimensions that make up a motorcycle's geometry.

Rake angle is defined as the distance between the contact patch of the front tire and the point of intersection on the road where the steering axis crosses it. Ground trail is positive when the point of intersection between the steering axis and the road surface, is in front of the point of contact between the tire and the road surface. Positive ground trail contributes to straight-line-feel which is a result of directional stability.

Wheelbase is defined as the horizontal distance between the front and the rear wheel axle. Wheelbase influences steering and directional stability. A short wheelbase allows the rider to make sharper turns due to a smaller turning radius. A longer wheelbase positively influences directional stability. Based on the abovementioned, it can be concluded that a compromise must be made between directional stability and the turning radius of the motorcycle. Also, wheelbase influences the amount of space available between the tires for components, whereby a large wheelbase allows for more space to install parts between the tires or provide cargo space.

Ground trail is defined as the distance between the contact patch of the front tire and the point of intersection on the road where the steering axis crosses it. Ground trail is positive when the point of intersection between the steering axis and the road surface, is in front of the point of contact between the tire and the road surface. Positive ground trail contributes to straight-line-feel which is a result of directional stability.

Steering

Steering of a motorcycle is a complicated sequence of actions conducted by the user. Most of the actions are unconscious and are a result of unconsciously mastering motoric skills and balance. It is not of relevance to this project to describe the process of steering in detail however, it is important to address the design consideration regarding a low-powered motorcycle's steering performance. The most important factors that influence motorcycle steering are wheelbase of the motorcycle, center of gravity and the rake angle [5].

Since this project considers a low-powered motorbike for urban commuting, its speed is limited, and this type of use requires being able to steer in tight spaces thus referring to a small turning radius. This can be achieved by selecting the right wheelbase. For urban motorbikes the wheelbase is around 1280-1400mm [5]. A wheelbase that is smaller might result in stability issues which out of safety reasons should be avoided.

Stability

Motorcycles in static condition are inherently unstable. This is proven by the simple fact that they fall over when stationary and left unsupported. However, when motorcycles are in motion and have a high enough speed, they become stable and remain upright. This stability is a result of gyroscopic forces as result of the moving wheels. The physics behind this phenomenon are explained in literature and are out of the scope of this research. Important to this study are the parameters which influence the stability of the motorbike. These are predominantly the wheelbase, the trail and the tire diameter. It is stated that large tires improve stability at slow speeds because increasing diameter positively influences the gyroscopic forces [5]. Also, a large wheelbase is said to promote stability. A positive value for trail or ground trail improves directional stability and is experience by riders as if the bike maintains a straight line without need for correction at the steering handlebar [5].

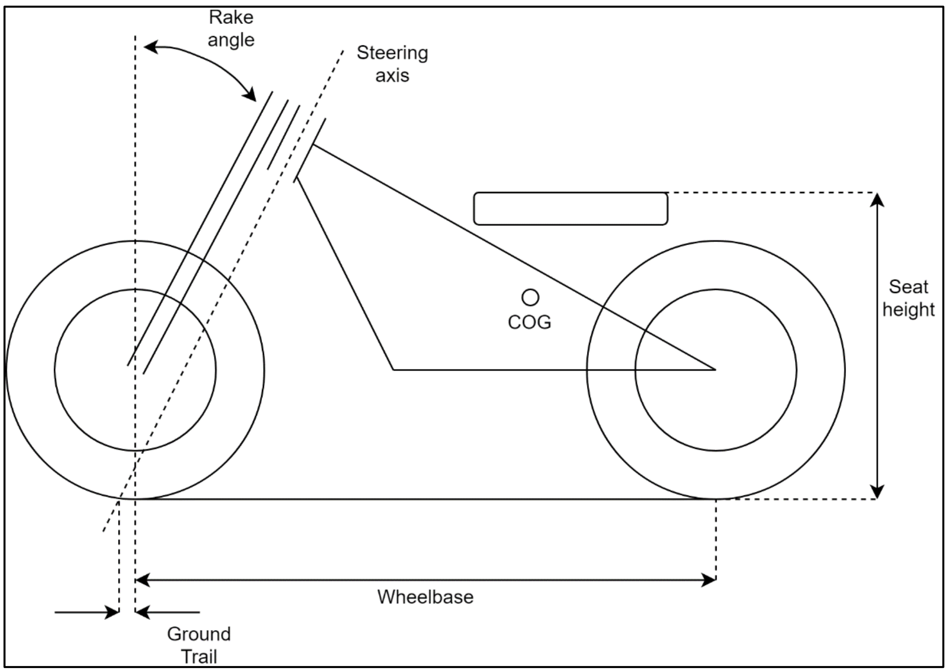

Figure 4: Geometric dimensions of a motorcycle

Motorcycle geometry is primarily determined by the frame, thus it’s design and specifications should be carefully matched to its intended use.

2.3 Motorcycle performance

Motorcycle performance in this document is defined by the parameters speed, acceleration, and operational range. The performance of a motorcycle is largely determined by the powertrain. This is limited by the motorcycle's frame, tires, safety and legislation. For electric motorcycles, the aspect of operational range, which is determined and limited by the battery, plays an important role. Motorcycle speed is a performance parameter determined by the powertrain of the vehicle. Vehicles in the L1E category are restricted to a speed of 50km/hr and there are often different license requirements for each vehicle category. Motorcycle acceleration is a performance parameter not subject to legislation and is often limited to the type of use for the motorbike. A racing motorbike often has a much higher acceleration than a scooter for example. Acceleration is also determined by the powertrain and is further discussed in the next chapter. The operational range of the motorbike is determined by the efficiency of the motorbike and the means of energy storage. Combustion engine motorbikes tend to have a superior range compared to electric motorbikes.

2.4 Motorcycle chassis

The motorcycle chassis consist of the frame, the steering assembly and the tires. The motorcycle geometry is defined by frame and thus the frame design is closely related to the intended use of the motorcycle. Frame performance is defined as the frame's ability to maintain the geometric dimension and the relationship between parts. A measure for expressing frame performance is the frame stiffness, which is the frame's ability to resist deformation (thus to maintain design dimensions).

Important factors in achieving frame stiffness are the type of construction (the design of the frame), the materials used and the dimensions of the frame [5].

3 E-motorbike powertrain design considerations

Electric vehicles differ from combustion engine vehicles in that they are propelled by electric powertrains. Electric powertrain design in this work is defined as the effort of carefully determining each of the specifications of the powertrain components to achieve the required performance of the motorcycle over its lifetime. Designing an electric vehicle requires enough knowledge of electric powertrains and their components. This chapter documents the necessary information for designing an electric motorcycle powertrain.

As briefly introduced in chapter 2, motorcycle performance refers to the maximum speed, gradeability, acceleration and operational range of an electric motorcycle, and is mainly determined by the electric powertrain. The electric powertrain consists of an electric motor, a motor drive, a power supply, a transmission and the final drive (the rear wheel and tire).

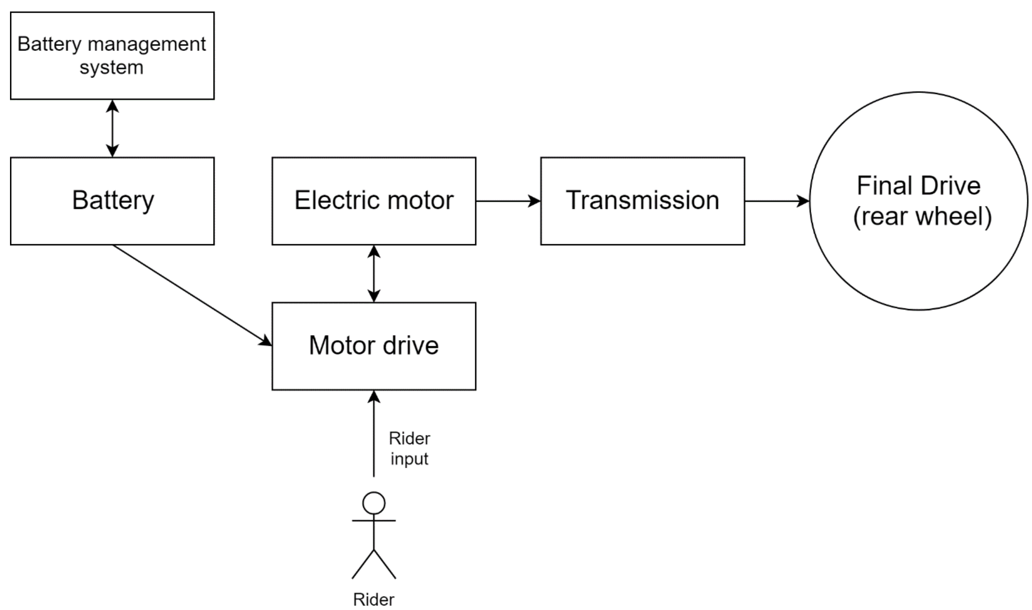

Figure 5: Electric motorcycle powertrain schematic

A major benefit of an electric powertrain is the simplicity of the system in terms of a relatively small number of components. The following paragraphs provide background information on the electric powertrain components.

3.1 Electric motor and motor drives

Electric motors convert electric energy to mechanical energy and provide the transmission with a tractive torque. The energy conversion is controlled by motor drives which provide significant flexibility in control. Electric motors have the benefit that they efficiently operate in a wide speed range which eliminates the need for a multi-geared transmission.

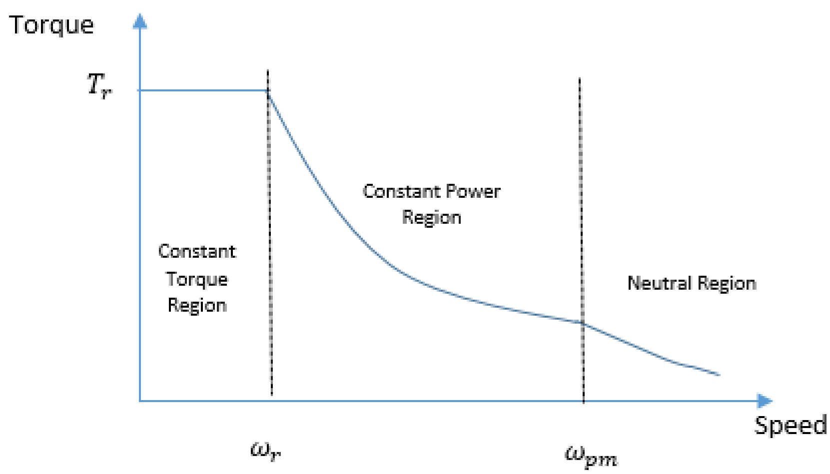

Figure 6: Electric motor envelope

Figure 3.2 illustrates the torque-speed envelope of an electric motor, which shows that during initial acceleration, the motor can deliver maximum torque up until the rated speed. This is referred to as the constant torque region. The motor delivers the rated torque up to the base speed/motor rated speed (the end of the constant torque region). The speed where the motor can deliver rated torque at rated power is referred to as the motor rated speed [6]. The speed range for electric motors for which the rated power can be delivered is large. For this reason, a single speed transmission is considered enough. Most small electric vehicles tend to use brushless DC electric motors, because of their high power to weight ratio, high speed and ease of control. Because the motor operates at higher speeds, the motor can be relatively compact and lightweight. For vehicle applications brushless DC motors can either be designed for mid-drive or hub-drive applications.

Figure 7: Brushless DC motor for mid-drive application

Figure 8: Brushless DC motor for Hub-drive application

Mid-drive brushless DC motors have the motor fixed to the frame, whereby a transmission transfers the motor torque to the final drive (rear-wheel). Hub-drive brushless DC motors have the motor integrated into the wheel and therefore the need for a transmission eliminated. Table 3.1 lists the advantages and disadvantages of both configurations.

BLDC Mid-drive	BLDC Hub-drive
Easily available from many manufacturers	Specialized motor produced by few manufacturers
Positioning freedom	Fixed in the rear or front tire
Can be installed in sprung portion of the motorbike	Contributes to un-sprung mass
Transmission required which increases amount of parts	No transmission required; less parts required
Higher rotational speed, so can be compact	No transmission, high torque required, heavier motor

Table 1: BLDC mid-drive VS Hub-drive

Legislative constraints

European legislation limits the power rating of motorbikes per category. The motorbike to be developed for this project is of the category L1e. This restricts the maximum speed of the motorbike to be 50 km/hr. Also, the motor power is restricted to 4kW nominal continuous power [7].

3.2 Single speed transmission

The function of a motorbike transmission is to transmit the power of the motor to the final drive and convert the torque of the motor to the required torque and speed for the motorcycle's desired acceleration and maximum speed. Motorbike transmissions often referred to as "type of drive", come in 3 types namely: Chain drive, Belt drive and Shaft drive.

3.3.1 Types of chain drives

Chain drives

Chain drives consist of a roller chain and sprockets. Most motorbikes and bicycles are fitted with chain drives because chain drives are reliable and cheap to maintain. Chain drives can withstand high torque applications and are therefore used by almost all high-power motorcycles. Power-loss in chain drives is said to be less than 3%, and thus considered an efficient means of transferring motor power to the final drive [8]. Roller chains are standardized parts, and therefore relatively cheap. Chain drives need alignment between the motor sprocket and the final drive sprocket. Also, chain tensioning is required for optimal operation. Roller chains are cheap to maintain but they require frequent and timely maintenance (cleaning, (de-)greasing). Because of grease on chains, they tend to get dirty and messy.

Chain failure, although uncommon and not likely to occur, it sometimes happens and might cause the rear wheel to lock. This is potentially very dangerous and might cause an accident.

Figure 9: Chain drive

Belt drives

Belt drives use a belt and pulleys to transfer power to the final drive. Belt drives are less common and are mostly used in cruiser motorbikes. It is said that belt drives have a smoother power delivery to the final drive and are therefore so frequently used in cruisers [9]. The power loss in a belt drive is claimed to be around 6 to 9%. The belt drive does not need maintenance; however, the belt is expensive to replace when replacement is required.

Figure 10: Belt drive

Shaft drive

Shaft drives consist of a shaft and gears to transmit power to the final drive. This system is unique for motorcycles and only a few specialized motorcycles use the shaft drive. The shaft drive is an expensive transmission that requires relatively no maintenance. Because of the special nature of this transmission type, it is not further considered in this document.

3.3.2 Torque – speed conversion

To achieve the desired tractive torque and speed at the final drive, the transmission must convert the motor torque and motor speed. This is done by the different diameters of the sprockets/pulleys. Hereby the number of teeth of sprockets/ number of grooves of a pulley are important. The transmission ratio for speed reduction is the ratio of the motor speed and the required final drive speed. Depending on the type of transmission, industry guidelines are used for design and specification. For chain drives, the transmission ratio is determined by the number of sprocket teeth of the driver and driven sprocket. For a belt drive, the transmission ratio is determined by the number of rib slots on the pulleys or the pulley diameters.

The motor power rating, the rotation speed of the motor and the transmission ratio are the primary parameters of interest for transmission design. Based on the type of transmission selected, there are other parameters of interest such as efficiency of the transmission type.

3.3 Power supply

The power supply of an electric motorbike serves two purposes. The first and main purpose is to supply power to the electric motor. The second purpose is to supply power to all other electronics and auxiliary devices. First the main purpose is discussed.

The range of an electric vehicle is determined by the battery capacity/energy capacity of the power supply and the efficiency of the powertrain. The energy required to drive a vehicle over a certain distance depends on the operating conditions and the vehicle parameters. To ensure that an electric motorbike has the intended operational range in real life, it is important that real life driving behavior can be modeled, and associated energy requirements calculated based on this driving behavior. The efficiency of an electric powertrain is easy to determine. This is the combined efficiency of each component of the powertrain. Knowing this only the vehicle parameters should be known. Initially in the design phase, the vehicle mass for example is assumed and later determined based on the sum of the mass of all components.

Important aspects of the design of an electric vehicle power supply are the selection of cell technology and the type of cells used. Cells are connected in series to achieve the voltage rating of the motor. Cells are connected in parallel to achieve the desired discharge current of the motor.

3.4.1 Cell characteristics: Cell voltage, Cell capacity, (dis)charge rate, capacity fade

Lithium ion cells come in various configurations/constructions. The 18650cell is by far the most popular for small electric vehicle applications and is therefore discussed in this paragraph.

Figure 11: 18650 Battery cell

The nominal voltage of 18650 cells is 3.6V and the cell capacity can range from 1600-3500mAh depending on the manufacturer and the specific cell model. The discharge rate of the cell is defined as the rate at which charge in Coulomb is drawn from the cell per unit of time. It should be noted that the discharge rate influences the capacity of the cell. When the current drawn from the battery increased, the cell capacity reduces. For example: when a battery is discharged with a current of 5A, the capacity is 2950mAh, however if the same battery were discharged at a current of 10A, the capacity would be around 2800mAh. These characteristics are determined per cell and are specified by the manufacturer and should be taken into consideration when designing a power supply.

Capacity fade is a phenomenon experienced in li-ion cells whereby the capacity of the cell reduces over time as a result of the discharge currents that the cell has been subject to and the amount of (dis)charge cycles that the cell has had. This characteristic is also specified on manufacturer specification sheets of the cells and should also be considered in the design of a power supply. An example of capacity fade specified on a manufacturer specification sheet is that the cell has a capacity of 75% after 300cycles whereby a discharge current of 15A was common. Furthermore, it should be noted that the larger the discharge current, the larger the capacity fade over time due to the temperatures that the cell is subject to. Although this paragraph discusses the 18650cell, the concept is similar for other li-ion cells. Based on these characteristics it is crucial to understand the cell manufacturing specifications when designing a battery pack.

3.4.2 Battery pack configuration: Pack voltage and pack capacity

The nominal voltage of a li-ion cell is 3.6V and a cell on its own is therefore practically useless for electric vehicle applications. Most electric motors for EV-applications have a voltage of 48V or higher. This in return requires a power supply of 48V of higher. To achieve this voltage, batteries can be connected in series as illustrated by figure 3.8. Hereby the positive anode of the cell is connected to the negative cathode of the next cell and so forth. By connecting cells in series, the voltage is multiplied by the number of cells in series. The current however remains the same. So, when 20 cells are connected in series, the discharge current of all the cells is the same as the discharge current of 1 cell. For this reason, connecting cells in series does not increase the capacity of the battery.

Ones the battery has the required voltage, it must be able to supply the motor current for a specific time, i.e. it must have the battery capacity to operate the motor for the required time. To achieve a specific capacity, battery cells must be connected in parallel configuration whereby the positive anodes of parallel cells are all connected, and the negative cathodes are all connected. Here the voltage between the common connection of anodes and cathodes is equal to the cell voltage of 3.6V. The discharge current however is multiplied by the number of cells in parallel. When designing a battery pack is it thus important that the battery can deliver the current required by the load while optimally utilizing the cells based on their characteristics as specified in the manufacturer's specification.

The design of a battery pack thus comes down to the series-parallel configuration of cells to achieve a certain voltage and capacity to power an electric load for a given amount of time.

3.4 Final drive

The final drive of an electric motorbike is the rear wheel assembly to which the driven end of the transmission is connected. The rear tire as part of the rear wheel assembly transmits the tractive force to the road surface. Hereby the rotational speed and the tractive torque at the rear wheel determine the acceleration and speed of the motorbike. An important parameter of the rear tire is therefore the tire diameter. A large tire diameter requires less rotations of the rear wheel to achieve a specified vehicle speed. For the selection of a tire as part of the powertrain design, the tire size must thus be optimally selected to allow for feasible transmission ratios and enough tractive torque.

4 Design approach

This chapter documents the approach taken to come to a design method suitable for motorcycle design which will then be implemented for the case study of this research design project. An approach refers to a direction or angle taken to perform a task or face a problem. A method is the way in which something is done and refers to a step-by-step set of guidelines that results in solving a problem.

The approach for this design project is mainly based on the following two notions:

1. Good design is not a random result of trial and error and it can be systematically achieved through the implementation of proven methods and principles.
2. A product characteristic attributes dictate the design method suitable for successful synthesis.

Proof of the first notion is given by the acceptance of the axiomatic design principle. An explanation of the second notion is given by comparison of a simple product and a complex product. For example, a method for designing a glass bottle might not be suitable for designing a fighter jet. The reason for this is that the products to be designed share different characteristic attributes, e.g., they differ in complexity, production quantities, number of parts, production cost, quality, level of reliability, market, lifespan, etc., each of which introduces its own challenges for the design of the product. To determine a suitable method for the product to be designed, one must have good insight in the characteristic attributes of the product, i.e., understand the product itself, its use and in which context it is developed. The product then dictates the requirements for the design method to be used.

Once the product is well-understood, the design challenges that come with that type of product must be identified. For example, a disposable plastic cup has, among others, the characteristic attributes: extremely low unit cost; annual production quantities in tens/hundreds of millions, relatively low product complexity, etc. The design challenges here might be to design for high production speed, low material cost, etc. On the other hand, a fighter jet has, among others, the characteristic attributes: extremely complex system; very large number of parts, extremely high cost unit, annual production in the tens or hundreds. The design challenges here might be to design for high level of reliability, to fulfill a very large number of requirements, proper integration of multiple subsystems, technical challenges in achieving the requirements, etc. Once the design challenges are identified, a method suitable for the design effort can be determined/selected to facilitate the designer to overcome these challenges. The method is selected/determined based on the designer needs which are in this case dictated by the product.

To aid in the description of a product, the "product descriptive attribute" (PDA) set has been defined. The PDA set has been defined by the author as a standardized set of characteristic attributes to describe a product to an extent, that a designer can get a good understanding of what the challenges will be during the design effort and can therefore determine a suitable method to overcome these challenges. Figure 3.1 illustrates the approach and how the PDA set is used to come to a method that suits the design effort for the product.

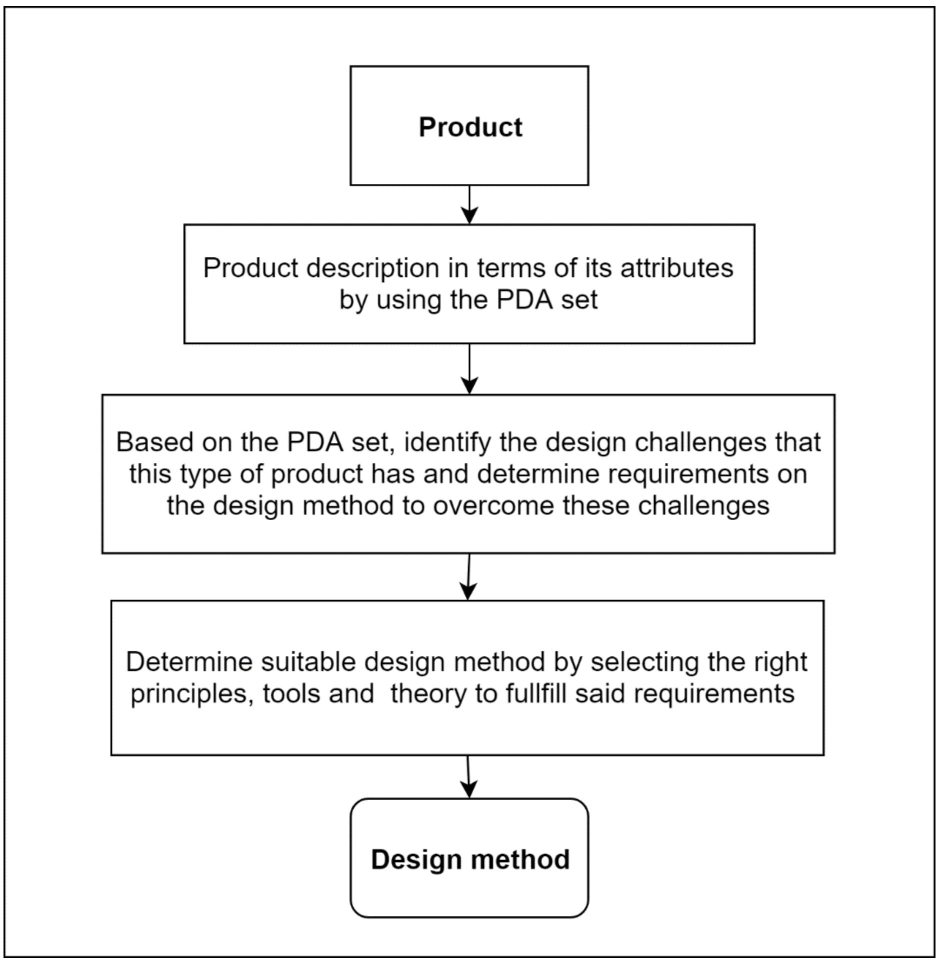

Figure 12: Method- based-on- the- product approach

4.1 Product Descriptive Attribute (PDA) set

In this paragraph the PDA set, as mentioned earlier, is defined.

The PDA set is a set of characteristic attributes used to describe a product's type. The characteristic attributes selected as part of the set and thus used for this design project to determine the challenges of motorcycle design are:

- **Industry/product category**

This characteristic attribute is used to categorize the product in a general sense and to identify designers with a development context in terms of industry and formal product classification. This characteristic can help designers identify to which standards the product must be designed and to which legislation the product will be subject of.

- **Product complexity (Product functions & number of components)**

The amount of product functions and the number of components that perform these functions indicate a level of complexity of a product. There exists a positive correlation between the complexity of a product and the amount of functions that the product fulfills, in that a product is likely to become more complex with an increasing number of functions. Designing a product with a lot of functions requires design engineers to carefully manage each function and the part that must fulfil it, whilst considering the relationship to other parts and functions of the system. This as opposed to a product with one function without any sub-functions where the focus of the design engineer is on only one function and the part/product in its totality that fulfills it. Moreover, multiple functional requirements and constraints need validation during the design effort, which adds to the amount of effort required to design the product.

- **Types of functions and components, type of technology, fields of expertise required**

This characteristic attribute identifies the relevant fields of expertise that the product requires. This is dictated by the product's types of technology which in turn is dictated by the types of functions and thus the types of components that fulfill these functions. For example, if a function requirement would be to "Provide watertight containment of 1liter of water", the technology is much different than, if a functional requirement would be to "Convert electrical energy to mechanical energy". This helps designers identify the technologies involved in a design effort and thus the required fields of expertise and tools that facilitate the design of products with said types of technology.

- **Technological maturity**

This characteristic attribute assesses whether the product to be designed is based on mature technology or on new technology. Hereby identifying uncertainty within the design effort and the availability of previous works conducted.

- **Product quality/reliability, product performance, product lifespan**

This characteristic attribute identifies the required precision in the design engineering effort. Precision here, refers to the accuracy and correctness of requirement specification efforts for a motorbike over its lifespan and to ensure that the requirements are met by the design.

4.2 Describing motorbikes in terms of the PDA set

In this paragraph motorcycles are described in term of their characteristic attributes that together form the type of product under consideration. This is done by first identifying important characteristic attributes that are of importance in the description of the product.

Electric Motorcycle description in terms of characteristic attributes	
Industry/Product category	Single track vehicle/motorcycles
Product complexity	Medium
Product functions	Multiple functions with dependencies
Number of components	50 - 200
Types of components	Electric propulsion, electrical, mechanical-structural
Fields of expertise required	Design, electrical, mechanical, software engineers
Quality/reliability	High
Technological maturity	High
Product lifespan (years)	4-6
Production quantity (annual)	1000s – 10000s (mass production)
Production cost (Euro)	2500-3000
Development time (years)	1-2
Lead time	4 - 6 weeks
Target user	Civilian, commuter
Frequency of use	Daily - intermittent
Type of Human-product interaction	Physical
Importance of aesthetics	High
Retail price (Euro)	3500 - 4500

Figure 13: The PDA set describing the intended motorcycle

The characteristic attributes in Table 4.1, illustrate that electric motorcycles are a product with relatively medium to high complexity and a low retail price. Furthermore, electric motorcycles are made through mass production, whereby cost price should be kept low and quality and reliability must be high. Additionally, electric motorcycles are made up of many parts, which fulfill mechanical, structural and electrical functions. Also, there is a high level of interaction with the user and frequent use, whereby aesthetics is very important to the user. Finally, the lifespan and life expectancy require a durable product.

It must be noted that motorcycles are a product which consist of several subsystems which each fulfill one or several dedicated functions. It is therefore important to consider the sub-systems of a motorcycle and to provide a more detailed description of the sub-systems that make up the motorcycle.

4.3 Identifying design challenges based on the PDA set, provide suggestions to face challenges

The PDA set is defined to identify potential challenges that a certain product type might have based on their characteristic attributes. This paragraph is focused on identifying these challenges which result from the characteristic attributes of motorbikes. Hereby the findings in the previous paragraph are used to determine the challenges of the design effort of this project.

> *Challenges inherent to designing a product with multiple functions (and multiple functional hierarchies) whereby interdependencies exist. Also, challenges inherent to designing a product with many parts, that each must fulfill one or multiple functions. Thus, challenges to a complex product.*

The first challenge is selecting the right FRs that if achieved, the user's needs are addressed. This is a concern of validation that the right product is designed for the target group. The second challenge here is that of designing for fulfillment of multiple FRs and thus managing the process of DP allocation to FRs and maintaining traceability throughout the design effort. The third challenge is to deal with interdependencies between FRs and to make sure that DPs only address one FR and avoid unwanted influences on other FRs.

Requirements on the method: The method must deal with FR identification, FR– DP allocation, FR independence for a complex system.

Suggestion: Axiomatic design principle integrated in the method.

Action: conduct literature research on axiomatic design and evaluate suitability for implementation in motorcycle design.

> *Designing a complex product, concerns the generation of a lot of information. To maintain traceability, information needs to be easily accessible, and information exchange between software platforms should be possible.*

Requirements on method: This introduces the need to use software whereby exchange of information across packages is possible. To cope with this, either an integrated software package such as a PLM software is needed, or a bridge software is needed to establish a means of exchanging information between otherwise incompatible packages.

Suggestion: Use of a software package that is easily available and cheap to manage information and potentially function as bridging software.

Action: Identify and select software that satisfies the requirements stated.

> *Electric motorbikes are of the product category "electric vehicle", which makes kinetic performance essential, energy conversion and efficiency important focus points. For this reason, mathematical analysis and evaluation on vehicle kinetic performance, energy conversion and efficiency are important, and therefore should be possible during the design of the motorcycle. To verify that the designed motorbike's FRs are fulfilled, models are to be developed.*

Requirement: A vehicle kinetic model must therefore be developed to streamline the execution of these analysis and evaluation tasks. Also, the modeling software should be compatible with the other software packages used in the design project to exchange information across these platforms.

> *Electric motorbikes are a product for which aesthetics and style are important. For this reason, the appearance and style of the motorbike must be designed.*

Requirement: The design effort requires aesthetic design and thus requires expression of form giving and ideation.

Suggestion: Use of traditional sketching and CAD to develop an aesthetically pleasing concept that suits the target group.

4.4 General design process considerations

This paragraph states the general activities in terms of design phases that a designer performs to design a product from stakeholder requirements.

Functional analysis and specification

A design project generally starts with a user group and their identified needs. The user is classified as the primary target group and the needs are translated to product functional requirements. The type of use, the product context and the stakeholder specify the constraints. The functional requirements are what is to be realized by the design. The constraints are the boundary conditions in which the design must be realized. To ensure that the designers are designing what the stakeholders require, validation procedures are specified. Validation considers whether the specified functional requirements address the stakeholder's needs and thus if the right product is designed. This refers to the question if the functional requirements address the stakeholder's needs [10]. To ensure that the functional requirements are being fulfilled under the given constraints, requirement verification procedures are specified. Verification considers whether the intended product is designed correctly and thus refers to whether the design fulfills the functional requirements [10]. The complete specification of the requirements and constraints, and the verification and validation procedures are referred to as the requirements specification.

Design synthesis

Once requirements are specified, design parameter allocation can be conducted. In the design synthesis phase DP allocation takes place and the system architecture is developed. Design parameters answer the question "how are the functional requirements of the product fulfilled" [10]. The design parameters and the physical interaction/relationship between them is referred to as the system structure/architecture [10]. The relationship of DPs and their respective FRs, and the tracking thereof throughout the design effort is referred to as traceability [10]. Traceability is important for designers to monitor that the parts designed fulfill their functional requirements and comply with the constraints specified and to do so as the design progresses.

Design evaluation

Design evaluation is conducted during the design and at the end of the design effort. Design evaluation consists primarily of design verification and requires tools to analyze the designed product in reference to its functional requirements and constraints.

4.5 Considering suitability of the axiomatic design principle for motorcycle design

The axiomatic design principle is a concept aimed at establishing a science base for design efforts and to improve design efforts based on logical and rational thought. Axiomatic design is claimed to help designers in structuring and understanding design problems and thus facilitating in the synthesis and analysis of functional requirements, solutions and processes [10]. According to Dr. Nam P. Suh, the developer of the axiomatic design principle, axiomatic design can help designers to be more creative by reducing the random search process often seen in traditional design, thereby minimizing the iterative trial-and-error process and determined the best design for given functional requirements.

4.5.1 Axiomatic design concept

The axiomatic design principle is based on a top down approach whereby user requirements are translated and organized into functional requirements [10]. Functional requirements serve as input and design parameters are defined to satisfy these requirements. The axiomatic design principle can lead a designer to a good design under the condition that the design must satisfy the two axiomatic design axioms, namely the **Independence Axiom** and the **Information Axiom**. An axiom is defined in dictionary as a statement or proposition which is regarded as being established, accepted, or self-evidently true. The Independence Axiom states that in good design the independence of functional requirements is realized. The information axiom states that in good design, the information content is minimized [10].

4.5.2 Axiomatic design framework

Several key concepts are fundamental to the axiomatic design principle, namely the existence of domains, mapping, axioms, theorems, corollaries and decomposition by zigzagging between the domains.

Domains

Axiomatic design is based on the perception that the design space consists of four domains, namely, the customer domain, the functional domain, the physical domain, and the process domain. The relationship between the domains is illustrated by figure 14.

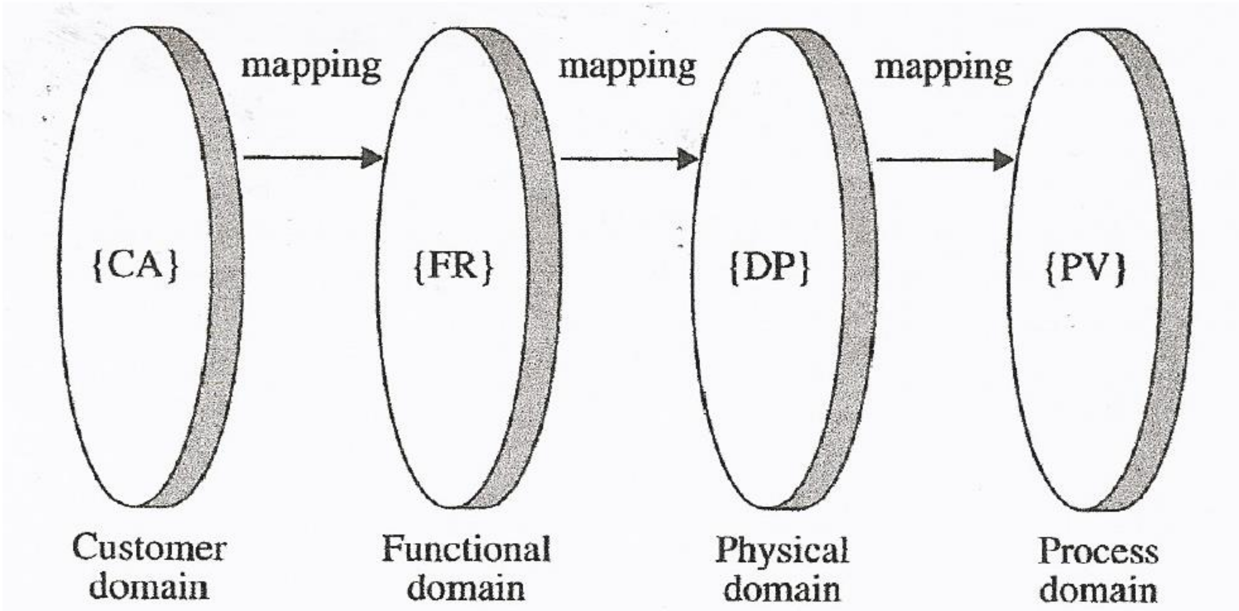

Figure 14: Mapping process according to axiomatic design principle

The domain on the left represents "what designers want to achieve" and the domain on the right "how designers want to achieve the requirements specified in the domain to the left". During the design process designers go from the left to the right across domains. This is referred to as mapping. Mapping is iterative and allows designers to go back to the domain on the left to make changes [10].

Customer attributes (CAs) characterize the customer domain and indicate what the customer is looking for in a product. Functional requirements (FRs) and constraints (Cs) characterize the functional domain. Design parameters (DPs) characterize the solution space or physical domain, i.e. how the FRs are achieved physically. The process variables define the process domain and specify how the DPs are produced [10].

It is stated that many different fields of products can be described in terms of the four domains and thus making the framework field independent.

Important definitions

Axiom: a self-evident truth, a statement or proposition which is regarded as being established or accepted.

Theorem: A proposition that is not self-evident but that can be proven from accepted premises or axioms and therefore is established as a law or principle.

Corollary: Inference derived from axioms or from theorems that follow from axioms or from other propositions that have been proven.

Functional requirement: FRs are a minimum set of independent requirements that completely characterize the functional needs of the product in the functional domain. Each FR is considered independent of every other FR at the time of establishment.

Design parameter: DPs are the key physical variables in the physical domain that characterize the design that satisfies the specified FRs.

Process variables: PVs are the key variables in the process domain that characterize the process that can generate the specified DPs.

Constraints: Cs provide bounds on the design solution space and differ from FRs in that they do not have to be independent.

Mapping explained

Once the CAs are identified, they must be translated into FRs in a solution neutral environment, i.e. without considering the solution in the physical domain. Once the FRs are chosen, they are mapped into the physical domain to determine a design with specific DPs that can satisfy the FRs. Hereby many DPs can satisfy an FR, however designers must make sure that a selected DP only affects the intended FR.

Axioms:

The independence axiom and the information axiom are the basic postulates of the axiomatic approach. These axioms were identified by examining the common elements that are always present in good designs.

The axiomatic design axioms are formally states:

Axiom 1: The Independence Axiom

> *"Maintain the independence of the functional requirements (FRs)".*

Axiom 2: The information Axiom

> *"Minimize the information content of the design".*

The axioms state that first, the independence of FRs must always be maintained by selecting the right DPs, and second, that among the designs that have independent FRs and thus satisfy the Independence Axiom, the design with the smallest information content is the best design. The information content is defined in terms of probability, and therefore, the second axiom also states that the best design is the design with the highest probability of success. Based on scientific research it is claimed that robustness, reliability and functionality of products are significantly improved when the axiom 1 and 2 are satisfied.

The first Axiom: The Independence Axiom

A set of FRs describes the design goals in the functional domain. When there are multiple FRs, the choice op DPs must be such that each FR can be satisfied without affecting any of the other FRs. The right choice of DPs determines whether FR independence is maintained. After FR establishment, conceptualization takes place, which consists of mapping from the functional to the physical domain, essentially going from "what" in the functional domain to "how" in the physical domain. This process consists of identifying plausible DPs to satisfy the respective FRs without violating Axiom 1 [10].

The mapping process can be expressed mathematically in terms of the characteristic vectors {FR} and {DP}, which defining the design goals and design solutions respectively. The relationship between these vectors can be written as

$$\{FR\} = [A]\,\{DP\} \qquad \text{Eq. 4.1}$$

, whereby [A] is referred to as the Design Matrix that expresses the relationship between FRs and DPs and characterized the product design. The equation above is the design equation for the design of a product.

Taking for example a design matrix which consist of 3FRs and 3DPs, the design matrix is as follows:

$$[A] = \begin{bmatrix} A11 & A12 & A13 \\ A21 & A22 & A23 \\ A31 & A32 & A33 \end{bmatrix}$$

Figure 15: The axiomatic design matrix

Writing equation 4.1 in differential form gives equation 4.2:

$$\{dFR\} = [A]\{dDP] \qquad \text{Eq. 4.2}$$

, the elements of the design matrix are given by:

$$Aij = \frac{\partial FRi}{\partial DPj}$$

With 3FRs and 3DPs, equation 4.1 can be written as in terms of its elements as:

$$FR1 = A11DP1 + A12DP2 + A13DP3$$

$$FR2 = A21DP1 + A22DP2 + A23DP3 \qquad \text{Eq. 4.3}$$

$$FR3 = A31DP1 + A32DP2 + A33DP3$$

In general,

$$FRi = \sum_{i=1}^{n} Aij\ DPj$$

, where n = the numbers of DPs.

To satisfy the independence axiom, DPs must be selected such that either a diagonal or triangular design matrix results. A diagonal design matrix [A] indicates that each FR can be satisfied independently by its respective DP, thus the design is uncoupled. A triangular design matrix indicates that the independence of FRs can only be guaranteed if and only if the respective DPs are determined in a proper sequence. Compliance with Axiom 1 is thus conditional and must be carefully realized through sequenced determination of DPs. Such a design is referred to as decoupled. Any other form of the design matrix is referred to as a full matrix and the resulting design thereof is coupled and thus in violation of Axiom 1 [10].

In the case of a full design matrix, a coupled design results which might give the right values for FRs; however, such a design is not robust and cannot withstand random variations of DPs and of the environment surrounding the design. An example to this is that when one FR would be changed, all DPs must also be changed to balance the system again. Moreover, when DPs are not exact in the case of a full design matrix, the FRs may not be satisfied. This illustrates the importance of compliance with Axiom 1 and thus the importance of developing designs that enable designers to create diagonal or triangular design matrices [10].

Design goals are often subject to constraints which are of two kinds: Input constraints and system constraints [10]. Input constraints are specific to the overall design goals which means that all proposed design must satisfy these constraints. System constraints are design specific and result from design decisions made. Input constraints are specified at the beginning of the design process because the system must satisfy external boundary conditions set by stakeholders or the environment. All potential designs must satisfy these constraints. Some constraints result from design decisions made along the design process. For the axiomatic design process, all higher-level decisions constrain the lower levels, these are the system constraints [10].

Design classification – Theorem 1, 3– 4

Depending on relative numbers of FRs and DPs, the design classification can be conducted, and the design can be classified as coupled, redundant or ideal.

Theorem 1. (Coupling due to insufficient number of DPs):

"When the number of DPs is less than the number of Fs, either a coupled design results or the FRs cannot be satisfied.

Theorem 3. (Redundant design due to excess of DPs relative to FRs):

"When there are more DPs than FRs, a redundant design results or a coupled design

Theorem 4. (ideal design):

"When the number of FRs equals the number of DPs, the design is ideal if the independence axiom is satisfied.

Decomposition, Zigzagging and Hierarchy

With missing design details on the highest level of design, the design equation represents design intent. The highest-level design must be decomposed to develop design details on the lower levels that can be implemented. The lower-level decisions must be consistent with the design intent specified at the highest-level. Through the decomposition process the designer transforms the higher-level design intent into realizable design details provided by the lowest-level design matrices. To ensure the right decisions are made, the designer must write the design equation at each level of decomposition.

The Second Axiom: The information Axiom

The information axiom states that given a set of uncoupled designs, the design with the least information content is the best design. The goal here is to reduce the information content to make a system function as designed, hereby the design must be able to accommodate large variations in design parameters and process variables, while maintaining satisfaction of the FRs. This is called a robust design.

Appendix provides collaries and theorems of the axiomatic design principle that provide guidelines on i

It is concluded that the axiomatic design principle is suitable for motorbike design. The principle allows for systematic design of systems with multiple functions and provides design guidance for conceptualization and detailed design. The principle also is a systematic approach that is said to lead to good design which supports the first notion mentioned in the design approach. Also, axiomatic design provides a scientific basis to ensure a design is robust while fulfilling the customer requirements.

4.6 Design method tailored for motorbike design

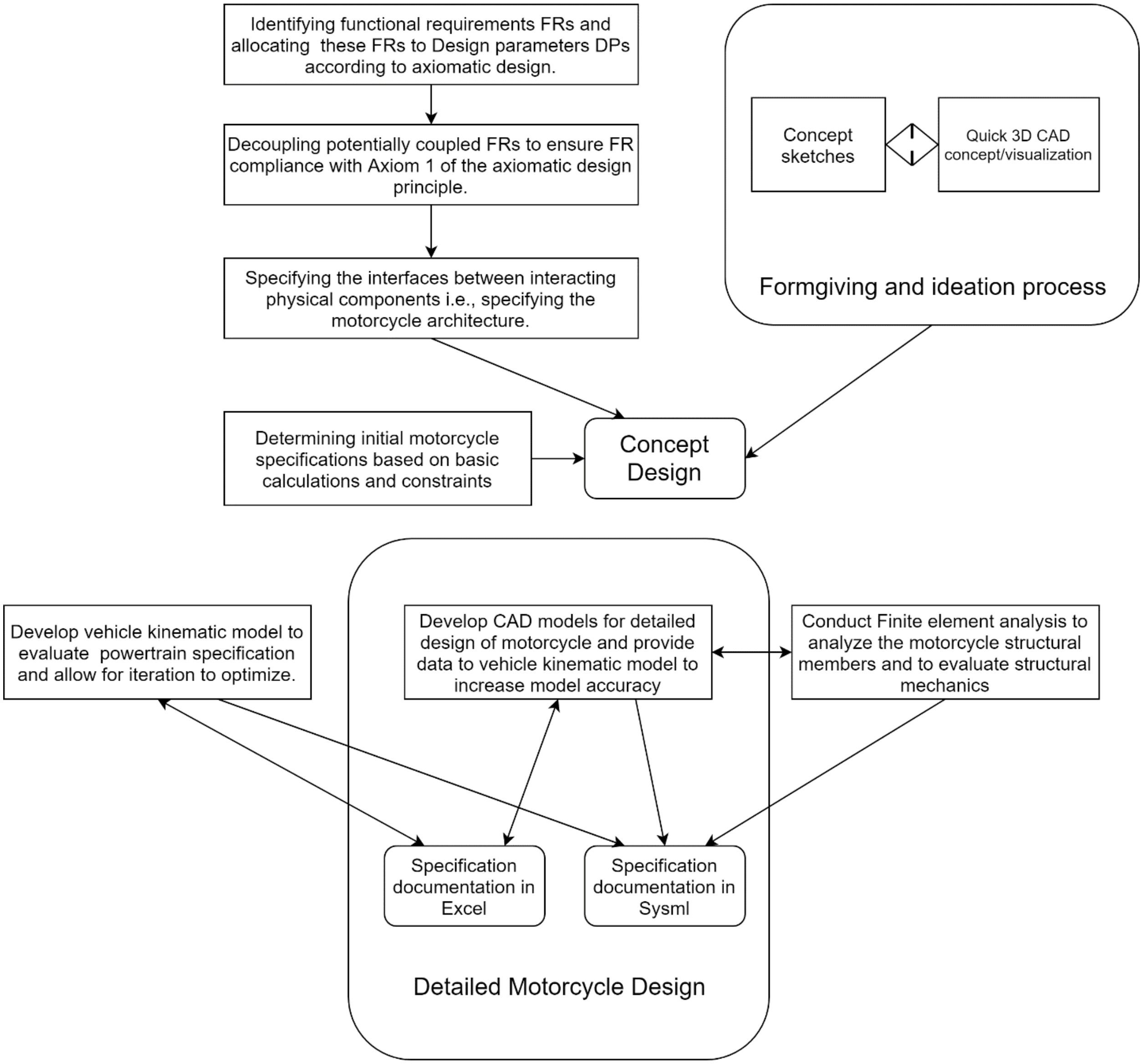

Figure 16. Design method tailored to motorcycle design

4.7 Tools used for design method implementation

This paragraph discusses the tools required for the implementation of the design method and how these are integrated to be used during implementation of the design method.

Detail design tools

4.5.1 SYSML modeler tool – SYSML architect: Modelio (open source)

Sysml modeler tool Modelio, is a Sysml based open source tool to design systems architectures. The tool allows systems modeling and design and can integrate with MS word and Excel. The tool is used to document the systems structure of the motorbike. Also, requirement traceability is facilitated by documenting the functional requirements and linking them to the design parameters/parts for which the structure is defined.

4.5.2 Siemens (NX and SIMCENTER)

Siemens NX is used as CAD software for the physical design of the chassis and the powertrain. An assembly is made to visualize the product. From NX, product parameters of the final product such as weight can be measured.

SIMCENTER, a CAE software package integrated with NX is used to analyze the structural performance of the motorbike's chassis.

4.5.3 MATLAB – Simulink

MATLAB – Simulink is used as a mathematical modeling tool to model the vehicle kinetics equations. This model enables analysis of the power trains specifications and allows for iterations in the design of the power train. The model calculates the energy and power requirements for a given drive cycle whereby specification of the power train and power supply can be conducted based on real life driving behavior.

4.5.4 Microsoft Excel

Microsoft excel is used as bridging software and documentation tool of quantitative data. E.g. the vehicle mass of the motorbike assembly is documented in Excel, whereby the information is fed into the MATLAB model and power and energy requirements can be verified. Adjustments to the Design will result in variations in for example weight, and thus iteration must be conducted in MATLAB Simulink. This process is streamlined with Microsoft Excel functioning as a bridge between software packages.

4.5.5 Microsoft Word

Microsoft Word is used as a tool to document textual information such as design rationale, requirements etc. Microsoft word is compatible with Modelio, which enables textual exchange between the packages.

Ideation /aesthetic design tool

4.5.6 Design sketching and CAD

Sketching is used to facilitate the ideation process of designing the style and appearance of the motorbike. 2D sketching is fast and facilitates fast iterations to put ideas on paper. For this reason, it was the primary method for generating ideas on the look and style of the motorbike. Ideas sketched in 2D can be design in 3D CAD to evaluate the form and judge the look/aesthetics.

4.5.7 Tool integration

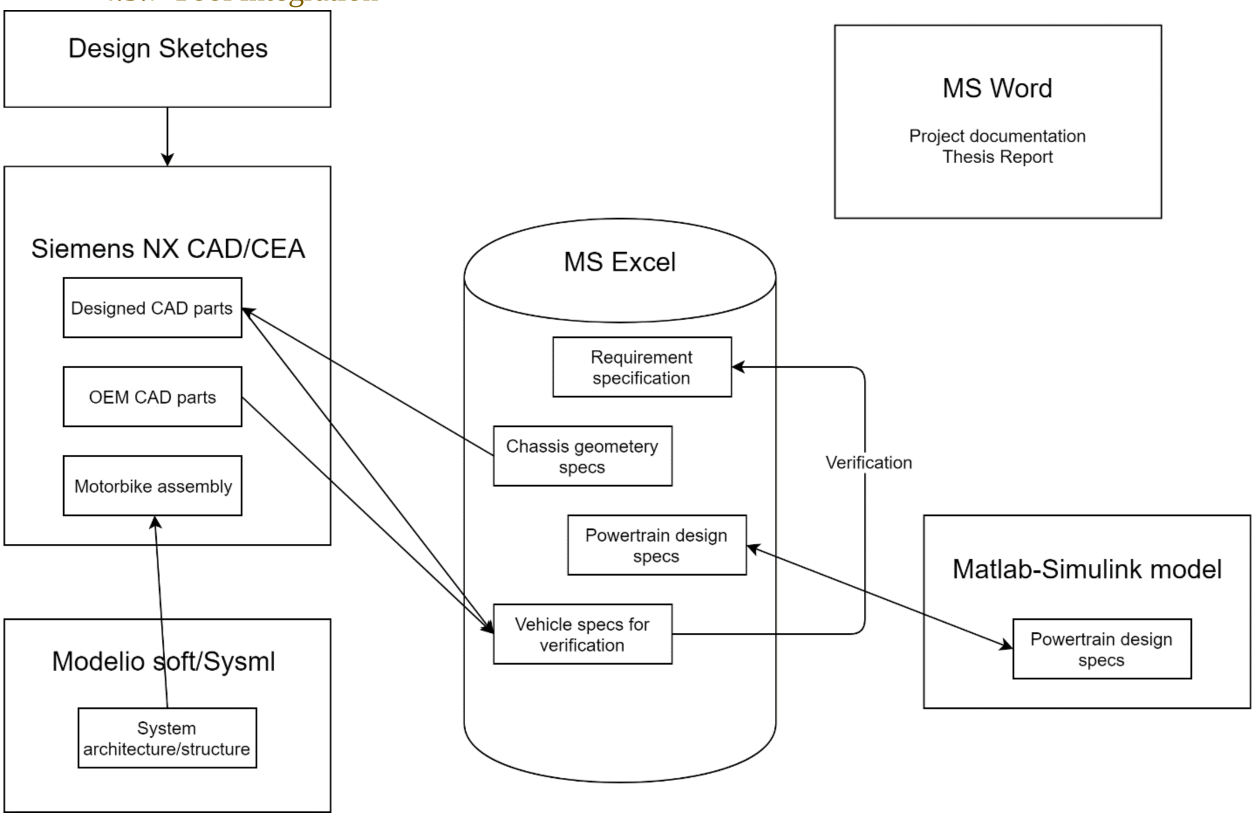

Figure 17: Design tool integration

5 Concept design

This chapter documents the conceptual design phase whereby the system's functions, constraints, parts and structure are defined. First the user needs are evaluated. Then from the user needs, functional requirements are deduced and decomposed, and constraints are identified. Hereafter, design parameters (solutions) are assigned to fulfill the functional requirements under the present constraints. This effort is conducted based on the axiomatic design principle, whereby the design solution is checked for compliance to the independence axiom, which states that functional requirements must be uncoupled, meaning that a functional requirement must be controlled by only one design parameter (uncoupled design) [10].

Concurrent to this process, concept sketches are developed to establish the style of the motorcycle and come to an aesthetically pleasing concept. Hereby 2D and 3D hand sketches are produced to help visualize the designer's ideas regarding form and style. Hereafter, the motorcycle's physical architecture is defined, then the interaction with the users is defined and the operation context is established.

Axiom 2 of the AD principle aims at minimizing the information content of a design. Along this line of reasoning, it was decided to minimize information content by using as much OEM parts as possible while avoiding custom designed parts. Thus, the concept design phase is concluded with part sourcing research and initial design decisions on which parts will be OEM sources or custom designed.

5.1 Identification and of stakeholder requirements (CAs)

User needs identification:

Customer requirement 1:	Affordable electric motorcycle transport for 1 person to cover three times the average home-to-work distance over a vehicle lifespan of 4 years. The average home to work distance in the Netherlands is 22.5 km. The customer requirement mentioned above indicates that the motorbike should be able to at least travel 67.5km during a lifespan of 4 years.
Customer requirement 2:	Operation of the motorbike should require no more than an AM category driver's license.
Customer requirement 3:	The motorbike should be easy to drive in urban environments of the Netherlands and should fit the purpose of commuting.
Customer requirement 4:	The motorbike should be comfortable to ride on
Customer requirement 5:	The motorbike should be aesthetically pleasing
Customer requirement 6:	The motorcycle should be safe and easy to operate

The CAs 1-6 are defined based on the project's design objective to design an affordable motorbike for urban commute in the Netherlands with enough operational range for its intended purpose. The design objective of this project is based on identified market needs of two-wheeled/single track electric vehicles. It is assumed that the customer requirements identified are reflecting the customer needs and satisfaction of these requirements would result in a stakeholder accepted design.

The objective of this design phase is to define the right functional requirements that address the customer needs and to design a concept solution that fulfills the functional requirements while conforming to axiom 1 of the axiomatic design principle. During this phase, input constraints are specified, and systems constraints identified. Means of verification are specified per functional requirement.

Moreover, a robust design is the aim of the design effort, and based on DP variation, the robustness of the design shall be evaluated at the end of this phase.

5.2 FR – Cs specification and DP allocation

In this paragraph the highest hierarchy functions are decomposed in specific lower level hierarchy functions according to the axiomatic design workflow, by zigzagging between functions and design parameters before stepping down in hierarchy. With each allocation of DPs to FRs, a design matrix is constructed to evaluate for compliance with the independence axiom. The higher-level FR-DPs constrain the lower-level FR-DPs. Furthermore, for high-level FR – DP pairs, a verification method is assigned to verify whether the functional requirement is met by the design parameter.

Level 1 Hierarchy FR specification and DP allocation

FR1.0: Provide a means to transport one commuter in the Netherlands from home to work and back.

Cs 1.0.A: Commuter should need no more than an AM category license and the solution should contain 2 wheels in a single-track configuration.

Cs 1.0.B: Solution should be capable of traveling 3 times the average home-to-work distance in the Netherlands, which equals 67.5km.

Cs 1.0.C: The commuter should be able to easily transport himself through urban traffic and thus requiring good maneuverability.

Cs 1.0.D: The solution should be ergonomic in terms of physical interaction between human and machine

Cs 1.0.E: The solution should cost no more than 3500 Euro to produce.

Level 1 (highest level hierarchy)				
FR_id	**FR_specification**	**DP_id**	**DP_specification**	**Verification**
FR_1	Provide a means to transport one commuter in the Netherlands from home to work and back.	DP_1	MK3 Electric Motorbike of Vehicle Category L1E	Excel overview model

Table 2: Highest level hierarchy motorcycle FR-DP allocation

As specified in Table 5.1, an excel overview model will be used to verify that FR1 is achieved by the MK3 electric motorbike design. The excel overview model will consist of a summary of all design evaluation results of lower-level FRs.

Level 2 hierarchy FR specification and DP allocation: decomposition of Level 1 FR1.0 and DP1.0

FR 2.1: **Provide tractive power for forward movement of the electric motorbike**

Cs 2.1.A: Mk3 shall be powered by electric propulsion

Cs 2.1.B: Mk3 shall have a power rating of maximum 4kW nominal continuous power

Cs 2.1.C: Mk3 shall have a maximum velocity of 50km/hr.

FR 2.2: **Provide ability to steer vehicle to change direction**

Cs 2.2.A: Turning radius shall not exceed 2 meters for a maximum steering angle of 45degrees.

Cs 2.3.B: Ability to steer shall be maintained at low speeds

FR 2.3: **Provide ability to stop forward movement of vehicle**

Cs 2.3.A: Distance to standstill for given initial speed.

FR 2.4: **Provide structural support to rider and parts, distribute weight and maintain geometric relationship**

Cs 2.4.A: Maintain geometric relationship during operation

FR 2.5: **Interact with user and avoid unwanted users.**

FR 2.6: **Allow for nighttime operation**

Cs 2.6.A: Nighttime operation devices should comply with legislation

FR 2.7: **Reduce road noise felt by the user**

FR 2.8: **Protect parts from the elements and protect user from moving parts**

FR 2.9: **Provide electric power to all onboard electric loads**

Cs 2.9.A: Mk3 shall be capable of covering 67.5km in one go.

Cs 2.9.B: Shall provide electric power to user’s mobile phone

	Level 2 (Second level hierarchy): Decomposition of FR_1 and DP_1			
FR_id	**FR_specification**	**DP_id**	**DP_specification**	**Verification**
FR_2.1	Provide tractive power for forward movement of the electric motorbike	DP_2.1	Powertrain	Vehicle kinetics model – Quantitative
FR_2.2	Provide ability to steer vehicle to change direction	DP_2.2	Steering assembly	CAD/practical data verification
FR_2.3	Provide ability to stop forward movement of vehicle	DP_2.3	Braking system	-
FR_2.4	Provide structural support to rider and parts, distribute weight and maintain geometric relationship	DP_2.4	Tubular frame	CAD & CAE - Quantitative
FR_2.5	Interact with user and avoid unwanted users	DP_2.5	UI system	-
FR_2.6	Allow for nighttime operation	DP_2.6	Lighting system	-
FR_2.7	Reduce road noise felt by the user	DP_2.7	Tires + suspension+saddle	-
FR_2.8	Protect parts from the elements and protect user from moving parts	DP_2.8	Body	CAD
FR_2.9	Provide electric power to all onboard electric loads	DP_2.9	Electric power supply and wiring system	-

Table 3: Second level hierarchy motorcycle FR-DP allocation

Design matrix for level 2 hierarchy										
FR_2.1	x	0	0	0	0	0	0	0	0	DP_2.1
FR_2.2	0	x	0	x	0	0	0	0	0	DP_2.2
FR_2.3	0	0	x	0	0	0	0	0	0	DP_2.3
FR_2.4	0	0	0	x	0	0	0	0	0	DP_2.4
FR_2.5	0	0	0	0	x	0	0	0	0	DP_2.5
FR_2.6	0	0	0	0	0	x	0	0	0	DP_2.6
FR_2.7	0	0	0	0	0	0	x	0	0	DP_2.7
FR_2.8	0	0	0	0	0	0	0	x	0	DP_2.8
FR_2.9	0	0	0	0	0	0	0	0	X	DP_2.9

Table 4: Design matrix second level hierarchy

Table 4 shows that FR_02 is a coupled functional requirement. This is because steering is influenced by the frame's geometry. FR_02 must be decoupled. This can be done by specifying a sequence in which the DPs must be defined. Defining DP0.4 first and then DP0.2, decouples the matrix. This can be seen in practice as, with the wheelbase fixed, manipulation of the steering angle is the only factor influencing the function of steering in terms of the turning radius.

As specified in table 3 a combination of vehicle kinetics model, CAD model, practical data, and CAE shall be used to verify that the FRs of the second level hierarchy are met.

Level 3 hierarchy FR specification and DP allocation: decomposition of Level 2 FR2.1 and DP2.1

FR 3.1.1: **Store energy to supply electric power for load**

Cs 3.1.1.A: Energy stored must be enough to travel 67.5km

Cs 3.1.1.B: Energy storage shall provide nominal voltage required by the propulsion unit

Cs 3.1.1.C: Energy storage shall provide nominal power required by propulsion unit

FR 3.1.2: **Monitor and protect electric power supply**

Cs 3.1.2.A: Shall comply with system voltage and power

FR 3.1.3: **Provide propulsion by converting electrical energy to mechanical energy to supply torque and speed**

Cs 3.1.3.A: Power rating shall not exceed 4kW.

FR 3.1.4: **Control propulsion unit and allow for generator operation of propulsion unit**

Cs 3.1.4.A: Shall comply with voltage and power rating of propulsion unit

FR 3.1.5: **Transmit mechanical energy from propulsion unit and convert torque and speed**

Cs 3.1.5.A: Capable of withstanding the power of the propulsion unit

Cs 3.1.5.B: Capable of converting motor speed and torque to final drive speed and torque without exceeding vehicle speed of 50km/hr

FR 3.1.6: **Transmit tractive force to road surface for specified speed**

Level 3 (third level hierarchy: Decomposition of FR_2.1-DP_2.1			
FR_id	**FR_specification**	**DP_id**	**DP_specification**
FR_3.1.1	Store energy to supply electric power for load	DP_3.1.1	Battery module
FR_3.1.2	Monitor and protect electric power supply	DP_3.1.2	BMS
FR_3.1.3	Convert electrical energy to mechanical energy to supply torque and speed	DP_3.1.3	BLDC motor
FR_3.1.4	Control propulsion unit and allow for generator operation of propulsion unit	DP_3.1.4	Motor drive
FR_3.1.5	Transmit mechanic energy from propulsion unit and convert propulsion unit torque and speed to final torque and final desired speed	DP_3.1.5	Single speed chain transmission
FR_3.1.6	Transmit tractive force to road surface for specified final speed	DP_3.1.6	Rear wheel assembly

Table 5: Third level hierarchy motorcycle FR-DP allocation

Table 5.5: Design matrix third level hierarchy: FR 3.1.1-3.1.6 – DP3.1.1-3.1.6

FR_3.1.1	X	0	0	0	0	0	DP_3.1.1
FR_3.1.2	0	X	0	0	0	0	DP_3.1.2
FR_3.1.3	0	0	X	0	0	0	DP_3.1.3
FR_3.1.4	0	0	0	X	0	0	DP_3.1.4
FR_3.1.5	0	X	0	0	X	X	DP_3.1.5
FR_3.1.6	0	0	0	0	0	X	DP_3.1.6

Table 6: Design matrix third level hierarchy: FR 3.1.1 - 6 - DP3.1.1-6

From table 5.5 it can be concluded that the FR 3.1.5 is coupled. This FR is influenced by both DP 3.1.3, DP 3.1.5 and DP 3.1.6. This FR can be uncoupled by defining the DPs in the right sequence. First DP 3.1.3 must be identified since this is the propulsion unit since values of other parameters are constrained based on this design parameter. Then DP 3.1.6 must be identified. Hereby the diameter of the final drive is specified. Knowing the propulsion speed and the diameter of the final drive, the speed conversion factor can be calculated. Thus, a decoupled design as a result.

Level 3 hierarchy FR specification and DP allocation: decomposition of Level 2 FR2.2 and DP2.2

FR 3.2.1: Provide easy user manipulation of steering angle up to 45 degrees

Cs 3.2.1.A: Physical effort must be kept to minimum requiring good steering ergonomics

Cs 3.2.2.B: Steering angle should not exceed 45 degrees

FR 3.2.2: Transfer change of direction to road surface

Level 3 (third level hierarchy: Decomposition of FR_2.2-DP_2.2

FR_id	**FR_specification**	**DP_id**	**DP_specification**
FR_3.2.1	Provide easy user manipulation of steering angle up to 45 degrees	DP_3.2.1	Triple tree assembly and handlebar
FR_3.2.2	Transfer change of direction to road surface	DP_3.2.2	Front wheel assembly

Table 7: Third level hierarchy: decomposition of FR 2.2 – DP 2.2

Level 3 design matrix FR 3.2.1-FR3.2.2 – DP 3.2.1-DP3.2.2

FR_3.2.1	X	0	DP_3.2.1
FR_3.2.2	0	X	DP_3.2.2

Table 8: Third level hierarchy design matrix

According to the design matrix of table 5.7, the design is uncoupled and thus in compliance with Axiom 1.

Level 3 hierarchy FR specification and DP allocation: decomposition of Level 2 FR2.3 and DP2.3

FR 3.3.1: Provide braking force on front wheel

FR 3.3.2: Provide braking force on rear wheel

FR 3.3.3: Control braking force on front wheel

FR 3.3.4: Control braking force on rear wheel

FR 3.3.5: Handle weight transfer during braking

Level 3 (third level hierarchy: Decomposition of FR_2.3-DP_2.3

FR_id	FR_specification	DP_id	DP_specification
FR_3.3.1	Provide braking force on front wheel	DP_3.3.1	Front disc-brake assembly
FR_3.3.2	Provide braking force on rear wheel	DP_3.3.2	Regen braking by powertrain
FR_3.3.3	Control braking force on front wheel	DP_3.3.3	Hydraulic brake actuating system
FR_3.3.4	Control braking force on rear wheel	DP_3.3.4	Motor drive
FR_3.3.5	Handle weight transfer during braking	DP_3.3.5	Fork

Table 9: Level 3 - Decomposition of FR_2.3-DP_2.3

Level 3 design matrix FR 3.3.1-FR3.3.5 – DP 3.3.1-DP3.3.5

FR_3.3.1	X	0	0	0	0	DP_3.3.1
FR_3.3.2	0	X	0	0	0	DP_3.3.2
FR_3.3.3	0	0	X	0	0	DP_3.3.3
FR_3.3.4	0	0	0	X	0	DP_3.3.4
FR_3.3.5	0	0	0	0	X	DP_3.3.5

Table 10: Level 3 design matrix FR3.3.1-5 - DP3.3.1-5

The design matrix in Table 10 indicates an uncoupled design and therefore a solution in compliance with Axiom 1.

Level 3 hierarchy FR specification and DP allocation: decomposition of Level 2 FR2.4 and DP2.4

FR 3.4.1: Provide stiffness and resist deformation to withstand dynamic loading

Cs 3.4.1.A: Lateral stiffness should be no less than……

Cs 3.4.1.B: Torsional stiffness should be no less than……

Cs 3.4.1.C: Braking stiffness should be no less than …….

FR 3.4.2: Distribute the rider's weight and that for the parts between the axles

Cs 3.4.2.A: The center of mass if projected on the road surface shall lie between the projects of the axles on the road surface.

FR 3.4.2: Avoid falling over of motorbike in static state.

Level 3 (third level hierarchy: Decomposition of FR_2.4-DP_2.4

FR_id	FR_specification	DP_id	DP_specification
FR_3.4.1	Provide stiffness and resist deformation to withstand dynamic loading	DP_3.4.1	Aluminum tubular structural members
FR_3.4.2	Distribute rider's weight and that of parts between the axles	DP_3.4.2	Position of rider and parts
FR_3.4.3	Avoid falling over of motorcycle in static state	DP_3.4.3	Stand

Table 11: Level 3 Decomposition of FR_2.4 - DP2.4

Level 3 design matrix

FR_3.4.1	X	0	0	DP_3.4.1
FR_3.4.2	0	X	0	DP_3.4.2
FR_3.4.3	0	0	X	DP_3.4.3

Table 12: Level 3 FR3.4.1-3 - DP3.4.1-3 design matrix

Table 12 indicates an uncoupled design which is in accordance to axiom 1.

Level 3 hierarchy FR specification and DP allocation: decomposition of Level 2 FR2.5 and DP2.5

FR 3.5.7: Allow for user to use power supply for telephone charging

Cs 3.5.7.A: Provide DC voltage of 5V.

FR 3.5.9: Provide user with cargo storage

CS 3.5.9: User shall be able to transport laptop bag/backpack-sized cargo in vehicle

Level 3 (third level hierarchy: Decomposition of FR_2.5-DP_2.5

FR_id	FR_specification	DP_id	DP_specification
FR_3.5.1	Provide user with operation specific information	DP_3.5.1	Dashboard display
FR_3.5.2	Allow user to manipulate speed	DP_3.5.2	Throttle control
FR_3.5.3	Allow user to manipulate front wheel braking	DP_3.5.3	Break lever left
FR_3.5.4	Allow user to manipulate rear wheel braking	DP_3.5.4	Break lever right
FR_3.5.5	Allow user to digitally connect and monitor the vehicle	DP_3.5.5	Vehicle onboard computer
FR_3.5.6	Allow user to turn on/off vehicle	DP_3.5.6	Keyed power switch
FR_3.5.7	Allow user to use power supply for telephone charging	DP_3.5.7	Voltage converter – USB outlet
FR_3.5.8	Allow for easy charging of vehicle	DP_3.5.8	Charging system
FR_3.5.9	Provide user with cargo storage	DP_3.5.9	Storage compartment

Table 13: Level 3 decomposition FR_2.5-DP_2.5

Design matrix for level 3 hierarchy										
FR_3.5.1	x	0	0	0	0	0	0	0	0	DP_3.5.1
FR_3.5.2	0	x	0	x	0	0	0	0	0	DP_3.5.2
FR_3.5.3	0	0	x	0	0	0	0	0	0	DP_3.5.3
FR_3.5.4	0	0	0	x	0	0	0	0	0	DP_3.5.4
FR_3.5.5	0	0	0	0	x	0	0	0	0	DP_3.5.5
FR_3.5.6	0	0	0	0	0	x	0	0	0	DP_3.5.6
FR_3.5.7	0	0	0	0	0	0	x	0	0	DP_3.5.7
FR_3.5.8	0	0	0	0	0	0	0	x	0	DP_3.5.8
FR_3.5.9	0	0	0	0	0	0	0	0	X	DP_3.5.9

Table 14:Level 3 design matrix FR 3.5.1 – FR3.5.9 – DP. 3.5.1 – DP 3.5.9

Table 5.13 shows uncoupled design and compliance to axiom 1.

Level 3 hierarchy FR specification and DP allocation: decomposition of Level 2 FR2.6 and DP2.6

Level 3 (third level hierarchy: Decomposition of FR_2.6-DP_2.6			
FR_id	**FR_specification**	**DP_id**	**DP_specification**
FR_3.6.1	Provide navigational lighting during driving operation	DP_3.6.1	12V Day time + Night-time headlight
FR_3.6.2	Provide change of direction light signal	DP_3.6.2	12V Signaling lighting system
FR_3.6.3	Provide braking light signal	DP_3.6.3	12V Brake lighting system
FR_3.6.4	Illuminate relevant UI components for low light operation	DP_3.6.4	12V System backlights

Table 15: Level 3 decomposition FR_2.6-DP_2.6

Level 3 design matrix FR 3.3.1-FR3.3.5 – DP 3.3.1-DP3.3.5						
FR_3.6.1	X	0	0	0	0	DP_3.6.1
FR_3.6.2	0	X	0	0	0	DP_3.6.2
FR_3.6.3	0	0	X	0	0	DP_3.6.3
FR_3.6.4	0	0	0	X	0	DP_3.6.4
FR_3.6.5	0	0	0	0	X	DP_3.6.5

Table 16: Level 3 design matrix FR_3.6.1-9 - DP_3.6.1-9

Level 3 (third level hierarchy: Decomposition of FR_2.7-DP_2.7			
FR_id	**FR_specification**	**DP_id**	**DP_specification**
FR_3.7.1	Provide front wheel with optimal road holding	DP_3.7.1	Fork
FR_3.7.2	Reduce noise due to road undulations	DP_3.7.2	Radial (tubeless) Tires

Table 17: Level 3 Decomposition FR_2.7 - DP_2.7

Level 3 design matrix FR 3.7.1-FR3.7.2 – DP 3.7.1-DP3.7.2			
FR_3.7.1	X	0	DP_3.7.1
FR_3.7.2	0	X	DP_3.7.2

Table 18: Level 3 design matrix FR_3.7.1-2 - DP_.7.1-2

Table18 illustrates that the FRs are uncoupled and that the solution complies with axiom 1.

Level 3 (third level hierarchy: Decomposition of FR_2.9-DP_2.9			
FR_id	**FR_specification**	**DP_id**	**DP_specification**
FR_3.9.1	Store energy to supply electric power for all loads	DP_3.9.1	Power supply
FR_3.9.2	Monitor and protect electric power supply	DP_3.9.2	BMS

Table 19: Level 3 Decomposition FR_2.9 - DP_2.9

Level 3 design matrix FR 3.9.1-FR3.9.2 – DP 3.9.1-DP3.9.2			
FR_3.9.1	X	0	DP_3.9.1
FR_3.9.2	0	X	DP_3.9.2

Table 20: Level 3 FR 3.9.1-2 - DP 3.9.2 design matrix

5.3 Motorcycle system architecture design

In addition to the FR – DP mapping in the previous paragraph, the structure of the motorcycle can be determined. Using SYSML Block Definition Diagrams (BDD) and Internal Block Diagrams (IBD), the interfaces between interacting physical parts (DPs) are identified based on the solutions and the structure in the previous paragraph. BDDs show the hierarchy of parts and how these relate to each other. IBDs provide the physical relationship between these parts and the exchange of information, flow of energy, flow of matter, etc. are herein specified.

The structure of the solution MK3 Electric Motorbike of Vehicle Category L1E is illustrated by the BDD diagram in the following figure.

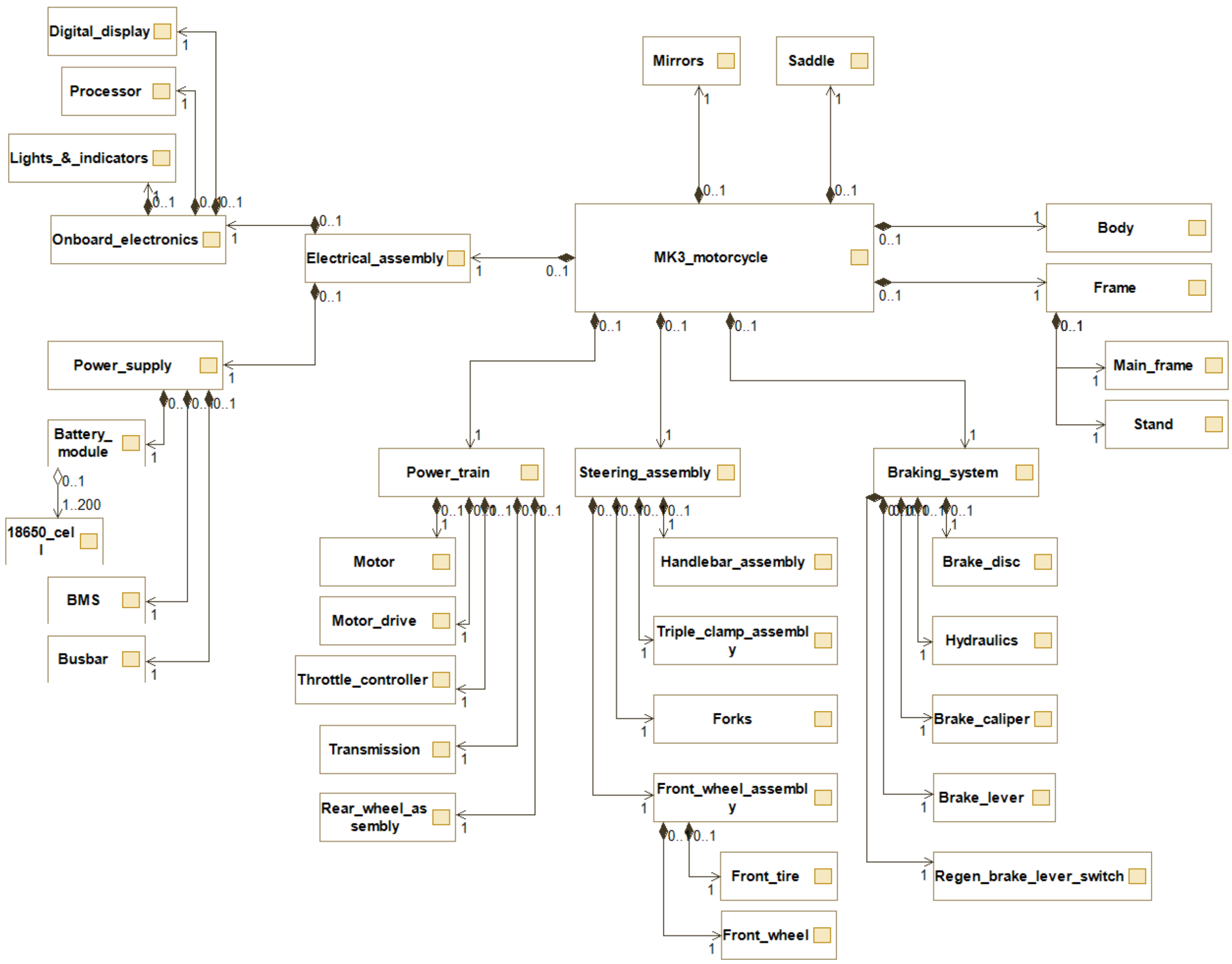

Figure 18: BDD - Motorbike system structure

The BDD diagram in figure 18 establishes the hierarchical structure of systems and sub-systems of the motorbike. The BDD provides information on which parts are part of which system but does not provide the interface between the parts or sub-systems. The IBD is intended to establish the interaction between parts/sub-systems within the whole system.

The scope of the project is aimed at powertrain and power supply design, and design of the motorbike's chassis. For this reason, detailed design focuses on these components of the motorbike. The internal structure of these sub-systems is therefore specified by Internal block diagrams.

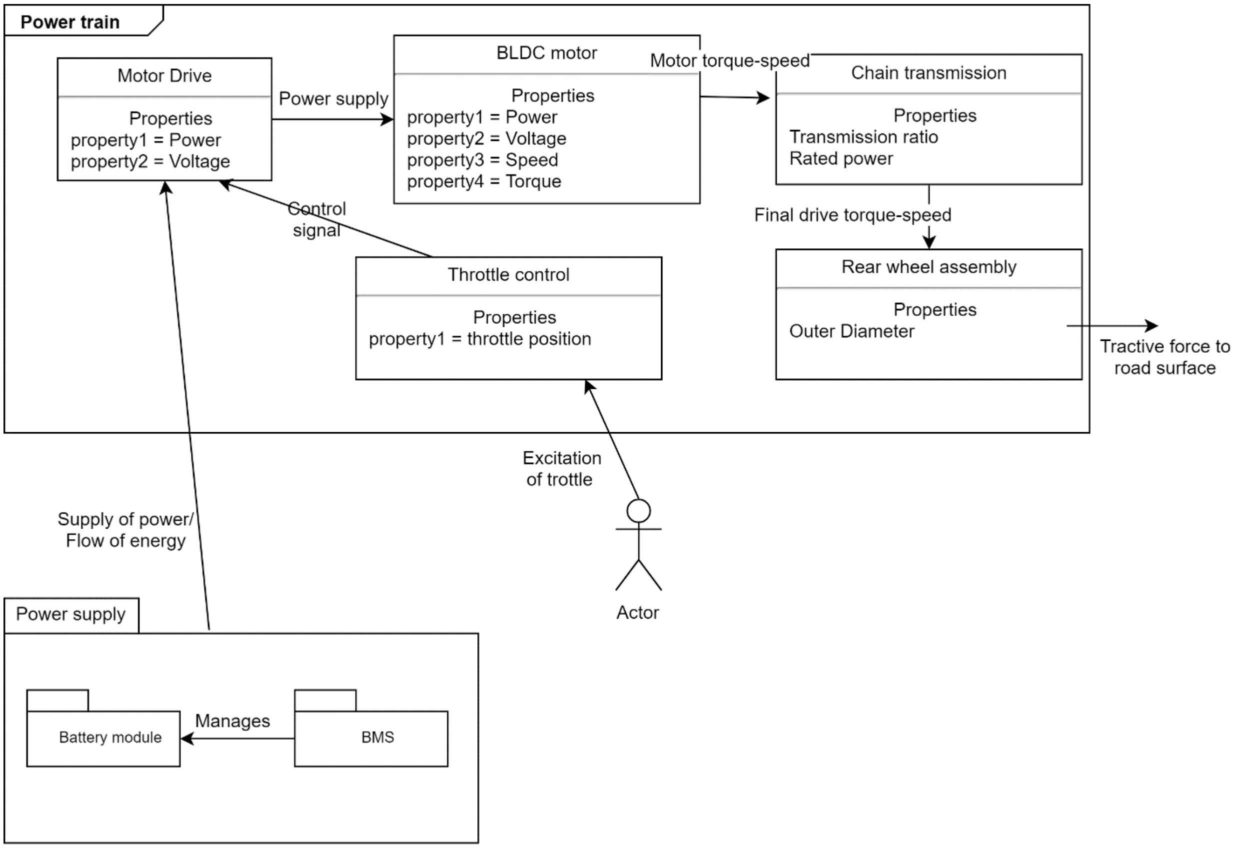

Figure 19: IBD of powertrain and power supply - indication of flow of energy during work

Modelio Sysml software allows for requirement documentation, which is coupled to the structure of the system, hereby documenting what is developed during the mapping process of the axiomatic design principle. Modelio software allows compatibility with MS Excel for tabular/quantitative information and MS word textual information.

5.4 Part sourcing research

Based on the parts identified in the BDD of the previous paragraph, internet research was conducted to find suppliers for the parts which can be OEM sourced.

Sourcing powertrain components

Motor and drives:

- BLDC Motor
- BLDC Motor driver
- BLDC Motor driver controls

Internet market research has indicated that most small electric motor – motor drive combos are available on the Chinese market. The Chinese dominate this market and their products are offered around the world. The identified leading manufacturers of BLDC motors for motorbike applications are QS Motors and Golden Motors in China. QS Motors offers a large assortment on BLDC hub motors and corresponding motor drives, while Golden Motors is most famous for BLDC motors for mid-drives. Both manufacturers offer motors in the range of 500W for bicycles to 20kW for small electric vehicles such as golf carts. Especially their electric scooter range of motors is famous. For an overview of the products supplied by QS motors visit their commercial website [11]. For an overview of the products supplied by Golden motors visit their commercial website [12].

Both manufacturers can deliver motors in the range of 2000-5000W with some level of customization in terms of motor speed and torque. The operating voltages of the motors usually range between 48V and 72V for said power ratings. Quality hub motors are produced by only a few manufacturers, while quality mid-drive BLDC motors are produced by many manufacturers.

Transmission components:

- Roller chain transmission parts
- Belt transmission parts

Roller chain transmissions

Roller chains are a standardized product and are therefore affordable and widely available. Chain transmissions consists of a chain and a sprocket set. There are many manufacturers that supply chains and sprockets, one of which SKF is a famous manufacturer supplier. Based on SKF's reputation and the fact that they are based around the World and in the Netherlands, they are identified as the supplier with most potential. SKF provides a selection process for determining the right chain and sprocket for a given application, i.e. for a given power rating and speed.

Belt transmission

Belt transmissions for motorbike applications tend to be custom. A belt transmission consists of a belt and a pulley set. Belt transmissions for motorcycle applications tend to be specially design for the application and thus are not standardized. SKF produces standardized belts, however, although supported by SKF belt selection software, finding a suitable belt for the intended purpose has proven to be difficult.

Tires

The market for scooter/moped tires is huge. For this reason, a list of reliable motorbike tire manufacturers is made. Also, potential tires for the intended are identified. From internet research, Michelin and Continental stood out as promising suppliers. This is based on the assortment, the price-quality relationship of their products, their reputation, their representation and product availability around the world and in the Netherlands.

Power supply components

Battery technology and cells

From most battery technologies, lithium-ion is the most used technology for small electric vehicle applications. The price of lithium-ion cells has reduced drastically in the past 10 years and for this reason, they have become even more popular. From all cell topologies, the 18650 cell is by far the most frequently used for EV-applications. This cell has become standardized and can be found in Tesla vehicles among others and electric bicycles. The most prominent manufacturers of 18650 cells are Panasonic, LG and Samsung, each of which their 18650 cells offer slightly different specifications.

BMS units

BMS units are supplied by primarily Chinese manufacturers. The selection of these units depends on the battery module configuration and the cells used. There are also many companies that make complete Battery pack solutions whereby the client provides the specifications and the battery pack is produced.

Chassis components:

Bearings and seals

Bearing and seals are made by many manufacturers however, SKF is the world leader in bearings and seals. SKF makes all kinds of bearings and seals for many applications. For this reason, SKF has been identified as most promising supplier. SKF offers a large variety of bearings and seals and offers selection software for selecting the right product. Furthermore, SKF products are widely available across the world and in the Netherlands [13].

Forks

Suspension forks are made by many manufacturers. Chinese manufacturers tend to develop and produce cheap motorcycle forks. While manufacturers in the US like FOX tend to develop premium and high-performance forks. Fork selection is therefore performance, quality and cost based and a supplier should be selected accordingly.

Brake systems

Brake systems are made throughout the world. Two brake technologies are most common, namely, the drum brake and hydraulic disc brakes. Disc brakes tend to be superior in performance and are therefore more frequently used than drum brakes. Chinese manufacturers make the cheapest disc brakes while there are also suppliers of premium brake systems in the US and Europe such as Brembo. As goes for forks, brake system supplier selection is a matter of required performance, quality and cost.

Frame materials and construction profiles

Tubular profiles are the most standardized frame constructing profile. These tubes can be sourced in aluminum and steel alloys. There are several steels suitable for frame construction from which 10xx steels and 41xx steels are suitable candidates [14]. Frame building requires steel with good bending characteristics, good weldability, high tensile and yield strength. AISI 4130 steel is a steel very suitable for motorcycle frame building, which is frequently used for chopper and custom cruiser frames. Steel provides good stiffness properties which is crucial in frame design to maintain geometric dimensions.

The most common aluminum alloy for frame construction is 6061 aluminum alloy [14]. Although aluminum has a lower density, its strength to weight ratio is much less, which eventually requires more volume to make an equally stiff frame when compared to steel frames. Aluminum is generally more expensive than steel. Aluminum welding is also more difficult than steel welding.

5.5 Concept design decisions on components

In this paragraph, decisions are made on power train and chassis components/materials

Power train components

Motor selection:

Since quality hub motors are produced by a few manufacturers, and that supplier dependence should be avoided, A BLDC motor for mid-drive application was chosen. To avoid supplier dependency, the more readily available mid-drive motor is a better option with more freedom with regards to supplier selection. Furthermore, the design of a motorbike with a mid-drive motor allows for a more flexible design in terms of the position of the motor.

Transmission selection:

A chain drive was selected because a chain drive consists of standardized components. Chain drives are a reliable and low-cost transmission technology with a lot of design flexibility when it comes to positioning of the motor, relative to the final drive. Chain drives do require frequent maintenance; however, this maintenance is cheap and easy.

Final Drive/Wheel assembly:

It was decided to use radial tubeless tires with cast aluminum wheels. Based on mass manufacturing constraints, the selection of cast aluminum wheels is considered better than spoked wheels. Spoked wheels require relatively a lot of assembly time to assemble the spokes and tighten them to specification. Also spoked wheels require maintenance to retighten the spokes. Cast aluminum wheels are more mass manufacturing oriented compared to spoke wheels and are therefore the selected type of wheels.

Power supply:

The obvious choice for battery cells is the 18650 li-ion cells. This is the case because of cost, availability and high battery capacity with large discharge currents possible.

Chassis:

It was decided to go with a tubular frame structure based on design freedom, ease of prototype, maturity of this type of frame building and the ability of producing this type of frame in every part of the world. The difficulty of producing a tubular frame is low and the construction profiles are standard. For the material it was decided to go with steel, since steel has very good weldability, a high strength to weight ratio, good deformability and relatively low cost.

Part 2: An electric motorcycle design case study

6 Detailed design

This chapter documents the detailed design phase whereby quantitative detailed design data is generated. According to the scope of the project, detail design is conducted for the powertrain and the chassis. In this chapter the motorbike design is split-up into powertrain design and chassis design, whereby necessary information exchange between the designs is realized through MS Excel. Keep in mind that the design of both systems is concurrent and back and forth information exchange is necessary.

Paragraph 6.1 documents the powertrain and power supply design, whereby first, the development of a MATLAB vehicle kinetics model is documented. Based on drive cycle input, initial assumptions and known parameters, the vehicle kinetics model is used to determine the power and energy requirements for the drivetrain. Based on these requirements, the individual parts of the powertrain are designed/specified/selected. This consists of selecting the electric motor and dimensioning/sizing the battery module, designing the transmission and determining the final drive dimensions. This process is iterative in nature, since the initial power and energy requirements are partly based on assumed values and can only be determined in more detail when the vehicle parameters have more accurate values.

Paragraph 6.2 documents the design of the powertrain, the power supply and electric system of the motorbike. Hereby the selection procedures and rationale are described and discussed.

Paragraph 6.3 documents the design of the motorbike's chassis. Here, first the motorbike's geometry is defined in accordance with intended dynamic behavior and physical ergonomic requirements. Secondly, the structural design is conducted whereby FEA is performed to assess structural performance. Chassis specifications and information are used to update the vehicle kinetics model (e.g. the mass of the vehicle or frontal area) and thus make it more representative of the design.

6.1 Development of MATLAB-Simulink vehicle kinetics model

The vehicle kinetics model developed in this paragraph is based on vehicle kinetic equations. The model receives as input a reference speed associated with a drive cycle speed profile. The model implements a PID control function which matches the vehicle speed to the drive cycle's reference speed by varying the tractive force input to the kinetic equation model. Based on the vehicle kinetic equations, the model calculates the tractive power and energy requirements for the specified vehicle. The model is a modification of the Mathworks racing lounge battery electric vehicle model used by racing teams that develop custom electric vehicles to partake in racing competitions. The model has proven to be successful in the design of electric vehicle powertrains and therefore assumed to be accurate enough for the scope of this project.

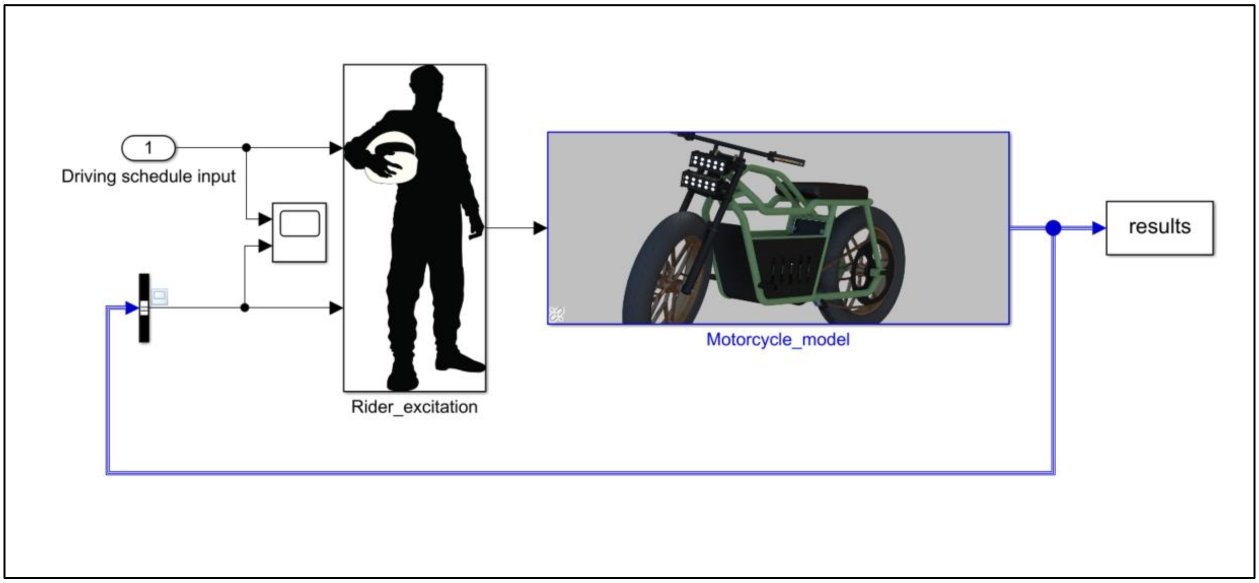

Figure 20: MATLAB - Simulink vehicle kinetics model

6.1.1 Vehicle kinetics equations & vehicle + rider parameters

The essence of the kinetic vehicle model is to determine the tractive power, tractive energy and tractive torque requirements for a specific vehicle and rider configuration under specific riding conditions. In this model the vehicle and rider are represented by a point-mass and require the following parameters to be specified.

Combined vehicle-rider weight: This parameter is the sum of the vehicle weight and the weight of the rider and cargo.

- The initial values of this parameter are assumed to be equal to the maximum target weight of the motorbike and the rider specified in the requirement specification.
- The specified max rider weight is set to xkg.
- The specified max vehicle weight is set to xkg.
- The specified max cargo weight is set to xkg.

Inertial mass factor:	This parameter compensates for the apparent increase in the vehicle's mass due to onboard rotating mass.
Frontal Area:	This parameter is the area of the projection of the motorbike and the rider on the perpendicular plane in front of the motorbike.
Rolling resistance coefficient:	This parameter considers the resistance of the motorbike's tires on the road surface.
Aerodynamic drag coefficient:	This parameter is a dimensionless quantity that is used to quantify the drag or resistance of a body in a fluid environment such as air. This value depends on the general form of the body and is an estimated value that is deduced from the comparison of the motorbike's body to the most representative general form such as a cylinder/sphere/etc. For the motorbike this value is assumed to be:
r-wheel:	Radius of the wheel under traction.
Powertrain efficiency:	The combined efficiency of the motor and transmission.
Battery to wheel efficiency:	Powertrain efficiency including the battery efficiency.

With the abovementioned parameters, the tractive power, energy and torque requirements for the motorbike can be calculated by using the following kinetic vehicle equations. The road load force is given by Eq 6.1:

Eq 6.1: $$F_{RL} = F_{grade} + F_{roll} + F_{AD}$$

whereby,

Eq 6.1.A: $$F_{grade} = mg\, sin\beta$$

Eq 6.1.B: $$F_{rollresist} = mgC_{rr}$$

Eq 6.1.C: $$F_{AD} = \frac{1}{2}\rho C_d A_f v^2.$$

The tractive force is given by Eq 6.2:

Eq 6.2: $$F_{TR} = k_m m \frac{\partial v}{\partial t} + F_{RL}$$

whereby,

km = inertial mass factor (-)

m = total vehicle mass + rider (kg)

$\frac{\partial v}{\partial t}$ = acceleration (m/s^2).

From the tractive force, the tractive power is determined by Eq. 6.3:

$$\text{Eq 6.3:} \qquad P_{TR} = F_{TR}\, v_{mc}$$

whereby,

v_{mc} = motorbike speed (m/s)

F_{TR} = tractive force (Nm).

P_{TR} = tractive power (W).

From the tractive power, the tractive torque can be determined with Eq. 6.4:

$$\text{Eq 6.4:} \qquad T_{TR} = P_{TR} * (\frac{r_{wh}}{v_{mc}})$$

whereby,

r_{wh} = traction wheel radius.

To determine the required motor power and torque the following equations are used.

$$\text{Eq 6.5:} \qquad P_m = P_{TR} / (\eta_{powertrain})$$

whereby,

P_m = motor power (W)

$\eta_{powertrain}$= powertrain efficiency.

$$\text{Eq 6.6:} \qquad T_m = T_{TR} / (\eta_{powertrain})$$

T_m = motor torque (Nm).

From the tractive power the tractive energy can be determined using the following equation.

$$\text{Eq 6.7:} \qquad E_{TR} = \int_{t=0}^{t=tf} P_{TR}\; dt$$

whereby,

E_{TR} = Tractive energy (J)

t_f = travel time (s)

6.1.2 Battery pack design with the MATLAB model

The model's use can be extended to determine practical battery capacity. With the energy calculated by the vehicle kinetics model, the required number of cells can be determined based on battery operational requirements and specifications. By considering specifications such as the battery shall not be used below a SoC below 10% and shall not be charged to a SoC higher than 95%. This results in an effective use of battery capacity of 85% which will require a higher designed battery capacity than initially determined by the basic model.

Furthermore, when motor specifications are known, the battery discharge current can be determined for a given load and specifications can be made to restrict discharge current per battery cell in benefit of lower operating temperature. So, by specifying a maximum operation temperature of the cell, the maximum allowable discharge current of the cell will be determined, and battery configuration will be influenced. Additional battery parameters to be specified for battery design with the model are:

Parameters and details to be specified for battery pack design:

Cell type and model:	This dictates the characteristics of the battery
Cell voltage:	This is the voltage of the individual cell
Battery pack voltage:	This is the voltage of the battery pack
Minimum SOC:	This is the bottom limit to which the battery is to be discharged.
Maximum SOC:	This is the upper limit to which the battery is charged.
Cell capacity fade:	This is the reduction in cell capacity over time/after x-cycles
Max. Operational cell temp:	This is the operating temperature of the cell, primarily in correlation with the discharge current.
Max. Discharge current spec:	For known load, the maximum current which is discharged from a cell. Not to be confused with the max discharge current that the cell is capable of.
Battery to wheel efficiency:	Powertrain efficiency including the power supply efficiency.
#cells series:	This is the number of cells connected in series to achieve the battery pack voltage
#cells parallel:	This is the number of cells connected in parallel to achieve the battery pack capacity.

Using the battery to wheel efficiency, the tractive energy determined earlier can be used to calculate the battery energy required. From the required battery pack voltage and the cell voltage the number of series connected cells can be determined.

Eq 6.8: $$\#cells_{series} = V_{pack} / V_{cell}$$

V_{pack}= Battery pack voltage

V_{cell}= Cell voltage.

With the maximum discharge current per cell specified and the maximum motor current known, the number of parallel cells can be determined. It must be noted that, this is the minimum number of parallel cells required to avoid that the cell discharge current exceeds its specified value. Furthermore, the required battery energy will dictate if addition parallel cells are required to increase the capacity of the battery. This can be done in the model until the required battery energy is achieved.

The available charge in the battery is given by the following equation:

Eq 6.9: $$C_{charge} = SOC_{max} - SOC_{min}$$

whereby,

C_{charge} = Available charge (%)

SOC_{max} = max state of charge (%)

SOC_{min} = min state of charge (%).

To compensate for capacity fade over time, the following equation is used.

Eq 6.10: $$C_{design} = C_{fade} * C_{charge}$$

Whereby,

C_{design} = % design capacity for the battery (%)

C_{fade} = cell capacity fade (%)

With the % design capacity for the battery and the earlier determined battery energy, the design battery energy can be determined.

Eq 6.11: $$E_{practical} = E_{TR} / C_{design}$$

$E_{battery\ design}$ (Wh) = the required installed battery capacity.

6.1.3 Model inputs

The input to the vehicle kinetics model is a drive cycle that represents the driving conditions that the motorbike is intended for. It is important that the drive cycle most accurately represents real life driving behavior for the intended type of use, in this case urban driving for L1E category vehicles in urban environments. L1E vehicles have a speed restriction to 50km/hr which restricts the use of most popular urban drive cycles. Selection criteria for drive cycles are the maximum speed of the drive cycle, the operating environment for which the drive cycle represents driving behavior and the category vehicle for which the drive cycle is intended. After researching drive cycles suitable for L1E power train design, the World Motorcycle Test Cycle (WMTC) was identified as a potentially suitable drive cycle. The part 1 of this drive cycle has a limited speed to 50km/hr and is intended for low powered motorcycles with a similar performance to a 50CC moped/scooter.

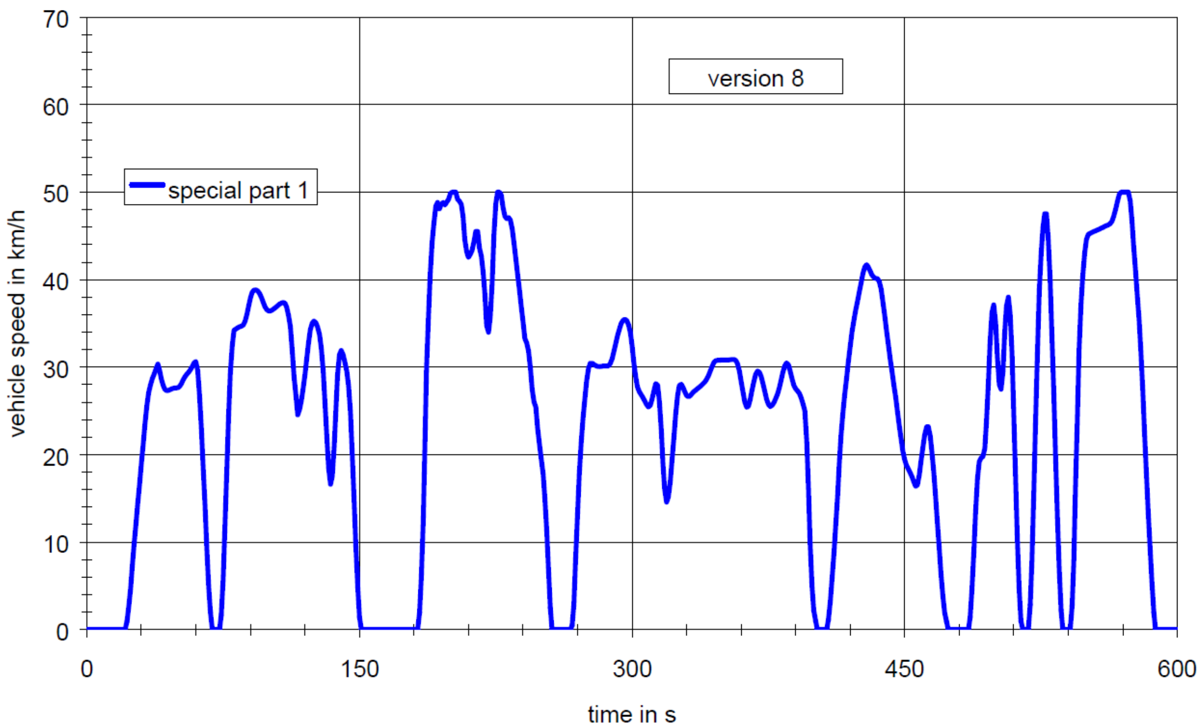

Figure 21: WMTC for low powered motorcycles

6.1.4 Model output and results

The model outputs the maximum power required for the drive cycles. Also, the distance traveled in meters and the energy required to travel that distance is calculated by the model. The model also calculates the power requirements at the constant maximum speed of 50km/hr for the given vehicle specifications. When further utilizing the model for battery module design, the model will further output effective installed battery capacity required and output the number of cells required and in which parallel series configuration.

6.2 Powertrain, power supply and electric system design

The powertrain converts electric energy to mechanical energy and transfers this to the road surface in the form of tractive force. The power supply provides power to the powertrain and all other electric loads in the motorcycle system. The motorbike's electric system is the electrical interface which transfers the electric energy from the power supply to all loads. This system includes all auxiliary electric devices in the motorbike such as lighting, voltage converters, etc.

The strategy implemented for powertrain and power supply system design was to divide the total design problem into smaller, more manageable portions. For each component, unknown specifications must be determined such that the system fulfills its intended function. First these specifications were identified, then the sequence of designing these parts and determining their specifications was established.

Figure 22 illustrates the start-off point in the powertrain – power supply design and which design specifications must be determined.

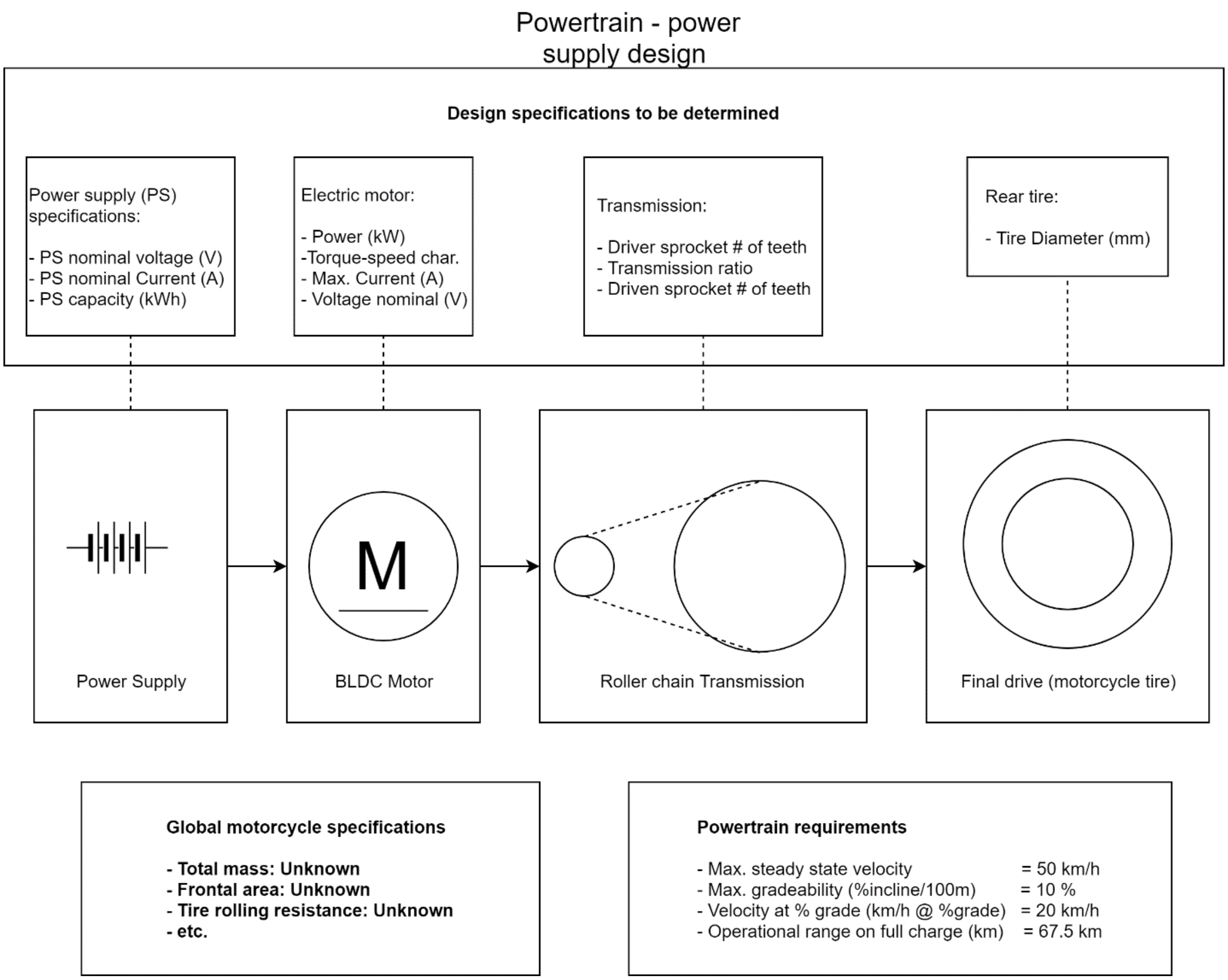

Figure 22: Starting point for powertrain and power supply design

Figure 23 illustrates the workflow and sequence of the design process for the powertrain. Based on the physical interaction of the powertrain and power supply components seen in the powertrain IBD of chapter 5, their inter-dependencies regarding, function, specifications and compatibility, the following sequence for designing/selecting components was implemented.

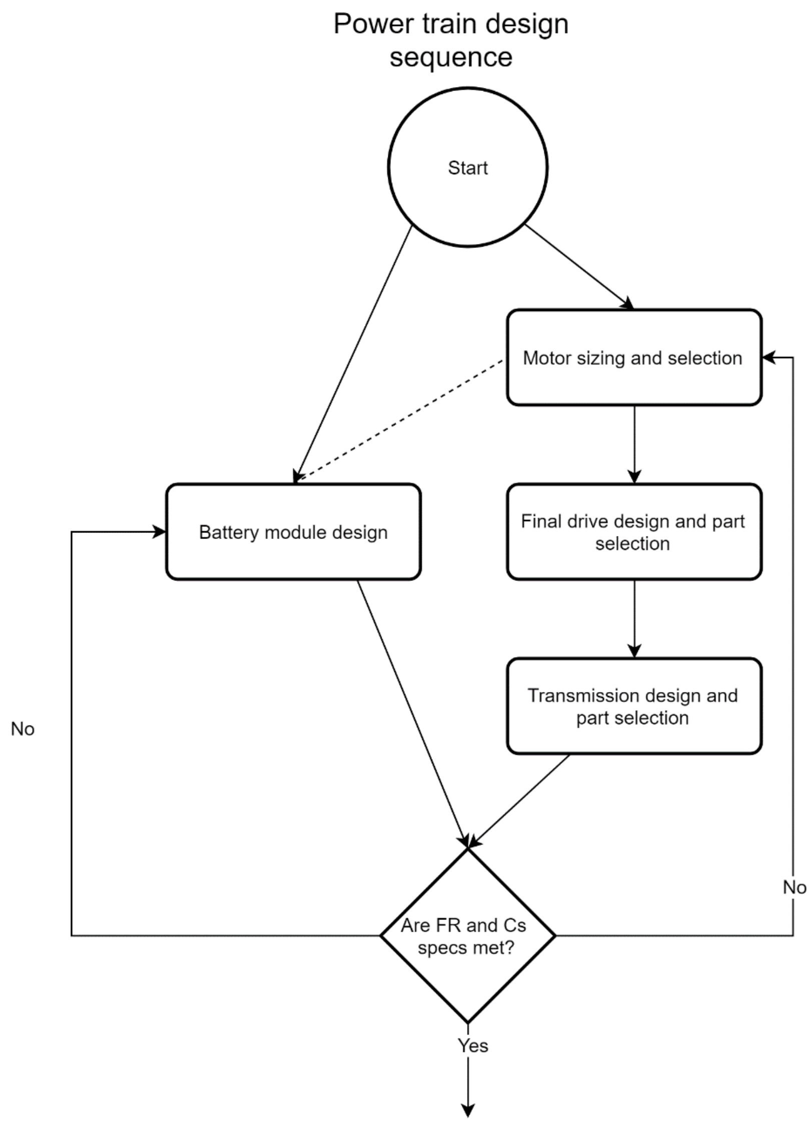

Figure 23 Power train - power supply design workflow

First the motor is selected based on initial assumption (mass & frontal area) for which the power requirements are determined by the MATLAB model for the drive cycle. Then, the selected motor dictates the voltage level of the system and the power rating, after which the battery can be designed. The battery is designed based on motor power rating, motor voltage, cell discharge rates, allowable operating temperature of the cells, assumed losses in the powertrain and energy requirements. Furthermore, the final drive is specified after which the transmission is designed based on the power rating of the motor and the required final drive speed. This process although sequential is an iterative process in the sense that it is repeated as the vehicle design develops and more details are fixed.

6.2.1 Electric motor, motor drive and controls selection

In the concept design phase, it was decided to use a brushless dc electric motor for the motorcycle powertrain. In the detailed design phase, the motor power, the motor voltage, the torque and speed are determined, i.e. the motor is sized/selected. The design problem for selecting the right motor is formulated as: Select a BLDC motor such that the power rating, torque and speed characteristics, satisfy the performance requirements and constraints of the motorbike.

Initial simulations of the WMTC drive cycle have indicated a required maximum tractive power of 4056W. These results are based on the following vehicle parameters, for which the total mass and frontal area are temporary assumed values until the vehicle is assembled and these values can be set to more precise values.

Vehicle parameters

Parameter	Value	Unit
Mass	160	kg
Inertial mass	167.5	kg
Frontal area	2	m^2
Rolling resistance coeff.	0.01	-
Aerodynamic drag coeff.	0.38	-
Air density	1.23	g/cm^3

Table 21: Vehicle parameters for preliminary powertrain design

Based on the abovementioned power requirements and the constraints present, two 3kW motors of the manufacturer Golden Motors were identified as suitable candidates for the motorbike. 3kW motors have a peak power around 5000W and can handle the power requirements for the WMTC drive cycle. The 5000W peak power of the motors does not violate legislation given that the constraint considers continuous rated power. The main difference between these motors is operating voltage of 48V and 72V respectively. It was decided to use the 72V motor based on lower operating currents (thus lower i^2r electric losses). Also, the 72V 3kW motor has 20% more torque than the 48V counterpart. Furthermore, the 72V motor has a slightly lower RPM rating which reduces the transmission ratio required to achieve the desired final drive speed. The selected motor is illustrated by figure 24.

Figure 24: HPM 3000 (3kW) air cooled BLDC motor by Golden Motors

Golden Motors provides along with their motors, motor drives and throttle controls specially tailored to the motor. It is decided that these components are used for this motorbike design and therefore there shall be no detailed design of these components. The motor controller selected is the VEC 200 motor controller as illustrated in figure 6.6.

Figure 25: VEC 200 Motor controller compatible with 3kW BLDC motor

6.2.2 Final drive (rear tire) selection

The rear tire selected for the motorbike is the 120/90 R17

The diameter of this tire is equal to 647.8mm. This equals to a circumference of 2035mm. A speed of 50km/hr, i.e. 13.89m/s, thus dictates 6.83 rotations per second. This equals to 409.5 rotations per minute. The 120/90 R17 is a radial tire which eliminates the use of tubes.

Figure 26: Michelin commander tire

6.2.3 Transmission design

The motorbike transmission is designed to transfer the power of the motor to the rear wheel of the motorbike and achieve the intended maximum speed of the motorbike. Given that BLDC motors' nominal operation speed is around 2000-3000 rpm. The transmission should convert the motor speed to the desired final drive speed. The desired final drive speed is determined by the maximum speed of the motorbike and the tractive tire diameter. It becomes thus evident that the tire size should be known before the transmission can be designed.

Given the required rotations of the final drive and that of the motor, a transmission ratio of between 4.88 and 7.32 must be implemented for a motor with 2000 and 3000 rpm respectively. To avoid large transmission ratios, it is decided to use a motor with a 2000rpm speed rating, which can be specified to the supplier. This motor has a maximum torque of around 30Nm. From the model, the required tractive torque is determined to be 138Nm. This requires a transmission ratio of 4.6 from the transmission.

For the transmission type, belt drives were compared to chain drives. Based on the power rating of the motor, rotational speed and transmission ratio, it was difficult to find standard/OEM parts to design a belt drive for this application. A belt drive design would require the use of a custom belt, however, with a chain drive standard components could be used. For this reason, it was decided to use a chain drive for this application.

The first step in chain design is selecting the right roller chain for the motor power and rotational speed of the motor. The second step is to select the sprockets for that chain size and determine the number of teeth for the driver and driven sprocket. To ensure uniform wear over the chain and the sprocket, an even number of chain pitches is used on an odd number of sprocket teeth. An even number of chain links eliminates the need to use a cranked link, which reduces the chain breaking strength by 20% [REF]. When selecting the chain size, a pre-selection is conducted based on the DIN 8187 performance diagram in figure 6.7, whereby the speed of the driver sprocket and the power of the motor are the determining criteria.

Power output of BLDC motor	P_{motor}	= 3kW
Driver sprocket speed	n1	= 2000 RPM
Target Driven sprocket speed	n2	= 433.44 RPM
Target transmission ratio:	t	= 4.6

BRITISH STANDARD CHAINS PERFORMANCE DIAGRAM DIN 8187

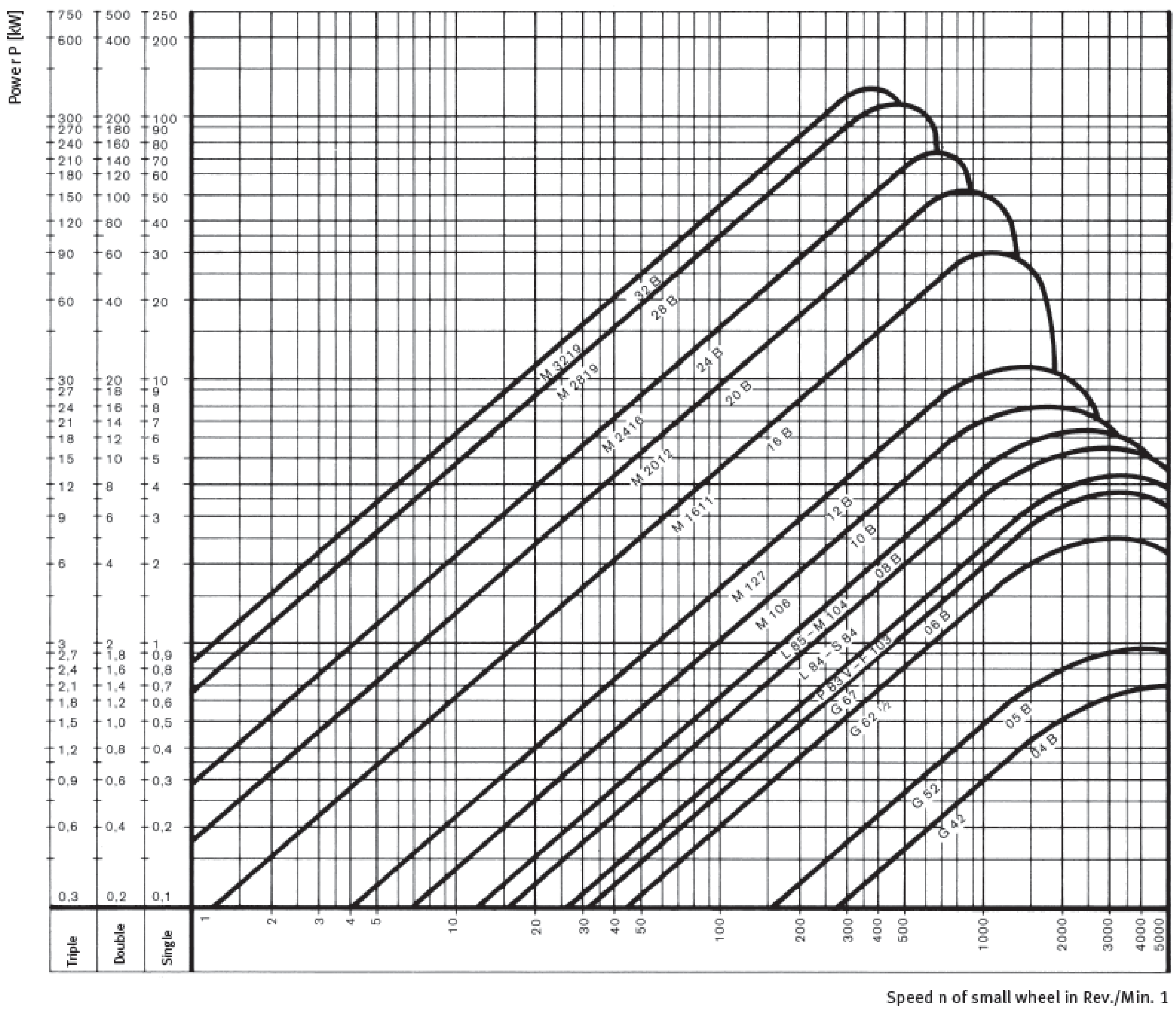

Figure 27: DIN 8187 British standard chain performance diagram

Based on the motor power and the motor speed, the 06B size chain was selected. To evaluate the initial chain selection, the following factors must be considered:

Factor 1 (f1):	Effect of the number of teeth of the small sprocket z (initially assumed to be z1 = 17 which results in a value of f1 = 1.12);
Factor 2 (f2):	Effect of the transmission ratio (i), for which a value of 4.6 results in a value of f2 = 0.92;
Factor 3 (f3):	Effect of shock factor (Y) which is assumed to be of level 1, thus the value of f3 = 1;
Factor 4 (f4):	Effect of ratio of center distance (a/p), whereby a is the estimated shaft center distance and p is the chain pitch; f4 = 0.955
Factor 5 (f5):	Effect of lubrication; Assuming perfect lubrication which results in f5 = 1.
Factor 6 (f6):	Effect of number of sprockets, for which f6 = 1 in the case of a drive comprising of 2 sprockets/shafts.

Values for these factors can be found in Appendix.

With the factors above, the diagram power P_d can be calculated and the initial chain selection can be evaluated.

Eq. 6.12 $$f_g = Product(\, f_1 : f_6)$$

Eq. 6.13 $$P_d = P.f_g$$

From Eq. 6.12, f_g = 0.984032 and therefore P_d = 2.952W

From the table it can be concluded that the initial selection is correct.

To evaluate the impact of the assumption of the shock factor on the selected chain, the shock factor level is increased to level 2. The f_g = 1.34 and Pd = 4.044kW. Now the initially selected chain is not suitable. From the diagram can be seen that the 3kW at the given speed just falls in the region where the 06B chain is suitable, however, almost any power output larger than the 3kW, immediately falls in the 08B chain range. Based on the f_g calculated earlier and an assumed safety factor, the 08B chain is selected. Based on this chain size and availability, a driver and driven sprocket with 19 and 85 teeth respectively, were selected from the SKF transmission catalog. With this selection, a transmission ratio of 4.47 is realized and matches the target transmission ratio.

Having selected the chain and the sprocket set, the number of chain links/chain length and the center distance between the sprockets has yet to be determined. The sprocket center distance depends on the distance between the motor and the final drive in the final design and is therefore determined in a later stadium of the design.

6.2.4 Power supply design

The power supply is designed based on the energy requirements as calculated by the model. Also, the system constraints determine the powertrain design. Based on the OEM part search, availability of detailed specifications and the good reputation of the manufacturer, it was decided to use the SAMSUNG INR 18650-30Q cell.

Figure 28: SAMSUNG INR 18650-30Q Li-ion cell

Target range of operation:	67.5km
Maximum Soc constraint:	Max SoC of 95%
Minimum SoC constraint:	Min SoC of 10%
Maximum Cell discharge current:	10A
Powertrain efficiency:	74.4%
Compensation Capacity Fade at 300Cycles:	75%
Calculated Energy required based on the WMTC:	1993Wh

Based on the WMTC cycle, the model has determined that 1993Wh of energy is required to drive 67,5km. Based on the abovementioned factors, a 200 Cell battery was designed. This battery has an energy capacity of 2120Wh and a 20Serie-10Parallel Cell configuration. The cells have a weight of 9600grams for which an enclosure and BMS is not included.

The battery module including BMS without external enclosure can be configured as seen in figure 29.

Figure 29: 20series-10parallel 18650 battery pack example

This configuration is to be verified once the motorcycle total mass is determined. For the 20-serie-10-parallel configuration, 2 BMS boards are selected with a maximum current handling capacity of 80A.

6.2.5 Electric system design

This section describes the design of the electric system of the motorbike which due to the scope of this project only includes a schematic design of the electric system.

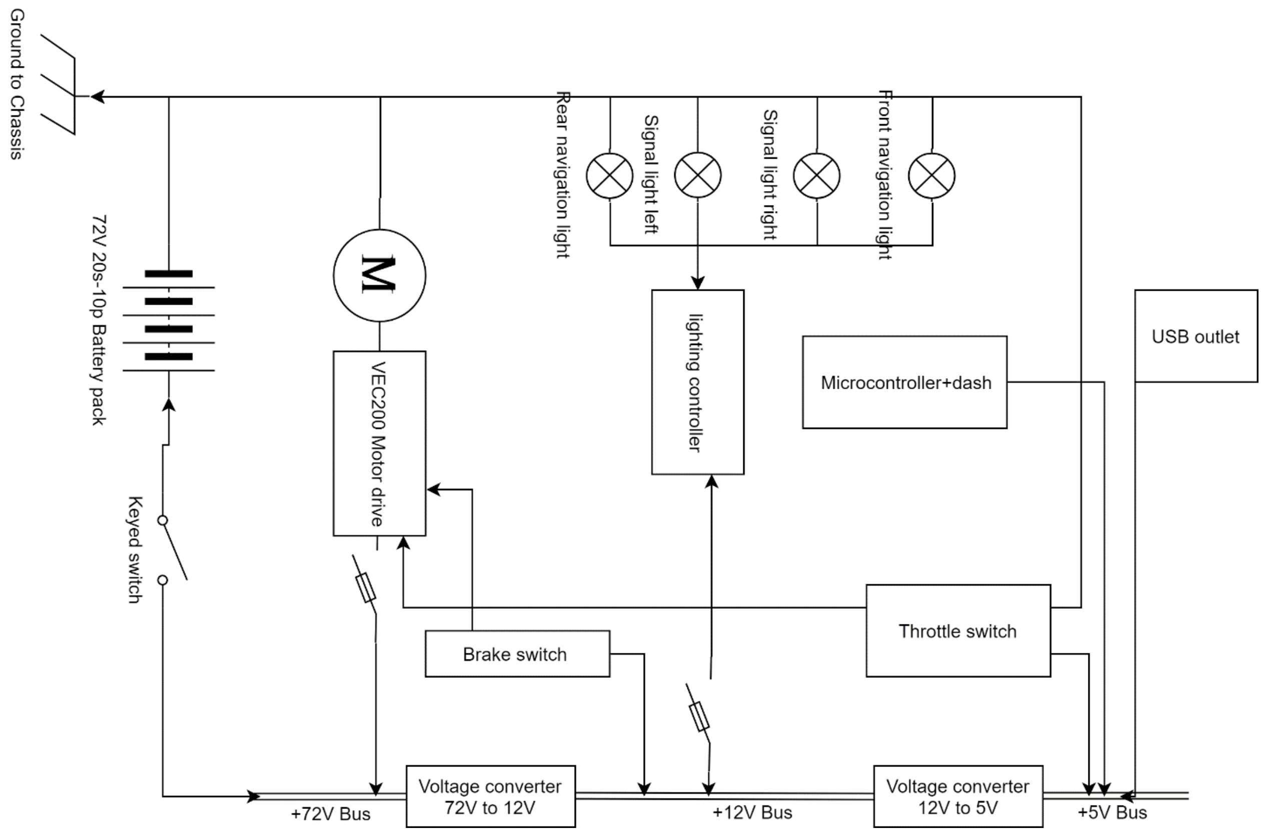

Figure 30: Electric wiring diagram for the motorbike

All loads such as the motor drive, the motor, the lights and the microcontroller/dashboard are supposed to be properly fused. Hereby a fuse is selected which is slightly above the maximum expected current rating of the specific load.

6.3 Chassis design

This paragraph documents the design of the motorbikes chassis which consists of the frame, the steering assembly and the wheels. Section 6.3.1 considers the frame design whereby first physical ergonomics and geometric parameters are considered. In section 6.3.2 a CAD model of the frame is presented along with its specifications regarding construction profiles and material selection. Furthermore, an FEA study on is presented which was conducted to evaluate and improve the structural performance of the frame. Section 6.3.3

6.3.1 Chassis geometry and physical ergonomics

Physical ergonomics:

FR_0 states that the motorcycle must be comfortable for urban transport for at least 80% of the Dutch people. Motorcycle comfort is important and largely influences the decision of the customer to buy the motorcycle or not. Motorcycle comfort is mainly determined by geometry of the frame. In contrast to a bicycle frame, which is made in several sizes and is fit to the human body, a motorcycle frame is one-size. For this reason, a motorcycle comfortable to a man with a height of 1.90m, might not be comfortable for a woman with a height of 1.60m. It is therefore important that the geometry is just right to fit an as large as possible portion of the target group. To achieve this, it is important to understand the body dimensions of the target group and how this relates to the physical interaction with the machine.

When riding a motorcycle, the body is in contact with the motorcycle at 3 locations. The hands on the handlebar-grips, the feet on the footrest (foot pegs) and the buttocks on the saddle. The imaginary connection between these points results to what is in the motorcycle industry referred to as the rider's triangle.

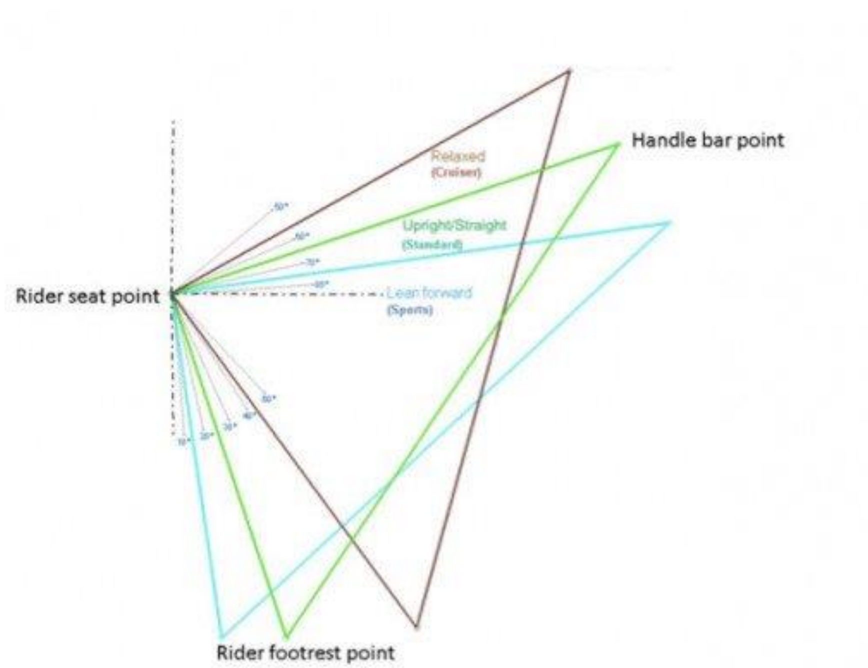

Figure 31: Rider's triangle

When the rider’s triangle is tilted forward (blue line), the hands are positioned low and the feet are arched back underneath the saddle. This is a typical posture for sport motorcycles whereby the rider is leaning forward.

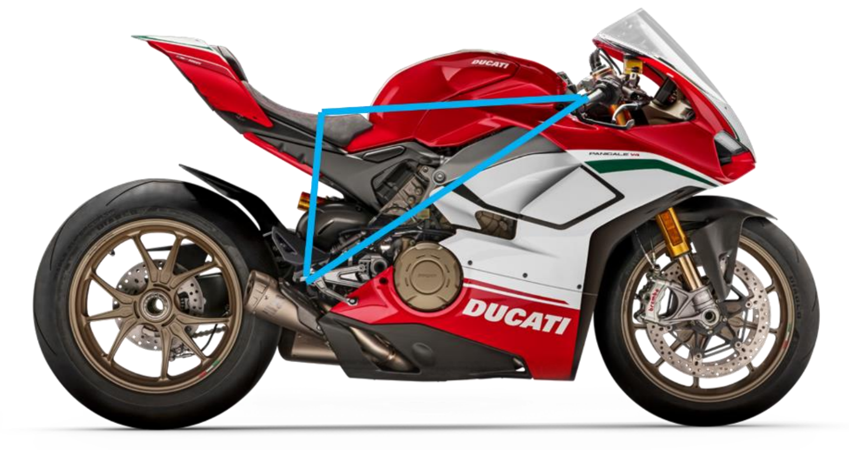

Figure 32: Rider triangle on sport bike with leaning posture

When the rider’s triangle is tilted back, the hands are positioned higher and are located almost above the knees. The feet are in front of the saddle and the rider is sitting upright. This is often a typical posture for commuter, touring and adventure motorcycles. For these motorcycles, the need for comfort outweighs that of streamlined aerodynamics.

For a low powered urban commuting machine, comfort is the most important factor when it comes to posture and therefore a posture is chosen whereby the rider’s triangle is tilted back such that an upright sitting posture is maintained.

Figure 33: Rider triangle on a Harley Davidson with comfortable posture

To ensure that the frame geometry will fit a large portion of the target users, their body dimensions are brought in relation to the rider's triangle, consequently an optimum triangle is chosen. The criteria for choosing an optimum triangle are:

- Angle between the back and the horizontal axis (90 degrees)
- Angle of the knees (90 - 130degrees)
- Angle of elbows (90-180degrees)

With the abovementioned criteria, one needs to find a rider's triangle that fits the shortest and the tallest in the target group. Before achieving this, the body dimensions of the shortest and tallest in the group are identified with the figure 6.14, which illustrates the length of body parts in relation to the total body length. This is very useful since it is easy to find statistics of body length of the Dutch people.

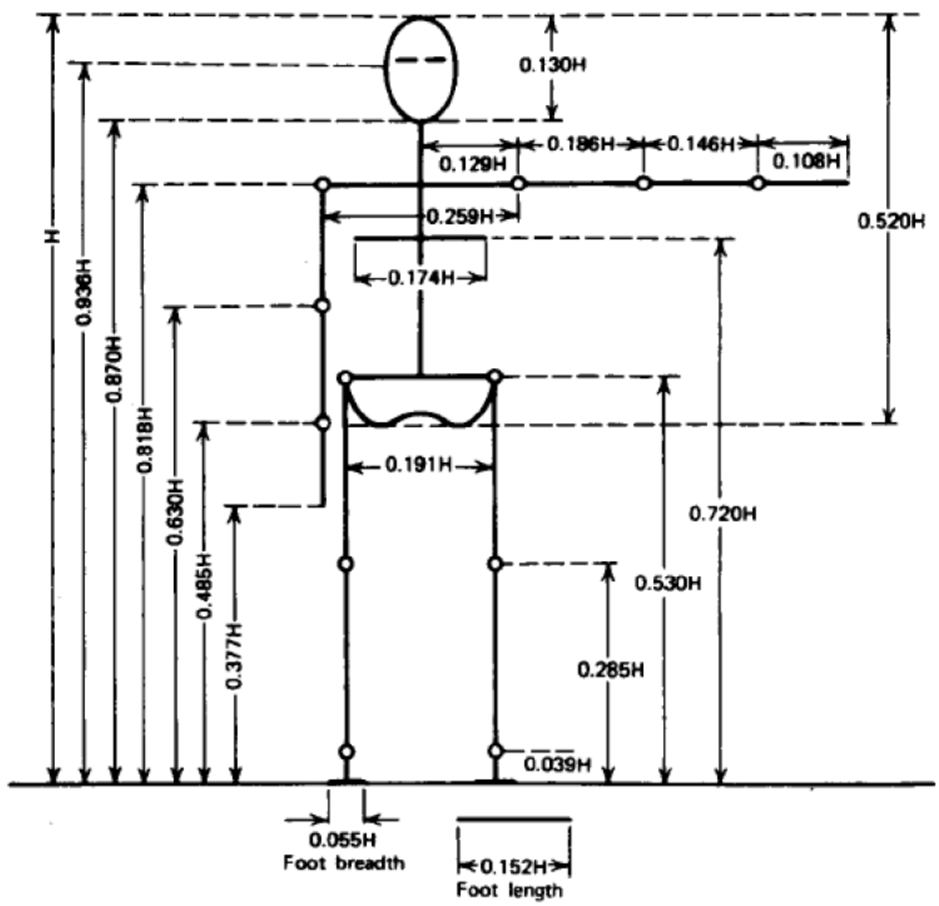

Figure 34: Body dimensions based on the body height

Onderwerpen	Lengte naar geslacht										
	Mannen										
	Kleiner dan 163 cm	163-167 cm	168-172 cm	173-177 cm	178-182 cm	183-187 cm	188-192 cm	193-197 cm	Groter dan 197 cm	Gemiddelde lengte	Standaardfout gemiddelde lengte
Leeftijden	%									cm	
Totaal 20 jaar en ouder	1,0	3,3	11,8	18,2	26,7	23,2	9,3	4,9	1,5	180,3	0,1

Onderwerpen	Lengte naar geslacht										
	Vrouwen										
	Kleiner dan 153 cm	153-157 cm	158-162 cm	163-167 cm	168-172 cm	173-177 cm	178-182 cm	183-187 cm	Groter dan 187 cm	Gemiddelde lengte	Standaardfout gemiddelde lengte
Leeftijden	%									cm	
Totaal 20 jaar en ouder	1,7	5,6	15,6	25,0	29,3	14,9	6,5	1,2	0,2	167,4	0,1

Figure 35: Body height/length dimensions of Dutch adults ages 20 and older

From figure6.15, it can be concluded that the lower limit of the length spectrum is set by women and the upper limit is set by men. By taking a minimum length of 158cm for women and a maximum length of 192 for men, at least 80% of people ages 20 and older are considered. Considering the body dimension of the target group, a rider's triangle was developed that both fits the shortest in the target group and the tallest.

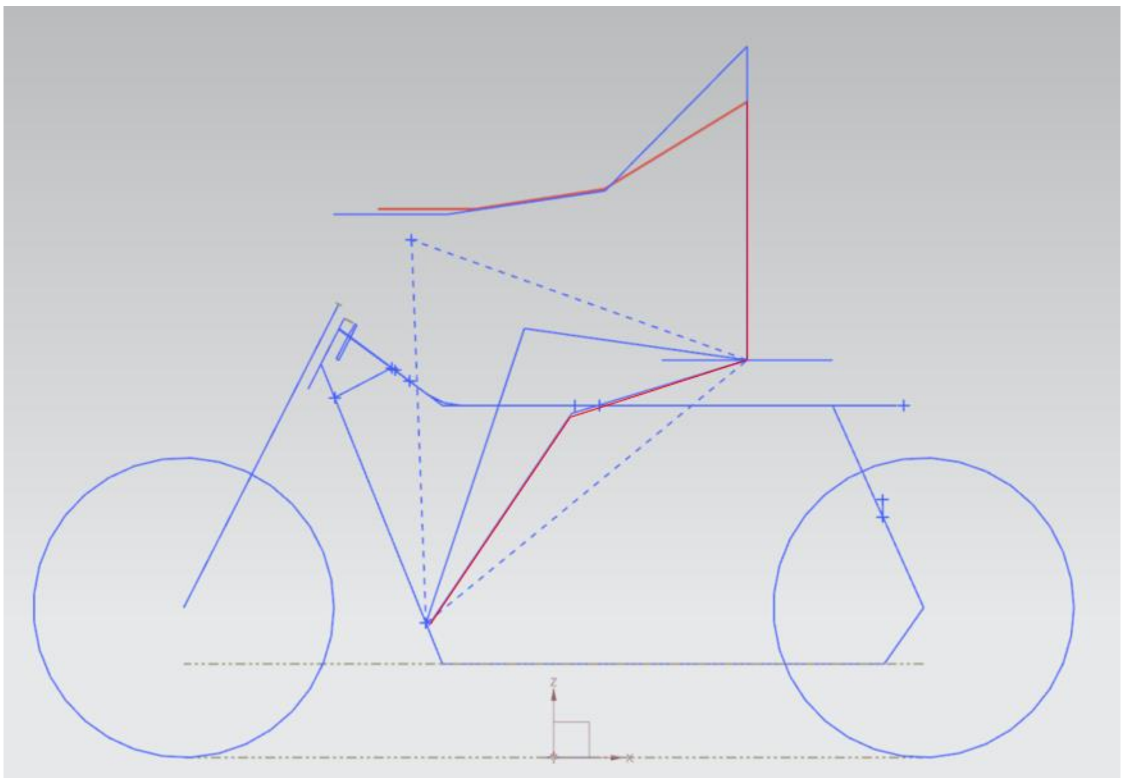

Figure 36: Determining rider triangle based on the shortest and tallest in the target group

The rider triangle defined illustrates where the body contacts the motorbike. It further established the posture on the motorbike. And it ensures that the tallest and shortest in the target group will fit the motorbike. Based on this rider triangle the contact point of human and machine are determined.

Frame geometry specs:

Wheelbase: 1300mm

A wheelbase of 1300mm has been determined to be optimum for this motorbike design. When determining the wheelbase, a tradeoff is made between directional stability and turning radius of the motorbike. A wheelbase of 1300mm is often seen in motorbikes for urban use where maneuverability is important. Directional stability is maintained for trial bikes with less than 1250mm wheelbase and thus it is concluded that with a wheelbase of 1300mm, directional stability is maintained [15].

Caster angle: 27 degrees

A caster angle of 27 degrees was taken due to popularity of this configuration. A caster angle of 27 degrees is famous of providing good directional stability and allows for enough space to construct the frame. Moreover, with limited fork offset, positive trail can be achieved.

Seat height: 700mm

This seat height is based on ergonomics and allows the target group of riders to support the motorbike when at rest with at least one foot on the road surface.

Ground clearance: 165mm

The design criteria for the ground clearance has been that the motorcycle should be able to bank at a 45-degree angle. Hereby the foot pegs should not tough the road surface.

Trail: 112mm

The trail is a result of the abovementioned geometry specifications. To ensure directional stability the trail must be positive.

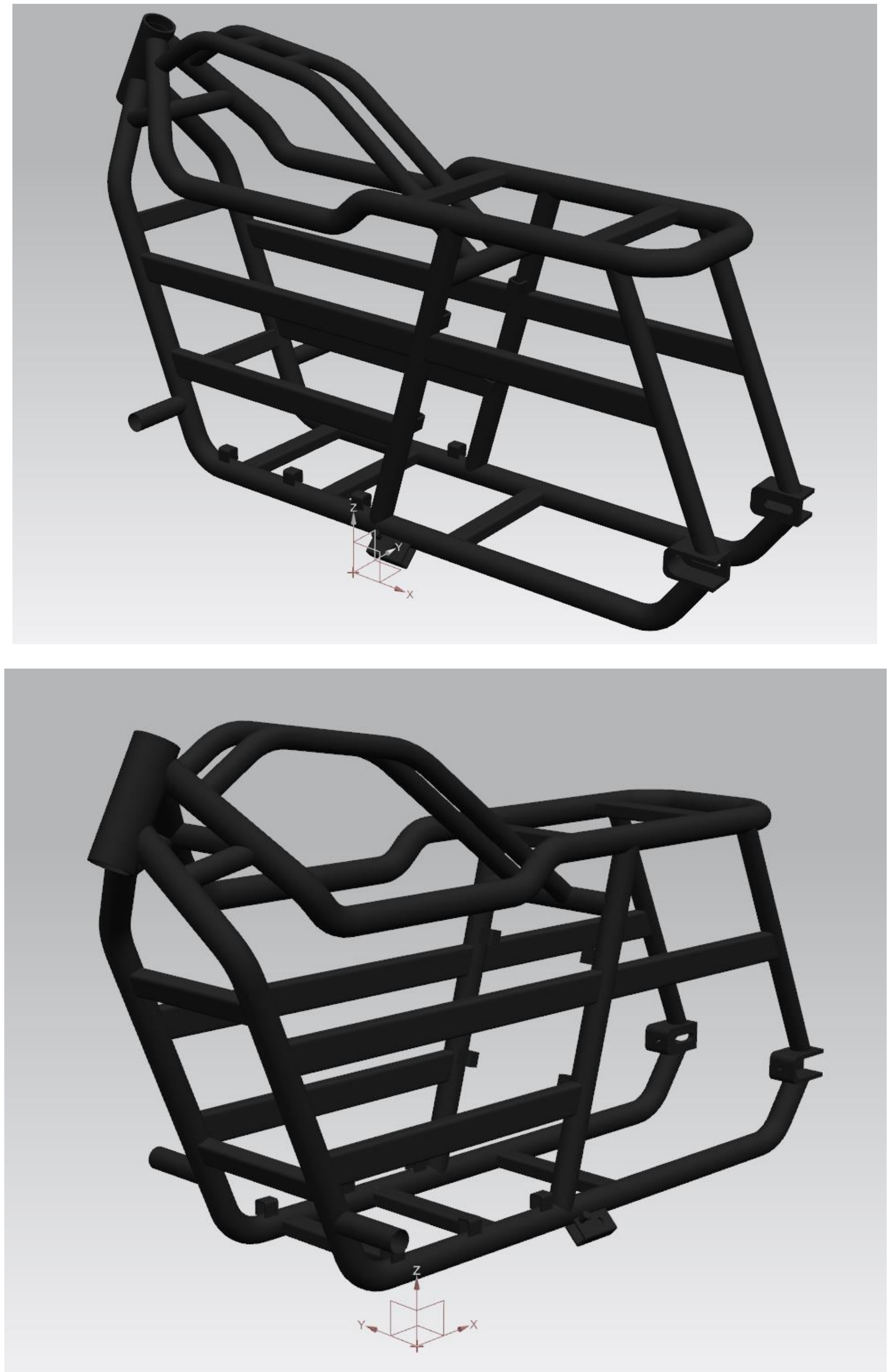

Figure 37: Concept frame design

Tubular and rectangular profiles used:

The structural profiles used for the design and construction of the frame are tubular and square. The tubular and square profile sections are standard tubing available at most manufacturers and as indicated by the OEM sourcing study conducted earlier. The dimensions of these tubes can be referenced in the CAD drawings presented in APPENDIX. Based on material properties and common use in the industry, it was decided to use AISI 4130 steel as construction material for the frame. The weldability, strength, ductility and stiffness to weight ratio are very suitable for motorcycle frame design.

Structural Stiffness:

The structural stiffness of a motorbike's assembly and of each part of the motorbike is key to good performance regarding handling and maneuverability [15]. The important parts considered here are the front fork, the frame front and the swingarm/frame rear.

If a motorbike's frame has enough lateral and torsional stiffness, the stability of the motorcycle no longer depends on the structural characteristics [15]. High stiffness values guarantee that there is precision in the trajectory and a quick response to the input of the rider. From a handling and maneuverability perspective, the frame's function is to maintain geometric dimensions under operational loads. The frame's ability to achieve this can be evaluated through measuring the stiffness properties of a design. Measuring stiffness of a frame may be carried out utilizing several different approaches.

Based on literature research it was difficult to find a method that accurately determines absolute values of frame stiffness. The essence of measuring stiffness is to determine deformation of the frame for a given load, which essentially can be seen in the units of stiffness (N/mm for translation displacement and N/° for angular displacement). The deformation of interest is where the axles are intersecting the vertical symmetric plane of the motorbike, as indicated by the red dots in figure 6.18. Measuring displacements at these points might not be the most accurate method to obtain absolute values of stiffness, however, it can be used as a qualitative point of reference to improve the frame design and to evaluate design changes relative to an old design.

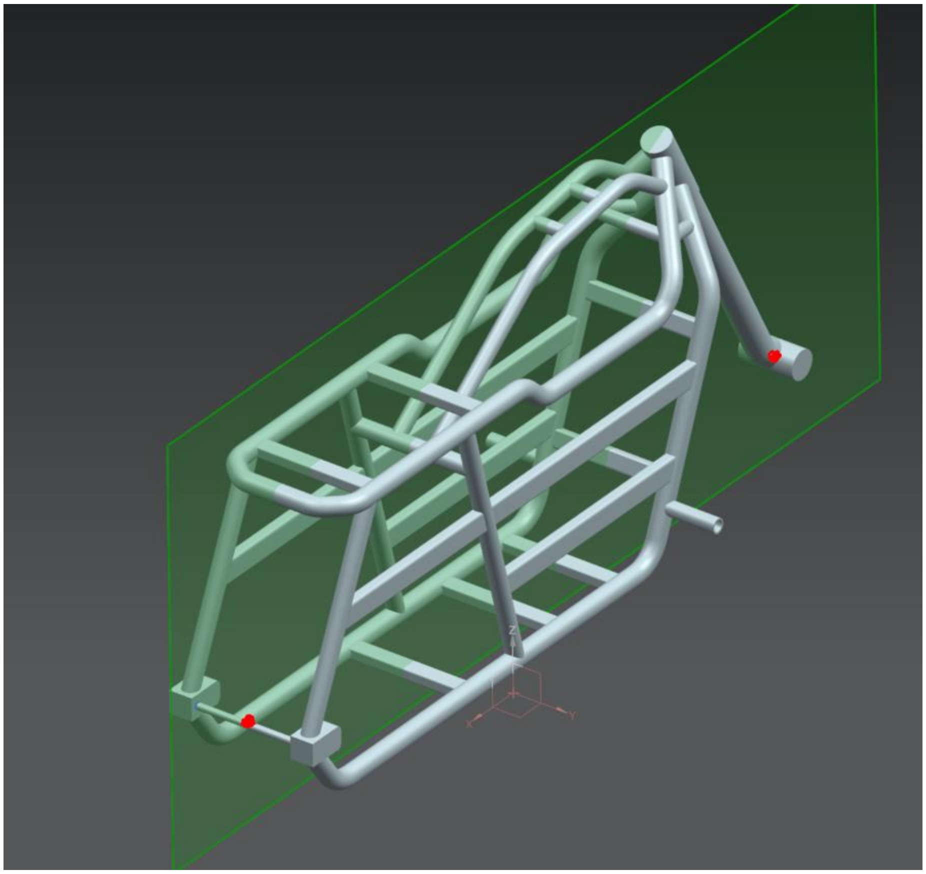

Figure 38: Points of reference in the wheel axles

Indications for target frame stiffness are provided by Table 6.2 [15]. The drawback of these reference values is that they are values of 1000CC sport bikes, which operate at speeds up to 300km/hr. Therefore, these values might not be suitable for a 50km/hr bike, but due to lack of reference values, these values shall be used as reference and target values. The design objective is therefore to optimize the design, such that the stiffness approaches the order of the values provided.

	Range	Unit
Lateral stiffness rear axle – front fork	0.1 – 0.2	kN/mm
Torsional stiffness rear axle – front fork	1.5-3.0	kN/°

Table 22: Reference frame stiffness for 1000CC motorcycles

6.3.2 FEA study of the MK3 frame

It is important to notice that FEA is conducted throughout the frame design process in an iterative manner, whereby the frame's "weak" spots are re-enforced/ adjustments are made.

Lateral stiffness

Scenario 1: Lateral loading at the steering head for measuring of the lateral stiffness whereby the rear axle is fixed. Hereby the lateral stiffness of the entire frame is determined.

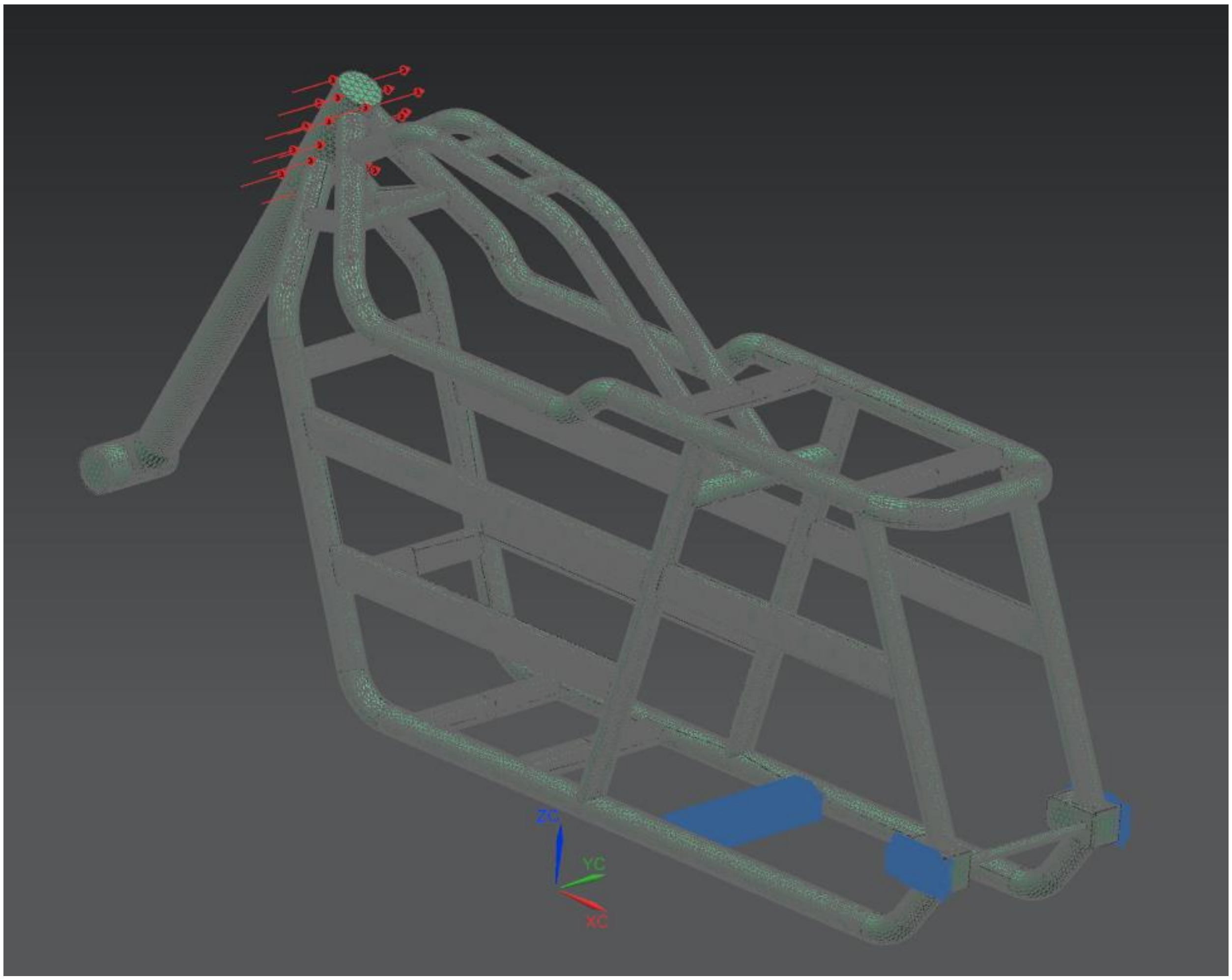

Figure 39: Scenario 1 Lateral stiffness loading and constraints

Results lateral stiffness scenario 1:

Scenario 1:

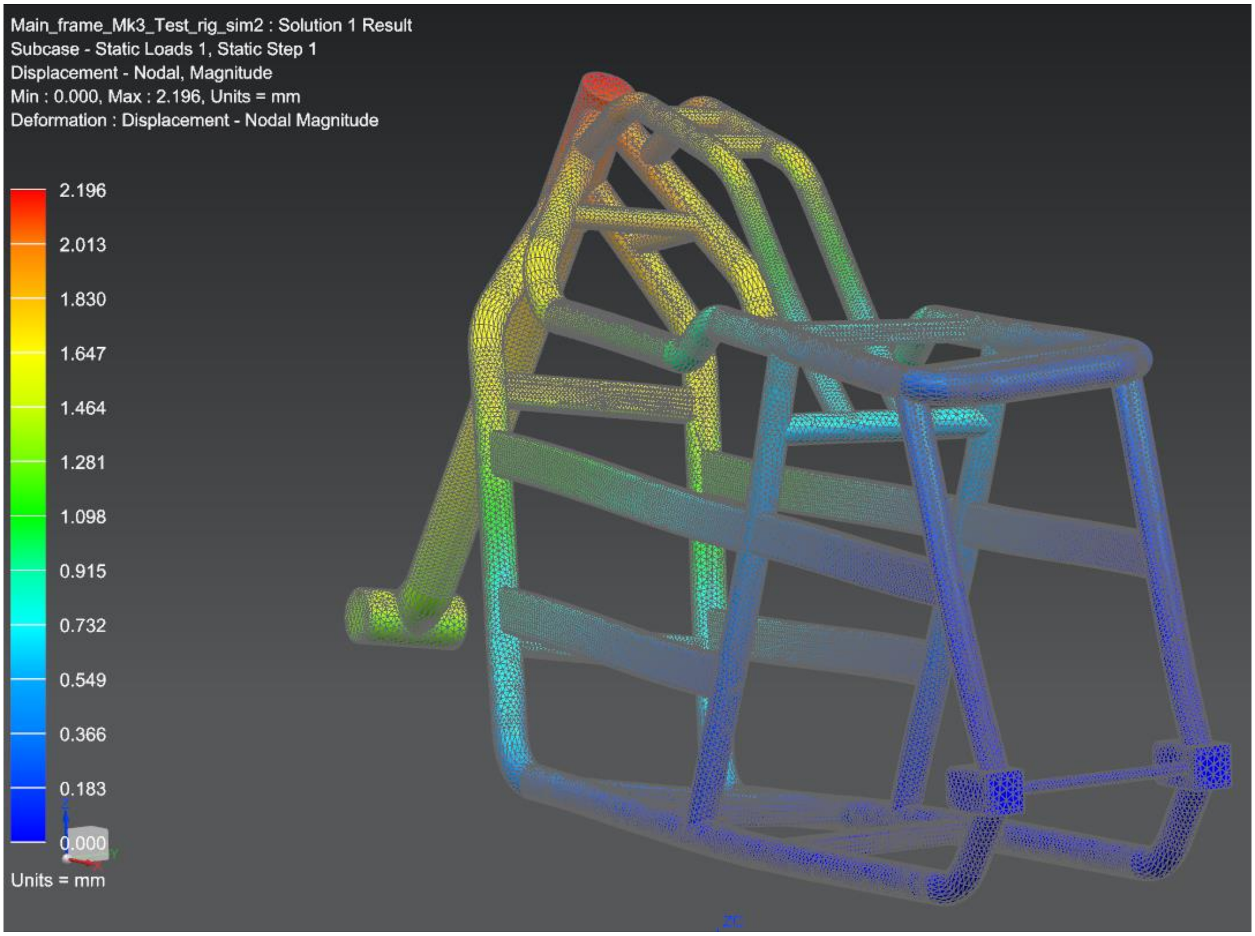

Figure 40: Results lateral stiffness scenario 1

From the FEA results of scenario 1, a lateral displacement of 2.196mm is measured. The lateral stiffness is equal to: 1000N/2.196mm = 544.3N/mm.

Scenario 2: Lateral loading at the rear axle for measuring of the lateral stiffness.

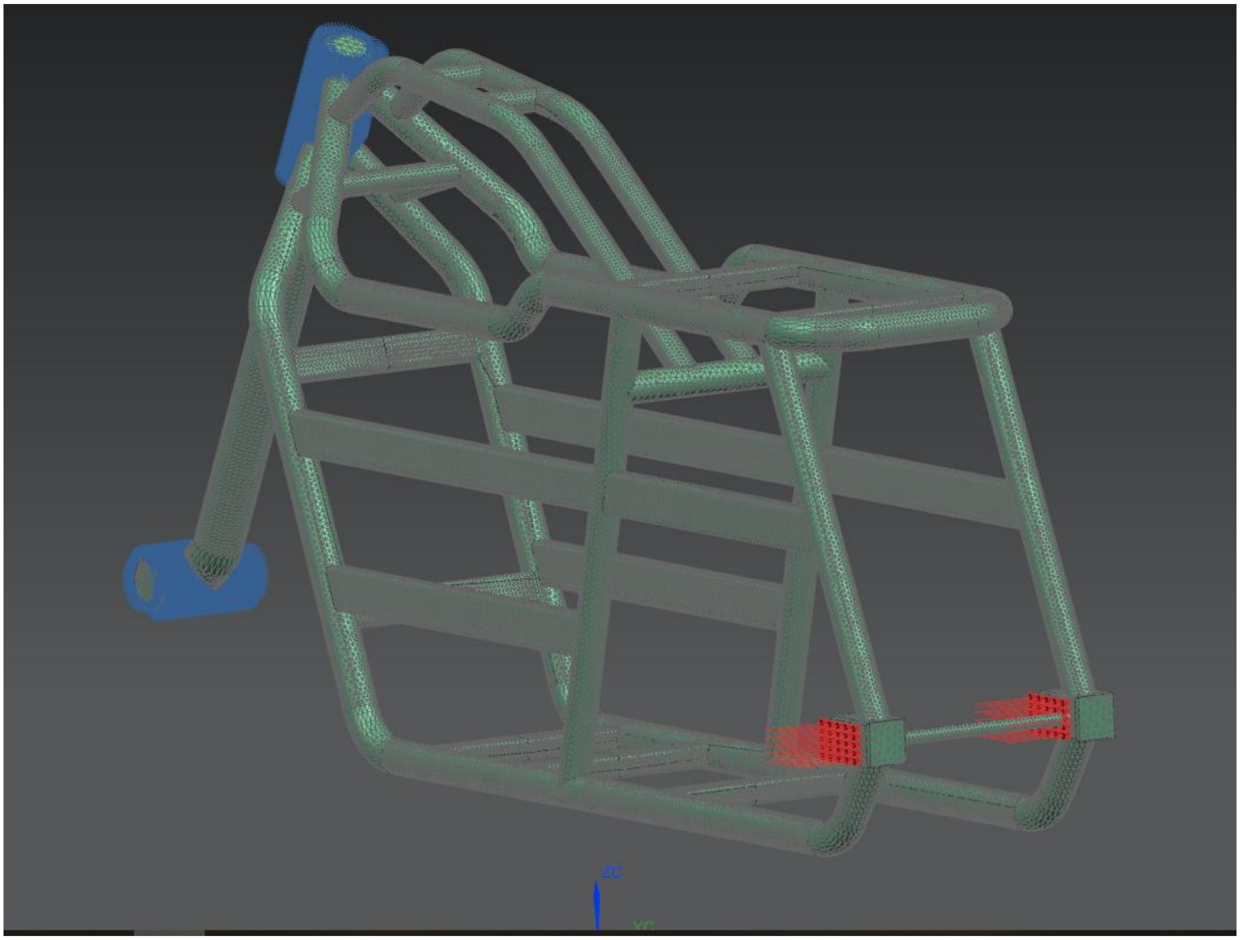

Figure 41: Loading conditions scenario 2 - steering head fixed - 1000N lateral force rear axle

Results lateral stiffness scenario 2:

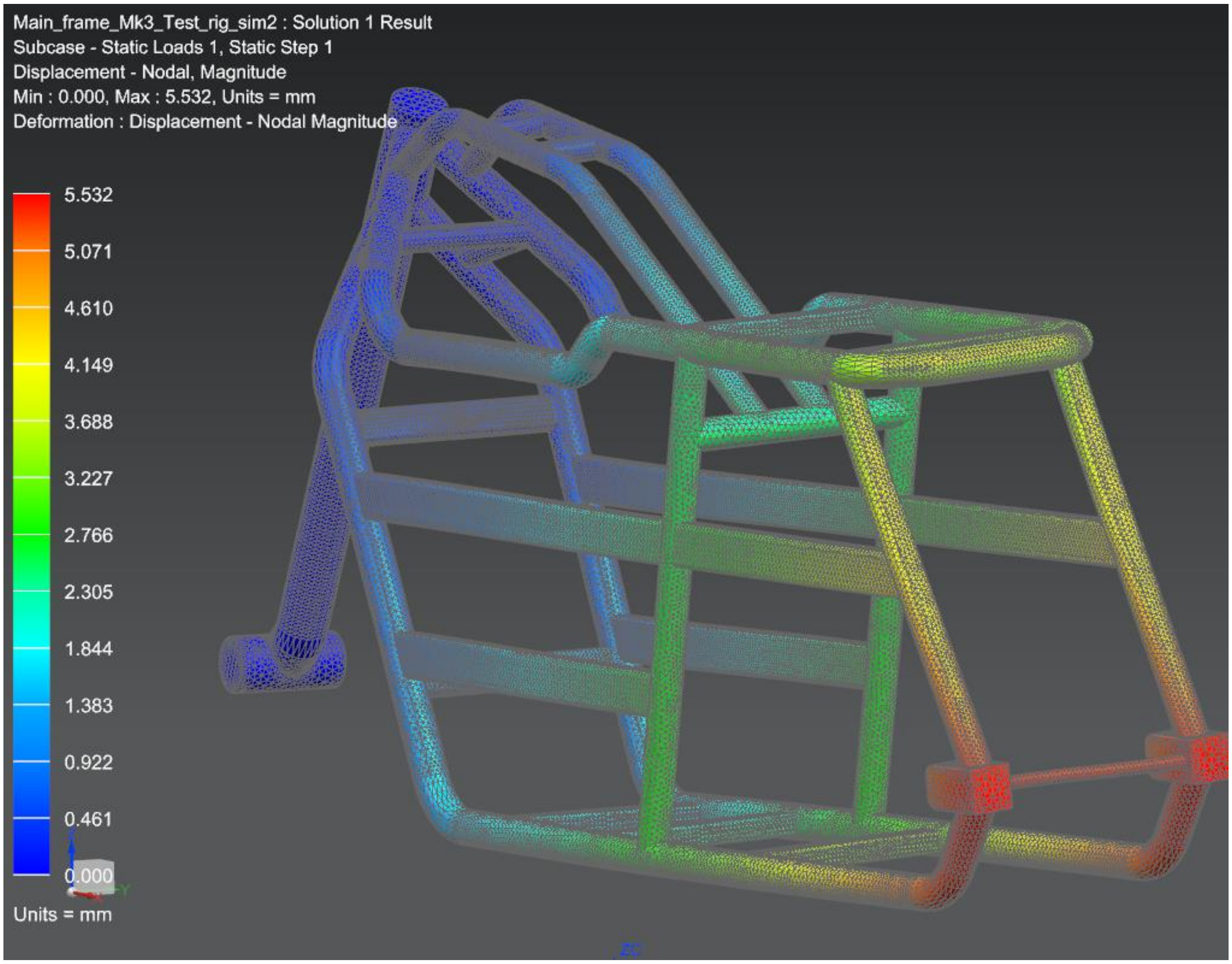

Figure 42: Results lateral stiffness scenario 2

From the FEA results of scenario 2, a lateral displacement of 5.532mm is measured. The lateral stiffness is equal to: 1000N/5.532mm= 180.8N/mm.

Torsional Stiffness

Scenario 1: 1000N Force exerted on the front axle in lateral direction assuming 100% stiff fork

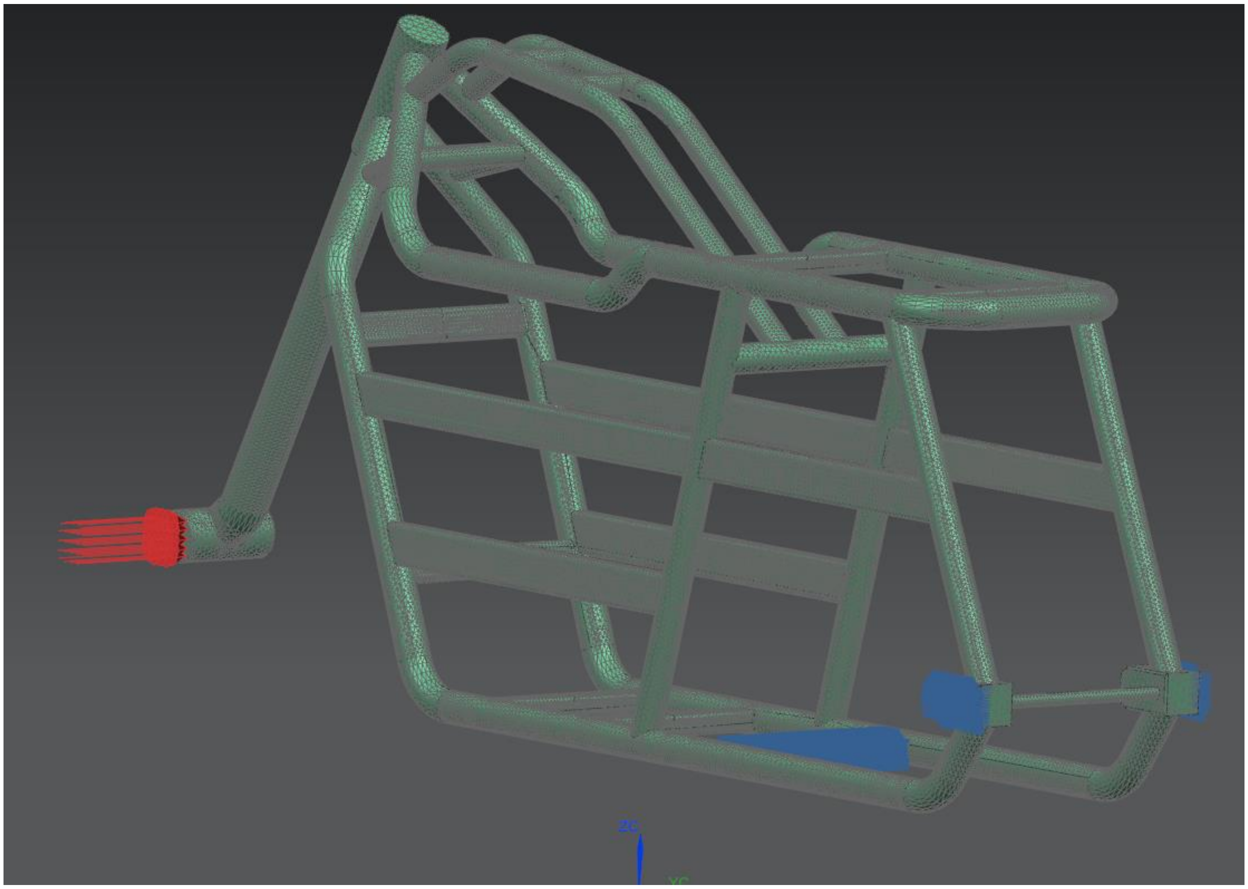

Figure 43: Torsional stiffness loading scenario 1 loads and constraints

Results torsional stiffness scenario 1:

Scenario 1 imitates torsional loading of the frame when cornering. This torsional loading is not only torsional and has a lateral component. For this reason, displacement results cannot be compared to the reference torsional stiffness. Scenario 1 is for indicative purposes to analyze how the frame reacts to loads exerted by the wheel during cornering.

Scenario 2: 3000Nm torque applied to the frame's steering head. Hereby the frame is locked in a test rig as seen in Figure 6.24. This setup allows only for torsion in the frame and prevents any other lateral displacement.

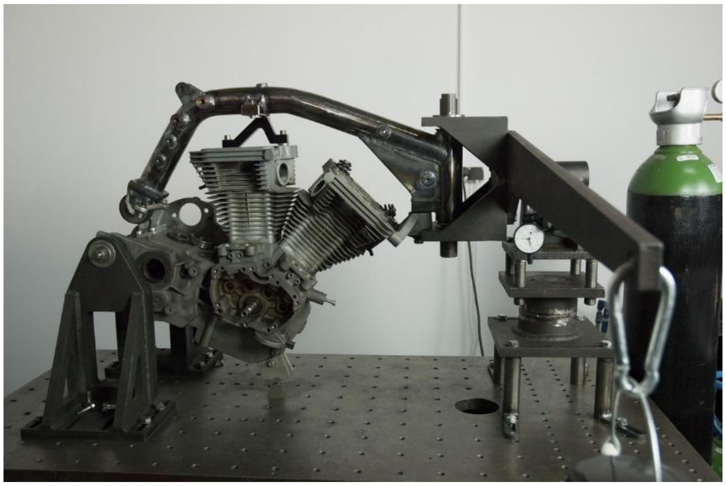

Figure 44: Test rig for torsional stiffness measurements

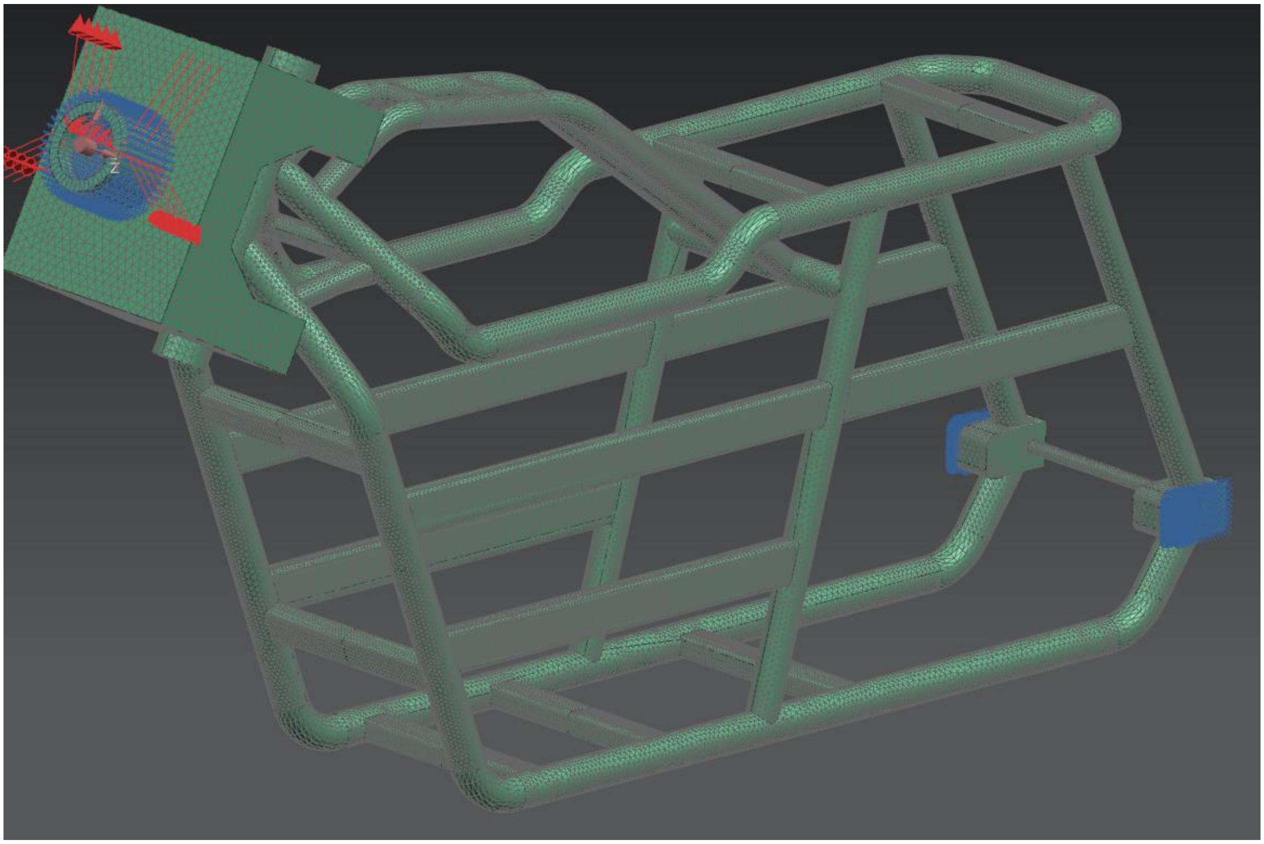

Figure 45: Loading conditions torsional stiffness scenario 2

Results torsional stiffness scenario 2:

The results of this analysis can be compared to the reference torsional stiffness since this setup only allows for torsion in the frame and thus any deformation will be torsional.

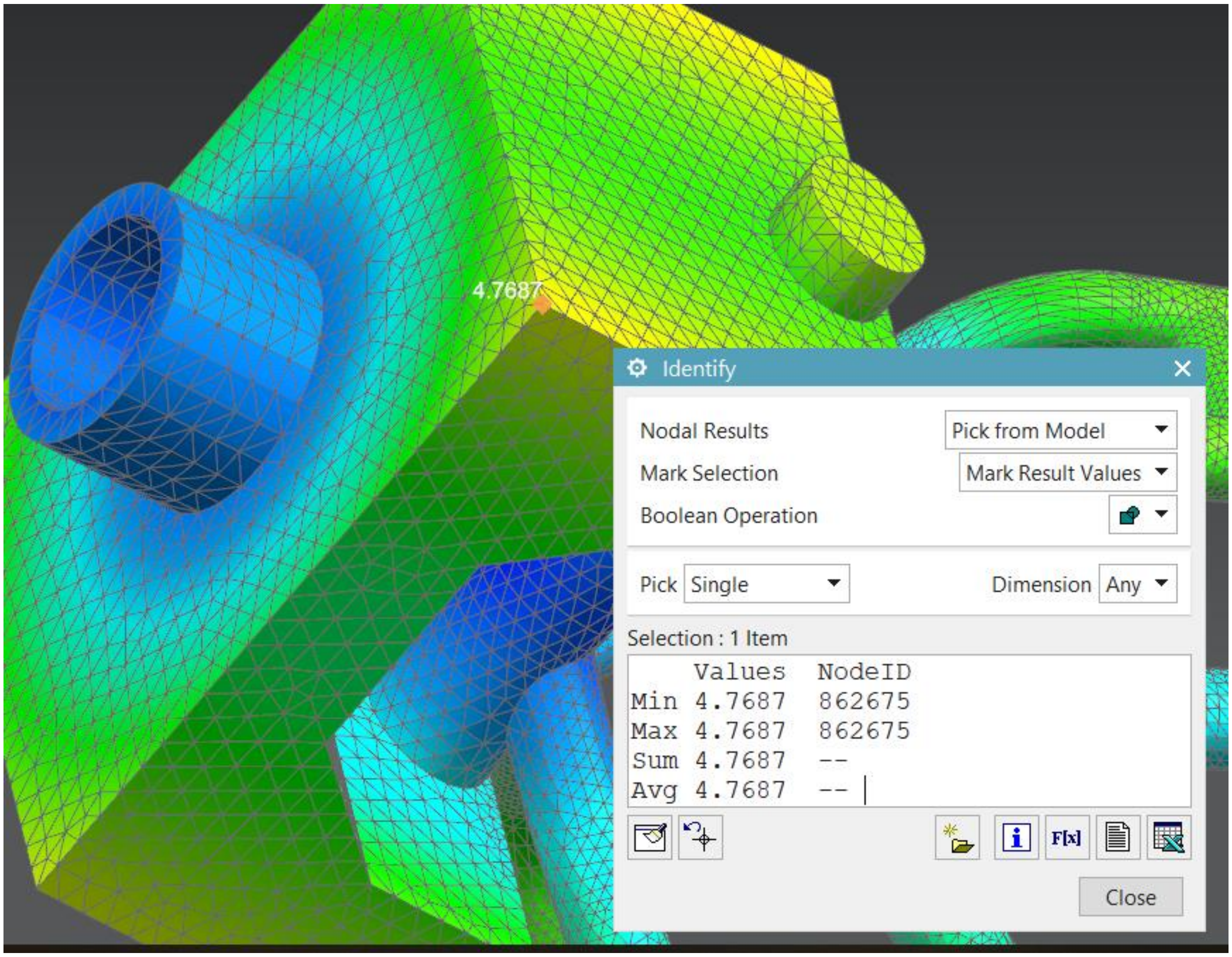

Figure 46: Results torsional loading scenario 2

Rotational displacement of the reference node indicates a displacement 0f 4.7686mm under the given loads and constraints. From the rotational displacement of this node, the angular displacement was calculated to be 1.75°. Given the angular displacement and the torque load of 3000Nm, the torsional stiffness is determined to be 1.714Nm/°. This less than the minimum of 3000Nm/° indicated in table 6.2. These results indicate that a design improvement can/should be made.

Static stress analysis in critical area of motorbike frame:

Longitudinal loading analyzed: Loading conditions during braking.

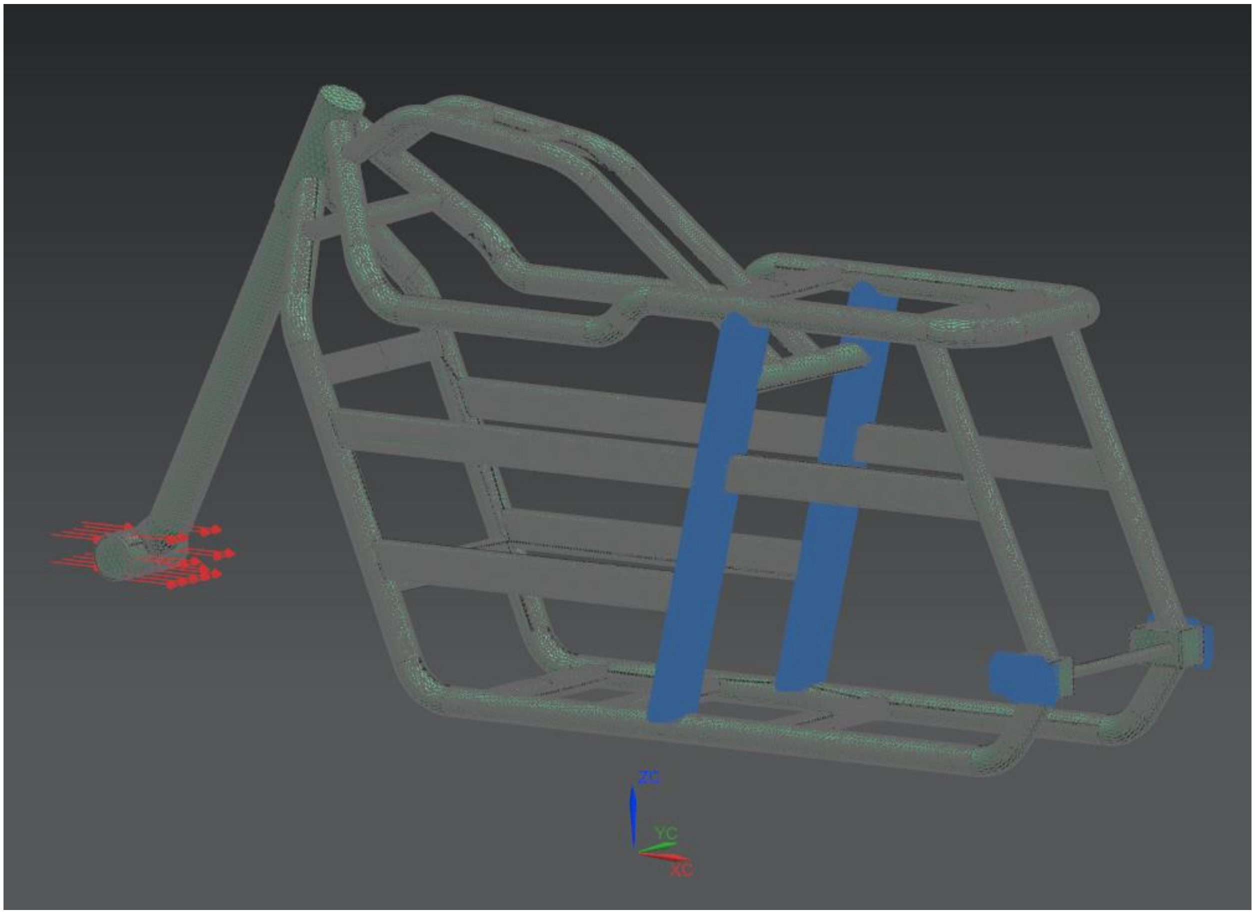

Figure 47: Loading conditions and constraints to evaluate high stress areas during braking

Evaluating Von-Mises stress near the head tube joints. This area is always subject to high stress values a thus shows the importance of good welding joints. Furthermore, the maximum stress value is around 74MPa. This is well below the Yield strength of AISI 4130 of 460MPa.

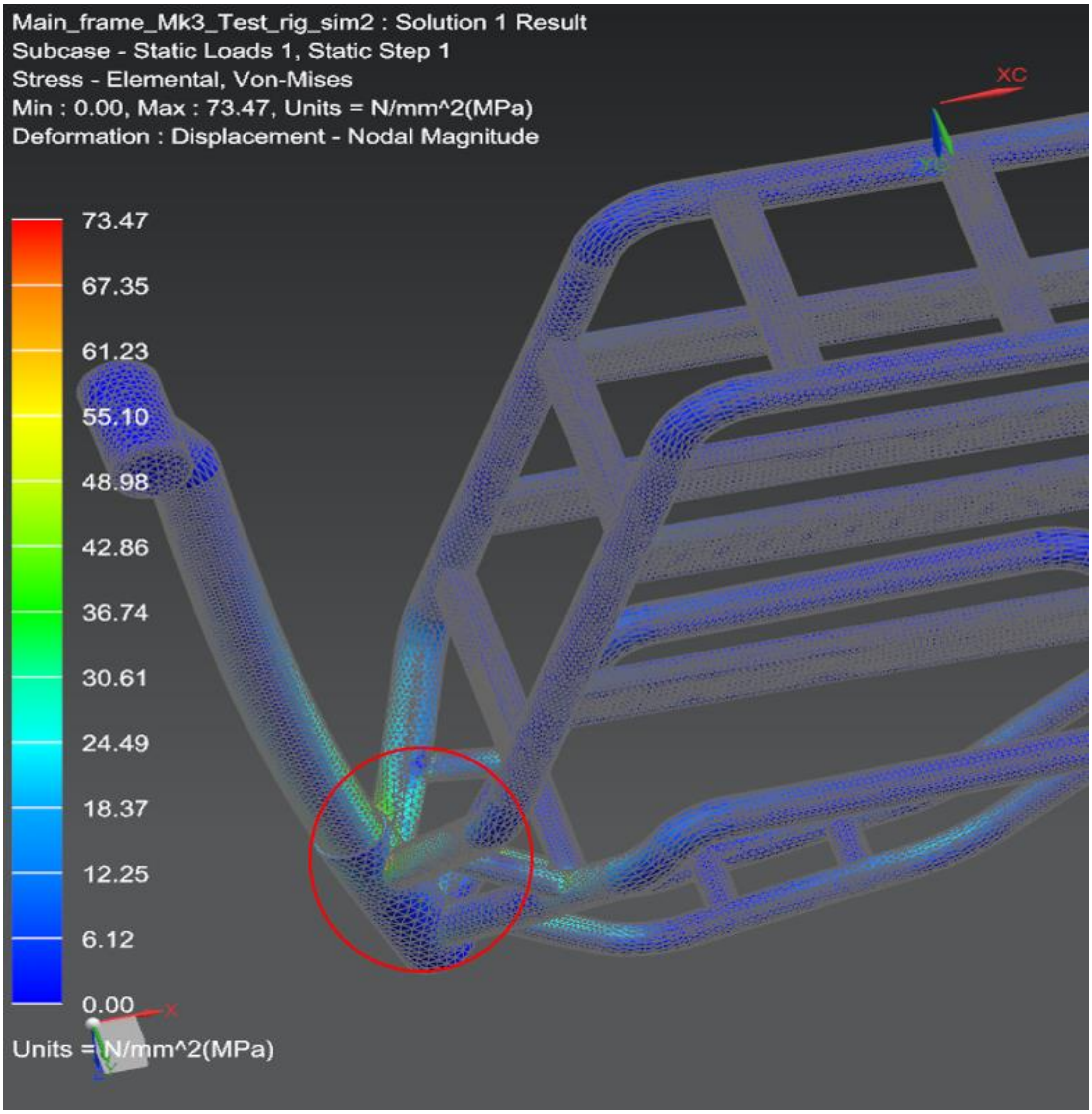

Figure 48: Higher stress in the steering head area due to braking

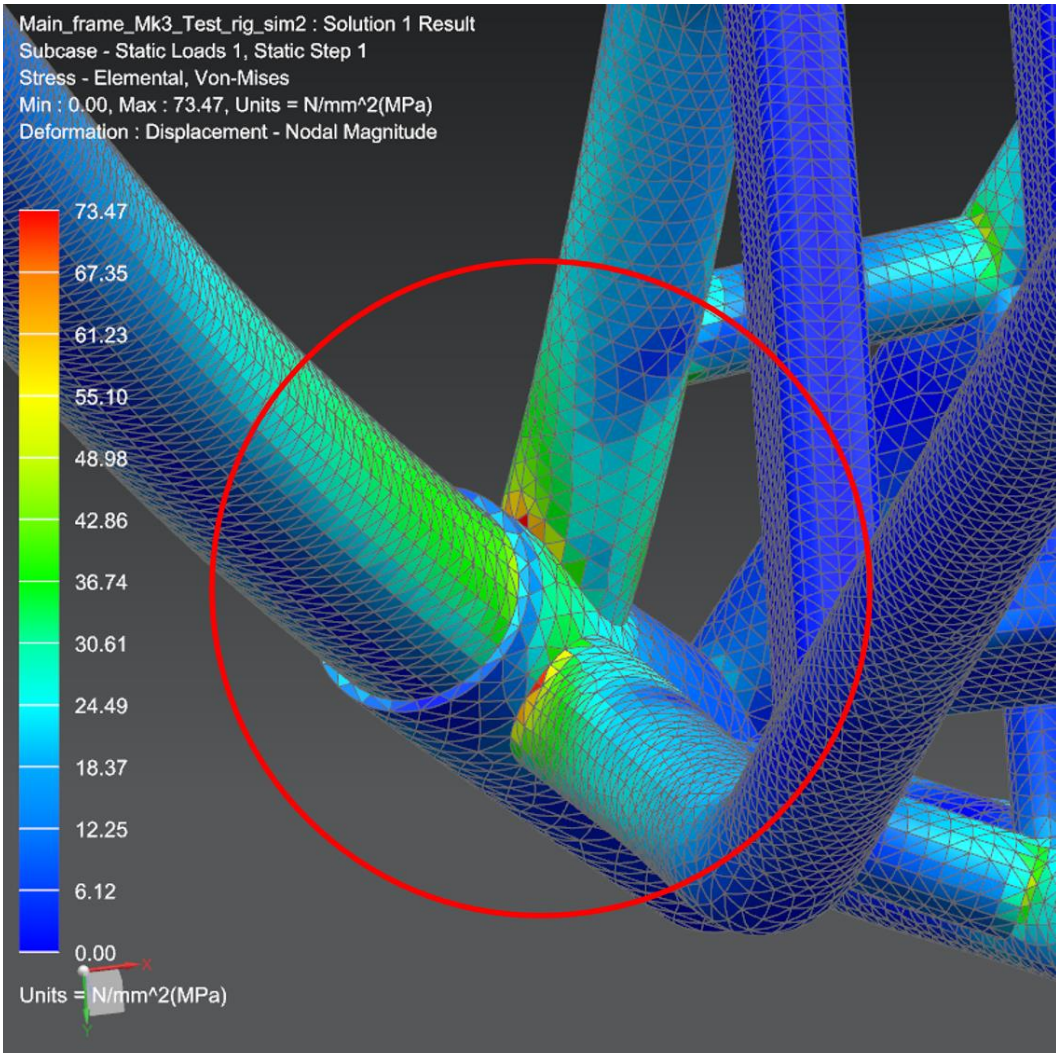

Figure 49: High stress nodes in steering head area during breaking

From figure 6.28 and 6.29 can be seen the high stress locations where eventual re-enforcements can be designed. For a 1000N load on the fork axle, the stress value is far below the yield strength of the material. It should however be considered regarding wear and fatigue over time.

Besides these results it is very important to know that stresses under dynamic loading will be more than under static loading. For this reason, a FEA study must be conducted which aims at accurately determining stress values under dynamic loading conditions. It is for this reason that the stiffness is considered a good measure for static analysis since the reference values are based on static loads.

Design improvements

Based on the FEA study conducted, design improvements can be made based on the results obtained. It is concluded from the results that improvements can be made near the joints of the tubing and the steering head. Based on the results and research on existing designs in Industry, it is decided to re-enforce the steering head area with plate steel, resulting in the design illustrated by the following figure.

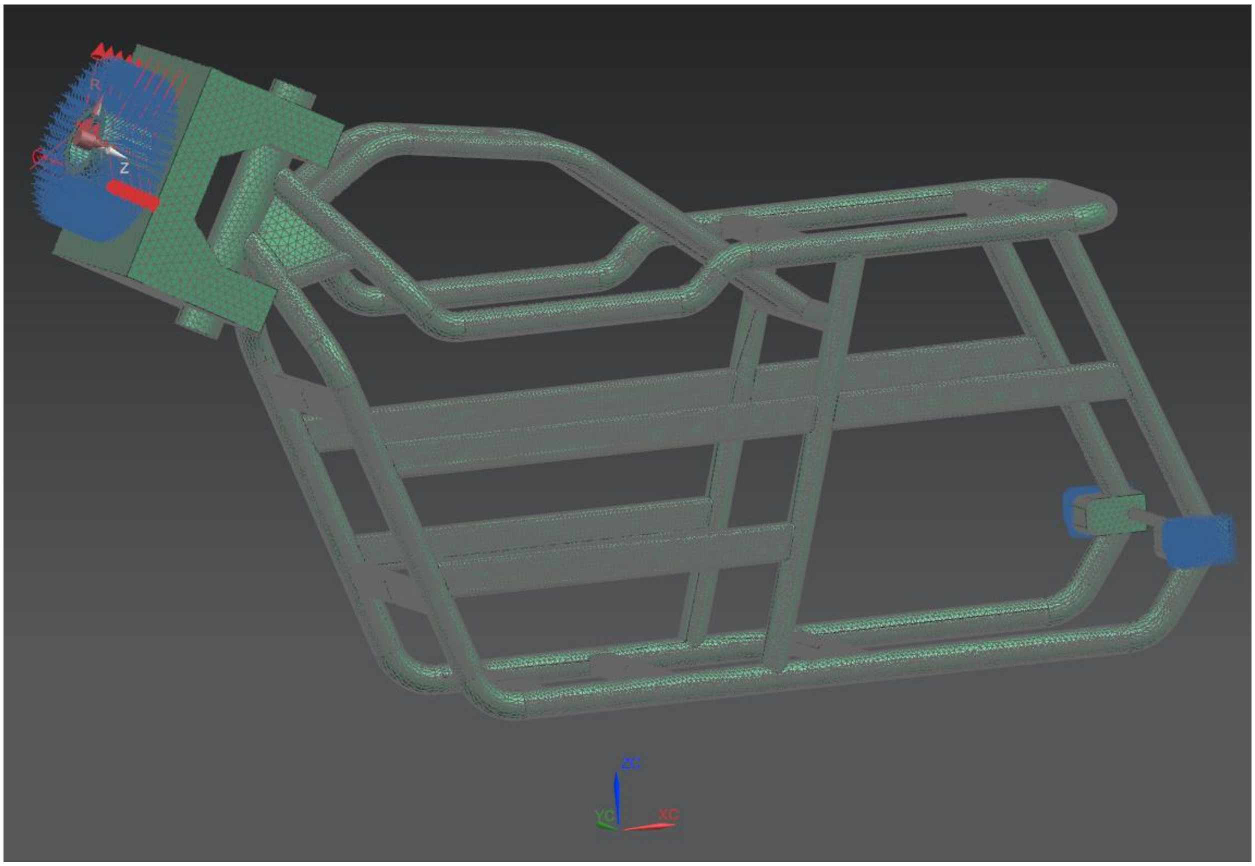

Figure 50: New frame design re-enforce at steering head

For this frame the same load is applied as in scenario 2 of torsional stiffness analysis.

Results:

For the same node analyzed earlier, a displacement of 4.4mm was measured, for which the angular displacement was calculated to be 1.61°. The torsional stiffness of the new frame is calculated to be 1863Nm/°. The proposed design change has improved the torsional stiffness from 1714Nm/° to 1863Nm/° which comes down to an 8.7% increase in torsional stiffness of the frame.

By comparing the torsional stiffness-to-weight ratio of the old and new frame, the proposed design can be evaluated. A successful design change would be to achieve a higher torsional stiffness to weight ratio while abiding by the maximum weight constraint of the frame.

Stiffness to weight ratio of the old frame:

old frame mass: 25.4195kg

old frame stiffness: 1714Nm/°

Stiffness-to-weight ratio: (67.43Nm/°)/kg

Stiffness to weight ratio of the new frame:

New frame mass: 25.6245kg

New frame stiffness: 1863Nm/°

Stiffness-to-weight ratio: (72.7Nm/°)/kg

The new design has improved the value of the stiffness-to-weight ratio from 67.43 to 72.7, which is an increase of 7.81%. The new design is therefore accepted and considered a successful improvement to the old design. Due to the already high mass of the frame and given that 1000CC motorcycle stiffness values are used, the new frame is accepted to be stiff enough and is therefore the frame used for the design of the motorbike.

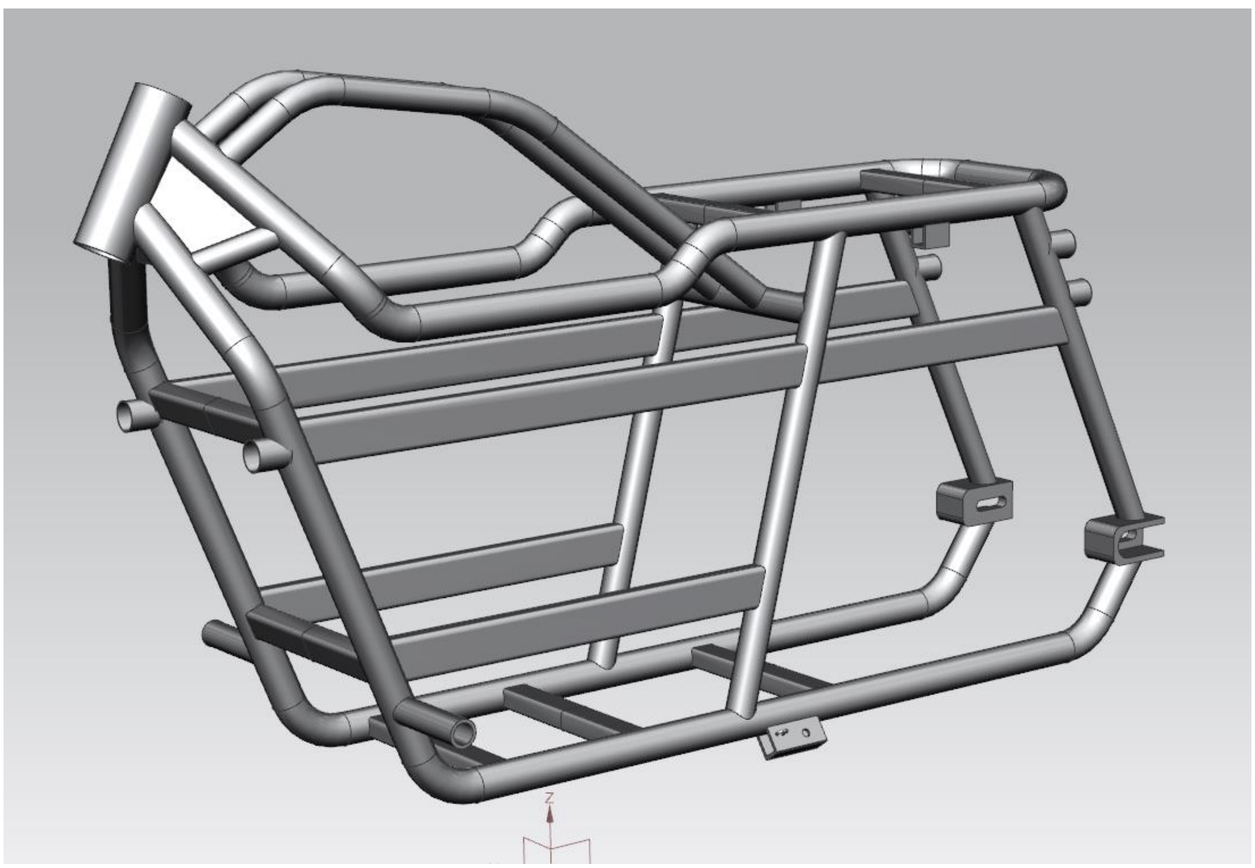

Figure 51: The accepted frame design

6.4 Frame design details and the body

Beside the structural performance of the frame and its geometry, the frame functions as backbone of the motorcycle and all other parts are connected to the frame. Therefore, the frame design dictates where parts are positioned and connected to it.

Steering assembly and steering head:

The steering assembly which should be capable of moving relative to the frame is fastened to the frame by means of tapered roller bearings. The specific bearings used are the SKF 30302 bearings which are based on specifications more than capable of handling the axial loads that the bearings are subject to. Due to these axial loads a tapered bearing is necessary and therefore the selected bearing.

Figure 52: SKF 30302 tapered roller bearing

The SKF 30302 is complemented with a dust/water seal to avoid dust and water entering the bearing and causing corrosion. Furthermore, the bearing is a wear part that requires grease to ensure smooth operation and a pro-longed lifespan.

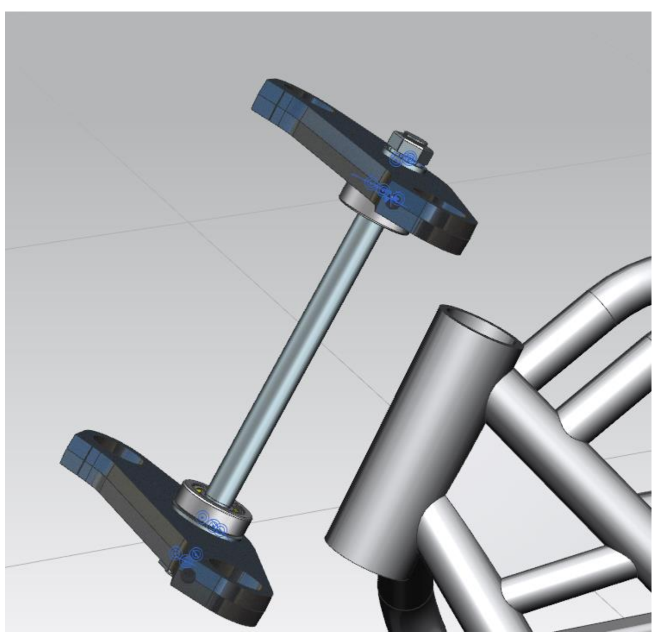

Figure 53: Triple tree assembly connected to steering head

The triple tree assembly as illustrated by figure 53 is connected to the frame's steering head by means of the tapered roller bearings.

Rear axle assembly connection to the frame:

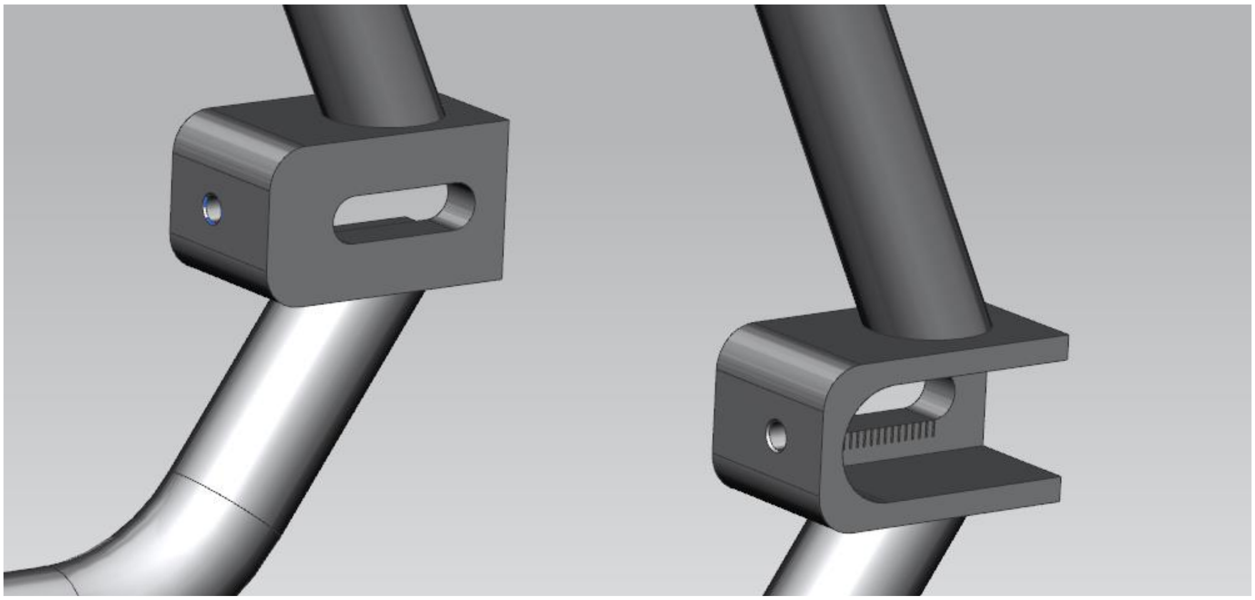

Figure 54: Rear axle connector

The rear axle connector of figure 6.34 is the location where the rear wheel is connected to the frame via the rear axle. This bracket has a treaded M8 screw hole whereby a screw can be used to adjust the location of the axle in the frame. The bracket has markings which provide as reference during the installation of the rear wheel to ensure that the wheel is properly aligned. Fine adjustments can of course be made by turning the M8 screw if the shaft is not aligned. This same screw can be used as tensioner of the transmission chain by sliding the axle to the back and thus increasing the distance between the sprockets of the transmission.

Fenders:

Skid Plate:

The skid plate is the sheet metal part that encloses the bottom of the frame, thereby protecting the parts against rubble from the road surface. It is designed out of aluminum to safe weight. Holes are design in the front of the skid plate to allow for air flow through the battery compartment.

Side Fenders:

The side fenders are the sheet metal panels connected to the frame to enclose the electric parts from direct contact with the elements. The side fenders are also made from aluminum to safe weight and are designed with louvers to allow for air circulation.

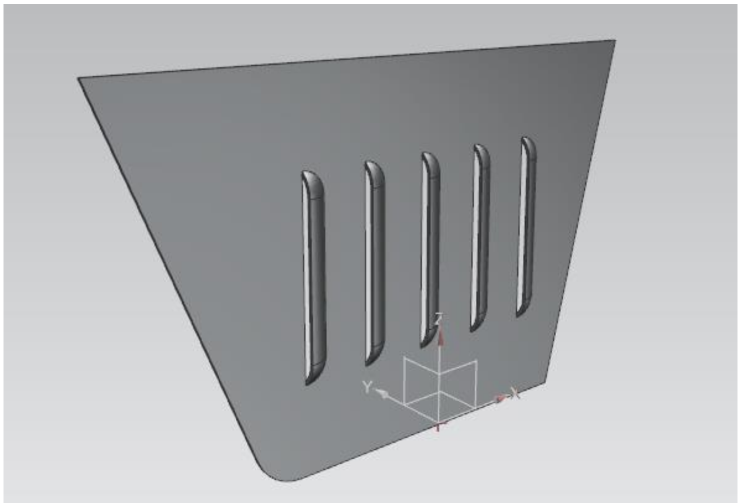

Figure 55: Side fender

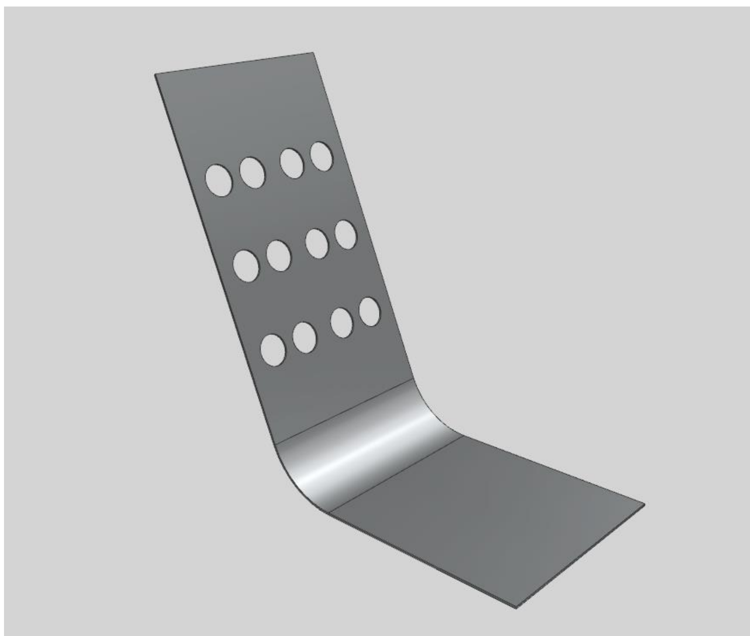

Figure 56: Skid plate

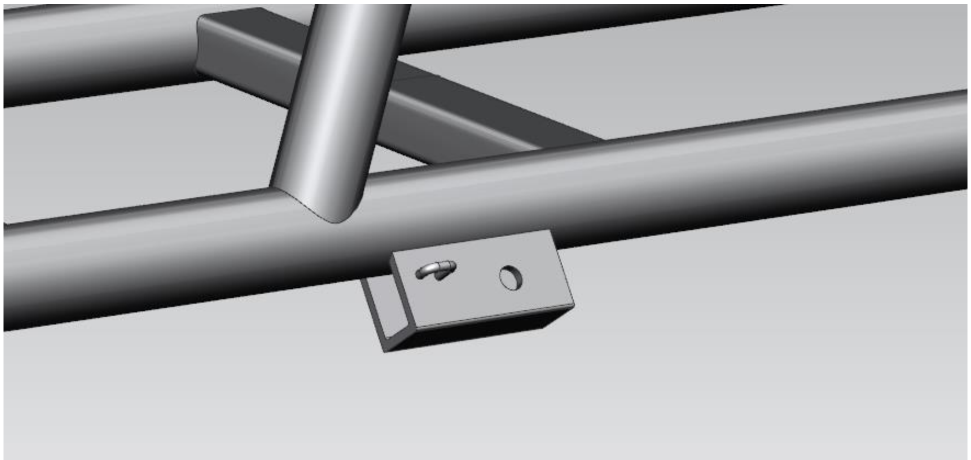

Figure 57: Motorcycle side stand mount

The motorcycle side stand is mounted to the frame's bottom tube in the same vertical plane as the COG of the motorbike assembly. This ensures that the stand is on the balance point of the motorbike and the front and back of the bike relative to the mounting location have the same mass distribution. The stander mount bracket is fitted with a hook to attach a pull spring which is also attached to the side stand. This spring keeps the side stand in the position set by the user.

Figure 58: Motorcycle side stand example with pull spring

6.5 MK3 Motorbike

This paragraph presents the motorbike design in full assembly, the individual custom designed parts and summarizes the motorbike specifications which will be used to verify that the functional requirements as set in the requirement specification have been achieved under the existing constraints.

6.5.1 The MK3 assembly

Figure 59: The MK3 assembly - rear view

Figure 60: The MK3 assembly side view

6.5.2 Specifications summary of the MK3 Motorbike

MK3 Motorbike spec summary	
Mass (kg)	85
Power rating(kW)	3
Peak Power(kW)	5.185
Power supply energy capacity (kWh)	2.120

Table 23: MK3 Motorbike specifications

The vehicle mass is determined by summing up the weight of all the OEM parts and custom designed parts. The OEM part weight is specified however, the part weight of the custom design parts is determined with NX measurements. The breakdown of the calculation of the total mass is described in Appendix D-1.

6.5.3 Final powertrain simulation using final parameters for mass and frontal area

To determine that the powertrain design is correct for the motorbike, the actual mass of the motorbike is simulated in MATLAB to determine the power requirements and energy requirements for the WMTC. Hereby the initial assumed values for vehicle mass are replaced with the actual vehicle mass. The MATLAB simulation results determine that a power supply energy of 2140Wh is necessary to allow the 67.5km of operational range. This is 20Wh more than the current 200Cell battery provides. Furthermore, the peak power required is determined to be 4908W. This is less than the 5185W peak power of the motor.

6.5.4 Cost estimation

The cost calculations for this design are based on the available prizing of components on internet. Furthermore, the cost of the custom design parts is calculated based on the material cost, estimated cost of manufacturing. The total cost of the motorbike is determined by a safety factor of 25% to account for overhead and faulty estimations. The cost of producing a motorcycle depends on many factors, namely the location of product (thus labor cost), the development company’s power regarding negotiations for procurement of parts, the company’s manufacturing capabilities, taxes and other operational cost. For this reason, a large safety factor is considered to determine the cost of the motorbike.

7.0 Design verification and sensitivity to variation, discussion and conclusions

In this chapter, the design is verified whereby according to the verification method specified during the axiomatic design process, the satisfaction of the FRs will be verified. Also, the sensitivity of the FRs to changes in DPs will be evaluated thus evaluating the robustness of the design.

Verification is the process of checking whether a design meets its requirements. According to the scope of this research the FRs to be verified are the FRs related to the powertrain, the power supply and the chassis.

7.1 Verification of the powertrain and power supply design and its sensitivity to DP variation

FR 2.1: Provide tractive power for forward movement of the electric motorbike

Cs 2.1.A: Mk3 shall be powered by electric propulsion

Cs 2.1.B: Mk3 shall have a power rating of maximum 4kW nominal continuous power

Cs 2.1.C: Mk3 shall have a maximum velocity of 50km/hr.

The designed powertrain fulfills the function of providing tractive power to achieve forward movement of the electric motorbike. Cs2.1. A is fulfilled by the selection of a BLDC electric motor. Cs2.1. B is fulfilled by selecting a 3kW motor. Based on the WMTC velocity profile which does not exceed 50km/hr and the actual vehicle parameters it is determined that 4908W power is required. This value is dictated by high acceleration in the drive cycle intended to simulate urban driving. The selected motor has a peak power of 5180W, which the motor can deliver for a short period of time. For this reason, the motor is considered a good selection. It must be noted that the motor power rating is 3kW and thus the motor selected complies with the legislative constraint Cs2.1. B, although its peak power exceeds the constraint value.

The maximum speed of the motor is established by the motor RPM at the end of the constant power region, the transmission ratio and the diameter of the rear tire. This was calculated to be approximately 50km/hr. This value will most likely not be exact due to variation in motor speed, tire pressure etc. For this reason, the electric motor can be electrically limited to 50km/hr. This ease of control is a benefit of electric motors. The design thus abides by the Cs 2.1.C constraint.

FR 2.9: Provide electric power to all onboard electric loads

Cs 2.9.A: Mk3 shall be capable of covering 67.5km in one go.

Cs 2.9.B: Shall provide electric power to user's mobile phone

Based on calculations with the MATLAB model and the actual vehicle parameters, it was noticed that the battery energy capacity was 20Wh too low. This value equals to 0.94% of the total energy capacity of the battery. Provided the redundancy for with which the battery is designed (85% use of charge) and (compensation for 75% capacity fade), it is concluded that the battery can power the motorbike for **at least** 67.5km. The electric system is configured with two voltage converters converting 72V to 12V and 5V, allowing for cell-phone charging.

Sensitivity analysis powertrain and power supply:

The robustness of the design can be evaluated through a sensitivity analysis. Hereby the mass of the vehicle is increased by 20%, and the required power and energy is determined by the MATLAB model. The results of this simulation will be compared to the installed motor power and battery energy and the effect of change in mass will be discussed.

MATLAB Results:

Tractive power required: 5247W

Battery energy required: 2197Wh.

These results indicated that a 20% increase in vehicle mass requires a motor with more power compared to the selected motor. Also, the battery energy required exceeds that of the battery pack. Increasing the motor power would violate the legislative constraint for an E1L vehicle. Based on these findings it is strongly recommended that the current vehicle weight be considered an absolute maximum and that weight reduction is recommended. Weight reduction is most likely successful by reducing the weight of the frame. While maintaining the geometry and structural design of the frame this can be realized through varying the tube thickness of structural members or the material itself.

By changing the material to 6061Al alloy, the frame weight is reduced from 25.1kg to 8kg. This results in:

The tractive power required: 4560W

Battery energy required: 2085Wh.

This results in approximately 440W difference in required power compared to the current power requirements for the motorbike with the steel frame. The battery energy required only differs 60Wh which indicates that during the drive cycle the motor does frequently operate at maximum power.

The WMTC has influenced this design a lot, in that it is the input to the vehicle kinetics model. Hereby it is assumed that the WMTC velocity profile resembles real world driving. The assurance that this drive cycle imitates real world driving is found in the calculated power requirements for the motorbike which are exactly at the maximum power allowed by legislation. It is however important that the drive cycle be validated through real life driving data or by evaluating the powertrain design resulting from the drive cycle and the vehicle kinetics model. The electric motorbike power train consist of standard OEM parts and is therefore not expensive to prototype and test. This design can thus easily be validated by prototyping its sub-systems and comparing these to the design specifications.

7.2 Verification of the chassis design

FR 2.4: **Provide structural support to rider and parts, distribute weight and maintain geometric relationship**

Cs 2.4.A: Maintain geometric relationship during operation

As was concluded in chapter 5, the steering function is also influenced by the frame and therefore the steering FR is included in this verification.

FR 2.2: **Provide ability to steer vehicle to change direction**

Cs 2.2.A: Turning radius shall not exceed 2 meters for a maximum steering angle of 45degrees.

Cs 2.3.B: Ability to steer shall be maintained at low speeds

The performance of the chassis is determined by its ability to maintain geometric dimensions. The frame stiffness is used as measure to denote this performance. Due to the lack of literature reference for frame stiffness for motorcycles in this power category, the reference stiffness for 1000CC bikes has been used. The objective was to approach this stiffness where it was not possible to achieve these frame stiffness values. This has resulted in a very stiff frame that is referenced to 1000CC bike standards.

The selected design has a mass of 25.1 kg. This is on the heavy side for a low powered motorbike. It is suggested that the use of aluminum be evaluated. The exact frame construction in AL 6061 alloy would weight 8kg. However, FEA results have indicated that the lateral and torsional stiffness are reduced by a factor 3. This is in accordance with the fact that aluminum has a stiffness to weight ratio that is 3 times less than that of steel.

It is important to understand that no FEA study can replace physical testing of the frames. Motorcycle developing companies conduct rigorous tests whereby they analyze stiffness, fatigue and the frame’s resistance to abuse. The benefit of the tubular frame in this regard is that it allows for easy prototyping. Changes in the design do not require new expensive tooling. It is thus suggested that physical tests be conducted on both the stiffness of aluminum and steel configurations of the frame and a decision/redesign can be suggested based on the results thereof. Also prototypes of the frame can be built for evaluating its handling capabilities and response to user input.

7.3 Discussion on the design method used and conclusions

The design method implementing axiomatic design facilitates a structured approach to motorcycle design. It allows the designer to divide the big design problem into more manageable portions. The axiomatic design principle has the benefit that it forces a designer to start at the customer and think in terms of functionality. It provides a structured approach to come to a solution and requires that solution to be robust. It also enhances traceability, as to what functions need to be realized by which parts. Due to a design with many parts, this can be difficult. The major drawback identified of the axiomatic design is that the axiomatic design only helps with designing for the functional requirements specified but does not validate whether the functions specified are the right functional requirements to design for. Application of the axiomatic design thus is only beneficial when the designer is knowledgeable and within the field of expertise of the product to be designed. A design resulting from the implementation of the axiomatic design principle is as good as the designer's ability to identify the right functional requirements.

The MATLAB vehicle kinetics model has aided tremendously in the design by allowing for quick iterations and calculations throughout the design process. The vehicle parameters in the MATLAB model can be easily updated and quick design iterations are facilitated. The MATLAB model is as good as its input; therefore, the drive cycle is an important factor. The World Motorcycle Test Cycle used has produced expected results in that it results in powertrain requirements that correspond to that of the vehicle category.

Siemens NX used as 3D CAD tool has aided in creating a detailed 3D model of the chassis. Creation of 3D drawings is fast with Siemens NX which allows for 3D ideation iterations. During the project several frame designs were created for which the form and aesthetics were evaluated. The drawback to Siemens NX is that the software lacks community support. Often problems were encountered during the design for which it was very difficult finding solutions online. Simcenter's FEA capabilities have enabled the qualitative evaluation of designs whereby the best design was chosen.

Based on the verification conducted, is concluded that an acceptable motorbike design is achieved which fulfills the functional requirements specified under the present constraints. Due to lack of references for stiffness values for the frame, a design was produced that has most likely a lot of redundancy. This has resulted in a relatively heavy frame. It is therefore concluded that due to lack of reference the frame design is not optimal in terms of its weight. Furthermore, the power supply has been designed with very strict specifications, taking in account all factors that influence battery capacity and it is therefore guaranteed that the power supply can achieve a operational range of 67.5km which is 3 time the average home to work distance in the Netherlands. The motor selection is restricted by legislation and therefore the maximum motor power is reached and increasing motor power would result in the motorbike falling in a different motorcycle category, requiring a motorcycle license. The cost of the motorbike is estimated to be at maximum 3500 Euro. Hereby a 25% safety factor was used to ensure that the calculated cost is a maximum value. Furthermore, low volume internet prices were used for OEM parts and economies of scale were not considered. Based on these considerations, it is concluded that the design is acceptable, however it can be optimized. The design allows for easy prototyping which will be required in further development of the design.

7.4 Recommendations

First, a motorcycle design is not to be conducted by one designer, it is a multi-disciplinary team effort. Secondly, the axiomatic design process can help with the design of a motorbike, however identifying the FRs must be done by experienced motorbike designers to ensure that the right FRs are identified.

Although the design is acceptable on paper, physical prototyping is required to verify that the on-paper results correspond to the real-life performance of the motorbike. Motorcycles are subject to rigorous safety testing procedures which include destructive tests. These tests must be conducted on prototypes before mass production is initiated. The tubular design of the frame facilitates cheap prototyping and is thus economical to test and to apply changes afterwards.

The author recommends that future research is conducted on designing a lightweight frame within the boundaries of specified geometry and dimensions to make an existing motorbike design more efficient. For the purpose of research, it might be interesting to use topology optimization to design a more efficient frame. Topology optimization might help a design team identify where structural members should be located.

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Appendix A.: Requirement specification summary

This appendix summarized the functional requirements and design constraints of each functional hierarchical level of the MK3 motorbike.

Level 1 hierarchy: FR to be satisfied by the MK3 motorbike system

FR1.0:	Provide a means to transport one commuter in the Netherlands from home to work and back.
Cs 1.0.A:	Commuter should need no more than an AM category license and the solution should contain 2 wheels in a single-track configuration.
Cs 1.0.B:	Solution should be capable of traveling 3 times the average home-to-work distance in the Netherlands, which equals 67.5km.
Cs 1.0.C:	The commuter should be able to easily transport himself through urban traffic and thus requiring good maneuverability.
Cs 1.0.D:	The solution should be ergonomic in terms of physical interaction between human and machine
Cs 1.0.E:	The solution should cost no more than 2500 Euro to produce

Level 2 hierarchy: FRs to be satisfied by the MK3 second level hierarchy of sub-systems

FR 2.1:	**Provide tractive power for forward movement of the electric motorbike**
Cs 2.1.A:	Mk3 shall be powered by electric propulsion
Cs 2.1.B:	Mk3 shall have a power rating of maximum 4kW nominal continuous power
Cs 2.1.C:	Mk3 shall have a maximum velocity of 50km/hr.

FR 2.2:	**Provide ability to steer vehicle to change direction**
Cs 2.2.A:	Turning radius shall not exceed 2 meters for a maximum steering angle of 45degrees.
Cs 2.3.B:	Ability to steer shall be maintained at low speeds

FR 2.3:	**Provide ability to stop forward movement of vehicle**

Cs 2.3.A: Distance to standstill for given initial speed:-

FR 2.4: Provide structural support to rider and parts, distribute weight and maintain geometric relationship

Cs 2.4.A: Keep center of gravity as low as possible (COG below wheel axles)

Cs 2.4.B: Maintain geometric relationship during operation

FR 2.5: Interact with user and other stakeholders

FR 2.6: Allow for nighttime operation

Cs 2.6.A: Nighttime operation devices should comply with legislation

Cs 2.6.B: Power supply should facilitate auxiliary voltage for lighting

FR 2.7: Reduce road noise felt by the user

FR 2.8: Protect parts from the elements and protect user from moving parts

Level 3 hierarchy: FRs to be satisfied by the MK3 second third hierarchy of sub-systems

FR 3.1.1: Store energy to supply electric power for load

Cs 3.1.1.A: Energy stored must be enough to travel 67.5km

Cs 3.1.1.B: Energy storage shall provide nominal voltage required by the propulsion unit

Cs 3.1.1.C: Energy storage shall provide nominal power required by propulsion unit

FR 3.1.2: Monitor and protect electric power supply

Cs 3.1.2.A: Shall comply with system voltage and power

FR 3.1.3: Provide propulsion by converting electrical energy to mechanical energy to supply torque and speed

Cs 3.1.3.A: Power rating shall not exceed 4kW.

FR 3.1.4: Control propulsion unit and allow for generator operation of propulsion unit

Cs 3.1.4.A: Shall comply with voltage and power rating of propulsion unit

FR 3.1.5: Transmit mechanical energy from propulsion unit and convert torque and speed

Cs 3.1.5.A: Capable of withstanding the power of the propulsion unit

Cs 3.1.5.B: Capable of converting motor speed and torque to final drive speed and torque without exceeding vehicle speed of 50km/hr

FR 3.1.6: Transmit tractive force to road surface for specified speed

Appendix B.: Axiomatic design corollaries and theorems

Axiomatic design Corollaries and Theorems

Corollaries:

Corollary 1	(Decoupling of Coupled Designs): Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the designs proposed.
Corollary 2	(Minimization of FRs): Minimize the number of FRs and constraints.
Corollary 3	(Integration of Physical Parts): Integrate design features into a single physical part if the FRs can be independently satisfied in the proposed solution.
Corollary 4	(Use of Standardization): Use standardized or interchangeable parts if the use of these parts is consistent with the FRs and constraints.
Corollary 5	(Use of Symmetry): Use symmetrical shapes and/or components if they are consistent with the FRs and constraints.
Corollary 6	(Largest Design Ranges): Specify the largest allowable design range in stating FRs.
Corollary 7	(Uncoupled Design with Less Information): Seek an uncoupled design that requires less information than coupled designs in satisfying a set of FRs.
Corollary 8	(Effective Reangularity of a Scalar) The effective reangularity R for a scalar coupling "matrix" or element is unity [REF].

General design theorems:

Theorem 1	(Coupling Due to Insufficient Number of DPs): When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied.
Theorem 2	(Decoupling of Coupled Design): When a design is coupled because of a larger number of FRs than DPs (i.e., m > n), it may be decoupled by the addition of new DPs so as to make the number of FRs and DPs equal to each other if a subset of the design matrix containing n x n elements constitutes a triangular matrix.
Theorem 3	(Redundant Design): When there are more DPs than FRs, the design is either a redundant design or a coupled design.
Theorem 4	(Ideal Design): In an ideal design, the number of DPs is equal to the number of FRs and the FRs are always maintained independent of each other.
Theorem 5	(Need for New Design): When a given set of FRs is changed by the addition of a new FR, by substitution of one of the FRs with a new one, or by selection of a completely different set of FRs, the design solution given by the original DPs cannot satisfy the new set of FRs. Consequently, a new design solution must be sought.

Theorem 6 (Path Independence of Uncoupled Design): The information content of an uncoupled design is independent of the sequence by which the DPs are changed to satisfy the given set of FRs.

Theorem 7 (Path Dependency of Coupled and Decoupled Design): The information contents of coupled and decoupled designs depend on the sequence by which the DPs are changed to satisfy the given set of FRs.

Theorem 8 (Independence and Design Range): A design is an uncoupled design when the designer-specified range is greater than

$$\left(\sum_{\substack{i \neq j \\ j=1}}^{n} \frac{\partial \mathrm{FRi}}{\partial \mathrm{DPj}} \Delta \mathrm{DPj} \right)$$

in which case, the non-diagonal elements of the design matrix can be neglected from design consideration.

Theorem 9 (Design for Manufacturability):

For a product to be manufacturable with reliability and robustness, the design matrix for the product, [A] (which relates the FR vector for the product to the DP vector of the product), times the design matrix for the manufacturing process, [B] (which relates the DP vector to the PV vector of the manufacturing process), must yield either a diagonal or a triangular matrix. Consequently, when either [A] or [B] represents a coupled design, the independence of FRs and robust design cannot be achieved. When they are full triangular matrices, either both of them must be upper Triangular or both, lower triangular for the manufacturing process to satisfy independence of functional requirements.

Theorem 10 (Modularity of Independence Measures): Suppose that a design matrix [DM] can be partitioned into square submatrices that are nonzero only along the main diagonal. Then the reangularity and semangularity for [DM] are equal to the product of their corresponding measures for each of the non-zero submatrices.

Theorem 11 (Invariance): Reangularity and semangularity for a design matrix [DM] are invariant under alternative orderings of the FR and DP variables, as long as the orderings preserve the association of each FR with its corresponding DP.

Theorem 12 (Sum of Information) The sum of information for a set of events is also information, provided that proper conditional probabilities are used when the events are not statistically independent.

Theorem 13 (Information Content of the Total System): If each DP is probabilistically independent of other DPs, the information content of the total system is the sum of the information of all individual events associated with the set of FRs that must be satisfied.

Theorem 14 (Information Content of Coupled versus Uncoupled Designs): When FRs are changed from one state to another in the functional domain, the information required for the change is greater for a coupled design than for an uncoupled design.

Theorem 15 (Design-Manufacturing Interface): When the manufacturing system compromises the independence of the FRs of the product, either the design of the product must be modified or a new manufacturing process must be designed and/or used to maintain the independence of the FRs of the products.

Theorem 16 (Equality of Information Content): All information contents that are relevant to the design task is equally important regardless of its physical origin, and no weighting factor should be applied to them.

Theorem 17 (Design in the Absence of Complete Information) Design can proceed even in the absence of complete information only in the case of a decoupled design if the missing information is related to the off-diagonal elements.

Theorem 18 (Existence of an Uncoupled or Decoupled Design) There always exists an uncoupled or a decoupled design that has less information than a coupled design.

Theorem 19 (Robustness of Design) An uncoupled design and a decoupled design are more robust than a coupled design in the sense that it is easier to reduce the information content of designs than to satisfy the Independence Axiom.

Theorem 20 (Design Range and Coupling)
If the design ranges of uncoupled or decoupled designs are tightened, they may become coupled designs. Conversely, if the design ranges of some coupled designs are relaxed, the designs may become either uncoupled or decoupled.

Theorem 21 (Robust Design When the Design Range has a Non-Uniform pdf): If the probability distribution function (pdf) of the FR in the design range is non-uniform, the probability of success is equal to 1 when the system range is inside the design range.

Theorem 22 (Comparative Robustness of a Decoupled Design): Given the maximum design ranges for a given set of FRs, decoupled designs cannot be as robust as uncoupled designs in that the allowable tolerances for the DPs of a decoupled design are less than those of an uncoupled design.

Theorem 23 (Decreasing Robustness of a Decoupled Design) The allowable tolerance and thus the robustness of a decoupled design with a full triangular matrix diminish with an increase in the number of functional requirements.

Theorem 24 (Optimum Scheduling) Before a schedule for robot motion or factory scheduling can be optimized, the design of the tasks must be made to satisfy the Independence Axiom by adding decouplers to eliminate coupling. The decouplers may be in the form of a queue or of separate hardware or buffer.

Theorem 25 ("Push" System vs "Pull" System): When identical parts are processed through a system, a "push" system can be designed with the use of decouplers to maximize productivity, whereas when irregular parts requiring different operations are processed, a "pull" system is the most effective system.

Theorem 26 (Conversion of a System with Infinite Time-Dependent Combinatorial Complexity to a System with Periodic Complexity) Uncertainty associated with a design (or a system) can be reduced significantly by changing the design from one of serial combinatorial complexity to one of periodic complexity [REF].

Theorems related to design and decomposition of large systems:

Theorem S1 (Decomposition and System Performance): The decomposition process does not affect the overall performance of the design if the highest-level FRs and Cs are satisfied and if the information content is zero, irrespective of the specific decomposition process.

Theorem S2 (Cost of Equivalent Systems): Two "equivalent" designs can have substantially different cost structures, although they perform the same set of functions and they may even have the same information content.

Theorem S3 (Importance of High-Level Decisions) The quality of design depends on the selection of FRs and the mapping from domain to domain. Wrong selection of FRs made at the highest levels of design hierarchy cannot be rectified through the lower-level design decisions.

Theorem S4 (The Best Design for Large Systems): The best design for a large flexible system that satisfies m FRs can be chosen among the proposed designs that satisfy the Independence Axiom if the complete set of the subsets of FRs that the large flexible system must satisfy over its life is known a priori.

Theorem S5 (The Need for a Better Design): When the complete set of the subsets of FRs that a given large flexible system must satisfy over its life is not known a priori, there is no guarantee that a specific design will always have the minimum information content for all possible subsets and thus there is no guarantee that the same design is the best at all times.

Theorem S6 (Improving the Probability of Success): The probability of choosing the best design for a large flexible system increases as the known subsets of FRs that the system must satisfy approach the complete set that the system is likely to encounter during its life.

Theorem S7 (Infinite Adaptability versus Completeness): A large flexible system with infinite adaptability (or flexibility) may not represent the best design when the large system is used in a situation where the complete set of the subsets of FRs that the system must satisfy is known a priori.

Theorem S8 (Complexity of a Large Flexible System): A large system is not necessarily complex if it has a high probability of satisfying the FRs specified for the system.

Theorem S9 (Quality of Design): The quality of design of a large flexible system is determined by the quality of the database, the proper selection of FRs, and the mapping process [REF].

Appendix C.: Frame designs considered during ideation

Appendix D.: Design calculations

D1: Total mass of motorcycle

Part	Quantity	Mass (kg)	Total mass (kg)
3kW motor	1	7.3	7.3
Frame	1	25.1	25.1
Motor driver	1	1.9	1.9
Tire front	1	4	4
Tire rear	1	4	4
Rim front	1	2.1	2.1
Rim rear	1	2.1	2.1
Steering assembly	1	6.6	6.6
Driver sprocket	1	0.67	0.67
Driven sprocket	1	5.05	5.05
Chain	1	1	1
Seat	1	1	1
Battery module	1	9.6	9.6
Battery module case	1	3.5	3.5
Side fenders	2	1.15	2.3
Rear fenders	2	0.3	0.6
Skid plate	1	1.5	1.5
Light bracket	1	0.1	0.1
Led bars	2	0.5	1
Side stand	1	0.4	0.4
Fasteners +bearings+ misc.		5	5

Table 24 Calculation of the total mass of MK3

Total mass: 85kg

D2: Cost calculation

The total cost is calculated to be 2740 Euro for which a margin of 25% was added. This resulted in an estimated maximum cost of 3500 Euro for the motorbike. Hereby, the internet prices of OEM parts are used as reference values. It is most likely that these values decrease as order quantities increase based on economies of scale. Because the negotiation power of companies and their existing supply chain infrastructure plays a tremendous role in the cost of parts, it is difficult to provide exact calculations, which is also not the objective of this study.

Part	Quantity	Unit cost (Euro)	Total cost (Euro)
OEM Parts			
Motor	1	260	260
Motor drive + throttle control	1	234	234
Battery module	1	334	334
BMS circuit board	2	40	80
4AWG wire (1meter)	2	18	36
Battery case	1	16	16
Tire Front	1	60	60
Tire Rear	1	60	60
SKF Roller Chain	1	25	25
SKF Driver Sprocket	1	20	20
SKF Driven Sprocket	1	60	60
SKF roller bearing	4	5	20
SKF tapered roller bearing	2	10	20
Dust seal	4	5	20
Snap ring	4	2	8
Front brake caliper+disc+2handles	1	50	50
Fork	2	60	120
Design Specific Parts			
Frame (AISI 3140)	1	255	255
Saddle	1	100	100
Motor bracket	1	50	50
Body parts	1	200	200
Seat	1	100	100
Handlebar	1	40	40
Parts Overhead	-	250	250
Assembly	-	350	350
		Total estimated cost	**2768**
		25% Safety factor	**3460**